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AUTHORS

Caroline Dieckhöner

Harald Hecking

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Institute of Energy Economics at the University of Cologne (EWI)
www.ewi.uni-koeln.de

Institute of Energy Economics
at the University of Cologne (EWI)

Alte Wagenfabrik
Vogelsanger Straße 321
50827 Köln
Germany

Tel.: +49 (0)221 277 29-100
Fax: +49 (0)221 277 29-400
www.ewi.uni-koeln.de

CORRESPONDING AUTHOR

Caroline Dieckhöner
Institute of Energy Economics at the University of Cologne (EWI)
Tel: +49 (0)221 277 29-312
Fax: +49 (0)221 277 29-400
Caroline.Dieckhoener@ewi.uni-koeln.de

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Caroline Dieckhöner
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Greenhouse gas abatement cost curves of the residential heating market – a microeconomic approach

Caroline Dieckhöner[a,**], Harald Hecking[a,**]

[a] *Institute of Energy Economics at the University of Cologne (EWI), Vogelsanger Str. 321, 50827 Cologne, Germany*

Abstract

In this paper, we develop a microeconomic approach to deduce greenhouse gas abatement cost curves of the residential heating sector. By accounting for household behavior, we find that welfare-based abatement costs are generally higher than pure technical equipment costs. Our results are based on a microsimulation of private households' investment decision for heating systems until 2030. The households' investment behavior in the simulation is derived from a discrete choice estimation which allows investigating the welfare costs of different abatement policies in terms of the compensating variation and the excess burden. We simulate greenhouse gas abatements and welfare costs of carbon taxes and subsidies on heating system investments until 2030 to deduce abatement curves. Given utility maximizing households, our results suggest a carbon tax to be the welfare efficient policy. Assuming behavioral misperceptions instead, a subsidy on investments might have lower marginal greenhouse gas abatement costs than a carbon tax.

Keywords: Household behavior, discrete choice, Pigou, greenhouse gas abatement costs

JEL classification: C35, C61, Q47, Q53, R21

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1. Introduction and Background

The social costs of greenhouse gas emissions as a global externality are more and more spotlighted in the worldwide public discussion. Since the UNCED[1] in Rio de Janeiro 1992, but latest since the Stern Review

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[*] The authors are solely responsible for the content of this paper, which may not necessarily represent the opinion of EWI.

[**] Corresponding authors. Tel. +49-221-27729-100.

Email addresses: Caroline.Dieckhoener@uni-koeln.de (Caroline Dieckhöner), Harald.Hecking@uni-koeln.de (Harald Hecking)

[1] United Nations Conference on Environment and Development

(Stern, 2007) and the IPCC report on climate change in 2007 (IPCC, 2007), politicians, engineers, ecologists and economists argue about optimal strategies of greenhouse gas avoidance. Consequently, national objectives and policies for greenhouse gas abatement have been introduced in the last years. Besides the emissions produced by major polluters such as the energy sector, a significant part of overall emissions stem from small emittents such as households. Hence, the achievement of reduction objectives strongly depends on the behavior of economic agents.

The heating sector is thereby a good example. In the discussion of greenhouse gas abatement, heat provision in residential buildings is often tagged the sleeping giant. Besides enhancing thermal insulation, the replacement of inefficient and carbon intense heating systems holds a huge potential of emission reduction. However, there is no easy wake-up call: the total greenhouse gas emissions in the residential sector is the aggregated result of millions of households' individual decisions on heating systems and building insulation. Thereby, each one faces different investment costs, habits, preferences and therefore motivation to reduce his building's greenhouse gas footprint. Subsidies and carbon taxes are two prominent policy measures to incentivize greenhouse gas reduction in the residential sector. However, either strategy imposes costs: not solely monetary for technical equipment, but also in terms of welfare losses due to tax and subsidy distortions. Thus, to quantify total social costs of emission reduction, our paper aims at deducing a welfare-based greenhouse gas abatement cost curve of the residential heating sector, thereby accounting for costs and households' behavior and preferences.

Several studies have already addressed pollution abatement curves based on welfare effects of environmental taxes using a general-equilibrium approach (Bovenberg and Goulder, 1996; Ballard and Medema, 1993). In addition to these studies on the macro level, among the analyses on the micro-level most studies are mainly technical thereby focusing on the technical equipment costs (Swan and Ugursal, 2009; Kavgic et al., 2010). One example of such technology-based approach is a recently published study by McKinsey & Company, Inc. (2009), which identifies significant energy savings with low costs for society. Huntington (2011) discusses the overestimation of the reduction potential in the McKinsey & Company, Inc. (2009) study, which results from assuming adoption rates of technologies of 100%. In an aggregated approach Huntington (2011) shows that accounting for the households' behavior and their reactions on policy measures would revise the greenhouse gas abatement curves downwards as well as by including policy costs. There are microeconomic analyses that investigate the impact of environmental policies: Tra (2010) evaluates the benefits of air quality improvements in a discrete choice locational equilibrium model that accounts for welfare impacts of policy interventions in a microeconomic context. However, to date there are few attempts to derive microeconomic greenhouse gas abatement curves that account for the behavior of economic agents. Our paper fills this gap.

In the light of current literature, our paper contributes to public economics, the analytical and the numerical literature in two ways: First, it extends earlier work by being the first paper to derive a greenhouse gas abatement cost curve based on household behavior and welfare losses on externalities in a microeconomic setting. We have chosen this approach because the abatement potential of many externalities depends on the behavior of microeconomic agents. Second, the paper investigates the impact of carbon taxes and subsidies numerically. Here we expand on the analytical work by developing a numerical microsimulation model based on an empirical discrete choice estimation. Microsimulation models are a useful tool to analyze the diffusion of technologies and the impact of environmental policies. Kazimi (1997) uses a microsimulation model to investigate the effects of vehicle price changes in emissions in the Los Angeles area. She applies a microsimulation model which – similar to our model DIscrHEat – also incorporates the results of a discrete choice estimation.

The use of the numerical model enables us to derive specific greenhouse gas abatement cost curves and analyze the welfare effects of different policies. Our paper thus combines the strengths of analytical and numerical approaches: in a stylized analytical model we present a microeconomic approach of how to derive a greenhouse gas abatement curve based on welfare measurement in discrete choice models. Our numerical model based on empirical household behavior allows to derive greenhouse gas abatement curves of specific policies and to explore their mechanisms in a more realistic setting.

To conduct our analysis, we choose Germany as exemplary case for two reasons: first, the insulation level of domestic buildings is already very high and further insulation is very cost-intense in terms of greenhouse gas abatement compared to the installation of new heating systems (International Energy Agency (IEA), 2011; Buildings Performance Institute Europe (BPIE), 2011). Second, since more than 90% of all residential buildings are heated decentrally, the households' individual heating system decisions have a strong impact on the total greenhouse gas emissions. Both aspects underline the importance to account for the household's decision behavior on investment in heating systems.[2]

We first derive analytically how the adoption of technologies takes place based on household behavior in a theoretical discrete choice framework.[3] We show how this diffusion process is affected by public policies and its impact on greenhouse gas abatement. The discrete choice approach further allows for the derivation of

[2]Because greenhouse gas abatement costs for insulation measures are so high in Germany, for simplification, we exclude the households' decisions on thermal insulation from our analysis.

[3]See for Train (2003) for an overview of discrete choice approaches on which we base our framework.

different welfare measures such as the compensating variation and excess burden (Diamond and McFadden, 1974; Small and Rosen, 1981; McFadden, 1999), which we use to derive welfare based greenhouse gas abatement curves. Second, given this setting, we develop DIscHEat, an economic microsimulation model of the German heat market for the years 2010 to 2030. Its core idea is to simulate the households' decision behavior on a new heating system. In the current market for heating systems, we observe that the heating system decision is based not only on observable heating system costs, but as well on hidden factors such as non-observable costs and preferences. To account for both aspects, we choose a discrete choice model estimated with current domestic investments into heating systems and their respective observable costs. We then apply our simulation model to investigate the impact of different greenhouse gas abatement policies on newly installed heating systems and greenhouse gas abatement until 2030: e.g. a carbon tax increases the observable costs of carbon intense technologies, thereby c.p. reducing their installations and consequently carbon emissions. Applying the approach of Small and Rosen (1981); McFadden (1999), we derive the welfare costs of policy measures in terms of excess burden in our numerical framework. From that we deduce welfare-based greenhouse gas abatement curves of the investigated policies, thereby accounting for household behavior.

Our results confirm the implications of Huntington's paper suggesting that welfare-based greenhouse gas abatement curves run above technical cost curves. Thus, accounting for the behavior of households and their reactions on policy measures implies greater costs for society than pure technical equipment costs. Second, despite a flat curve of marginal excess burden of greenhouse gas abatement, the marginal costs of public funds might increase very steeply getting closer to the peak of the Laffer curve. This indicates the limits on an implementable level of a carbon tax rate in reality. Third, our results suggest that in most cases a carbon tax causes less welfare losses than subsidies on technology investments. However, in case of behavioral misperceptions or credit barriers, subsidies on investments might be reasonable.

The paper is organized as follows: The next section provides a brief overview of previous research and presents the theoretical approach to the derivation of microeconomic greenhouse gas abatement cost curves. Section 4.1 describes the microsimulation model DIscrHEat and the different policy scenarios we consider. Section 5 presents our results, first, in Section 5.1 on the effects of the policies on greenhouse gas abatement and the diffusion of technologies. Second, Section 5.2 presents the welfare impacts of the different policies to derive greenhouse gas abatement cost curves. Section 6 concludes.

2. Previous research

There are two strands of literature which are related to our paper. The first strand is on energy demand modeling in general. There are a variety of studies that model the energy demand of the private sector and that identify drivers of energy consumption and energy efficiency. Swan and Ugursal (2009) and Kavgic et al. (2010) give an overview of different bottom-up models and models to analyze residential energy consumption, i.e. mainly technology-based energy demand modeling approaches. These bottom-up models are based on extensive disaggregated data and components that influence energy demand on an individual detailed level. This model type is often applied to identify cost-efficient technology options for achieving certain greenhouse gas emission abatement targets. There are also a variety of top-down models that focus on rather macroeconomic relationships. These models use aggregated empirical data to investigate the interrelation of the energy sector and the economy as a whole by variables like GDP, income, temperature and prices of energy carriers. Mansur et al. (2008) analyze the impact of climate change on energy demand and welfare in the US applying a discrete-continuous model of fuel choice and energy consumption. They find a potential increase of American energy expenditures and welfare losses caused by temperature rise. Madlener (1996) provides an overview of the different time-series based methodologies applied to analyze residential energy demand. Rehdanz (2007) examines the determinants of household expenditures on space heating and hot water supply in Germany based on panel data and covers a number of socio-economic characteristics of households along with dwelling characteristics. Braun (2010) examines building, socio-economic and regional characteristics in a discrete choice model focusing on space heating technologies applied by households but not on the heating system choice in terms of new heating system installations. Michelsen and Madlener (2012) conduct a survey about heating system installations to analyze the influence of preferences about residential heating system specific attributes on the adoption decision in a discrete choice estimation.

The second strand of related literature focuses on numerical approaches to the deduction of greenhouse gas abatement costs. The literature on greenhouse gas abatement modeling can be categorized into general equilibrium modeling approaches and technical models. Bovenberg and Goulder (1996) develop an emission abatement curve based on marginal welfare costs in a general equilibrium setting. Nordhaus (2011) and Pearce (2003) determine different social damage costs of greenhouse gas. Morris et al. (2008) apply a general equilibrium model to compute marginal abatement costs and marginal welfare costs for different greenhouse gas prices. They argue that the marginal abatement costs in their model reflect the shadow prices on the greenhouse gas constraint on certain countries or sectors. This is interpretable as a price that would be obtained under an allowance market that developed under a cap and trade system. They come to the conclusion that these marginal abatement costs are not closely related to the marginal welfare costs. The marginal abatement costs of their model vary over countries and are sometimes above and sometimes below the marginal welfare costs and therefore they conclude that they should not be used to derive estimates of welfare change.

A recent study on greenhouse gas abatement curves on the micro-level has been published by McKinsey & Company, Inc. (2009) which establishes a cost-efficient greenhouse gas abatement curve for different energy efficiency measures. Huntington (2011) discusses the overestimation of the reduction potential in the McKinsey & Company, Inc. (2009) study. According to Huntington (2011), McKinsey & Company, Inc. (2009) neglect the real behavior of private households assuming adoption rates of technologies of 100%. In reality, a new technology might not be cost-efficient for everyone even if it is cost-efficient for the average consumer. In addition, the adoption and diffusion of technologies proceeds slowly in general. Huntington (2011) also mentions the exclusion of the households' reactions to the introduction of policy measures and the exclusion of policy costs in the McKinsey & Company, Inc. (2009) study. Introducing basic assumptions to these additional costs and impacts on the greenhouse gas abatement curve, Huntington (2011) revises the curve to highlight implications for policymakers if they base their decisions on a what he calls "out-of-pocket" technology based cost curve.

3. Theoretical approach

Energy efficiency and greenhouse gas abatement policies can have different impacts and purposes. They can either try to influence the number of low emission investments made by trying to incentivize the household to invest earlier or more often; or they try to make the household investing in less greenhouse-gas-intense technologies. We focus on the latter.

Diffusion process of technologies

We have different representative household categories n ($n \in \{1, ..., N\}$) that have to install a new greenhouse-gas-emitting technology j ($j \in$ {1,...,J}) as the previous system has to be replaced due to break-down.[4] Each alternative technology causes different amounts of greenhouse gas emissions. The probability $P_{n,j}$ that a representative household n chooses a technology j is a function of the total annual system costs $c_{n,j}$[5] and

[4]This is a realistic assumption for heating systems as shown in IWU / BEI (2010), but also holds for expensive building insulation or other investments into energy efficiency.

[5]We do not consider the impact of policy measures on the number of investments, but only on the structure of heating

some household specific characteristics z_n:

$$P_{n,j} = f(c_{n,j}, z_n) \tag{1}$$

The total annual system costs $c_{n,j}$ are a function of the investment costs $i_{n,j}$, the energy consumption $e_{n,j}$, the energy price p_j and two policy measures that we model: Pigovian carbon taxes T_j and subsidies on the investment S_j:

$$c_{n,j} = f(i_{n,j}, e_{n,j}, p_j, T_j, S_j) \tag{2}$$

Based on the alternative-specific conditional logit model, first presented by McFadden (1974, 1976), the indirect utility $U_{n,j}$ of household n that chooses between different technologies j is given by:

$$U_{n,j} = V_{n,j} + \epsilon_{n,j} \tag{3}$$

$V_{n,j}$ is the observable utility of the household whereas $\epsilon_{n,j}$ captures further factors that influence the utility but are not in $V_{n,j}$.

$V_{n,j}$ is:

$$V_{n,j} = \alpha_j + \beta c_{n,j} + \gamma_j z_n \tag{4}$$

with α_j being alternative-specific constants that give an extra value to each technology. β represents the negative total annual system cost impact and γ_j is a vector of technology-specific impacts on the household characteristics. We get:

$$U_{n,j} = \alpha_j + \beta c_{n,j} + \gamma_j z_n + \epsilon_{n,j} \tag{5}$$

system choices. Therefore, the total annual system costs are relevant and not a differentiation between investment costs and future energy savings. Based on IWU / BEI (2010), we argue that households only change their heating system when it is broken. Finding out reasons for this behavior is open for further research.

The choice of a household can be described as a dummy variable $y_{n,j}$:

$$y_{n,j} = \begin{cases} 1, \text{if} \quad U_{n,j} > U_{n,i} \quad \forall i \neq j \\ 0, \text{else} \end{cases} \tag{6}$$

The choice probability that determines the diffusion process of a technology is defined as:

$$\begin{aligned} P_{n,j} &= Prob(y_{n,j} = 1) = Prob(U_{n,j} - U_{n,i} > 0, \quad \forall i \neq j) \\ &= Prob(\epsilon_{n,i} - \epsilon_{n,j} < V_{n,j} - V_{n,i} \quad \forall i \neq j) \end{aligned} \tag{7}$$

where $\epsilon_{n,i}, \epsilon_{n,j} \sim iid\ extreme\ value, \quad \epsilon_{n,i} - \epsilon_{n,j}$ has a logistic distribution[6] and only the difference between two utility levels has an impact on the choice probability and not the absolute utility level.
The probability that household n chooses alternative j is[7]:

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} = \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_j z_n}}{\sum_i e^{\alpha_i + \beta c_{n,i} + \gamma_i z_n}} \tag{8}$$

This determines the proportion of installations of technology j among the new systems chosen by household type n.

Own cost changes and those of alternative heating systems affect the choice probabilities of a heating system. These cost impacts on the choice probability of a heating system can be described in terms of elasticities. The elasticity of a household's choice probability with respect to heating costs of the system j that he chooses is given by:

$$\frac{\partial P_{n,j}}{\partial c_{n,j}} \frac{c_{n,j}}{P_{n,j}} \quad = \beta(1 - P_{n,j}) c_{n,j} < 0 \tag{9}$$

which is negative because of the negative cost impact $\beta < 0$.

The elasticity of a household's choice probability for j with respect to heating costs of an alternative system i is given by:

$$\frac{\partial P_{n,j}}{\partial c_{n,i}} \frac{c_{n,i}}{P_{n,j}} \quad = -\beta P_{n,i} c_{n,i} > 0 \tag{10}$$

[6]The logit model with its elasticities are a standard approach to model the diffusion of technologies. See for instance Geroski (2000).

[7]For detailed mathematical derivations and explanations of logit and conditional logit models see McFadden (1974) and Train (2003).

with $i \neq j$.

The effects of the model are ceteris paribus and allow for the computation of own and cross cost elasticities on the diffusion rates of the different technologies, i.e. the choice probabilities of an alternative, keeping all values fixed. The changes in the total greenhouse gas emission level are determined by the diffusion process.

The elasticities account for the cost effect β on the technology choice. An advantage of the inclusion of $P_{n,j}$ in the elasticities is that changes of $P_{n,j}$ depend on the current level of $P_{n,j}$.[8] The restricted substitution pattern of the choice probability holds on the individual level and is much more flexible on the aggregated level over all household types. On the aggregated level, the substitution pattern also accounts for the heterogeneity of households.

Welfare effects of different policies

The aggregated net utility in our model over all households that change their technology and install a new one in period (year) $y \in 2010, ..., 2030$ is defined as follows:

$$U^{aggr.} = nC + \sum_{n,j=1}^{N,J} V_{n,j} \tag{11}$$

C is a constant positive utility level that is assumed to be the same for all household types n and indicates the minimum utility of a new technology. $nC \geq \sum_{n,j=1}^{N,J} V_{n,j}$ by definition because a new technology needs to be installed when the old one is broken and thus is assumed to imply a higher utility than costs. The utility $V_{n,j}$ is negative because it indicates the cost impact of the essential new systems on the aggregated utility. As for the welfare analysis only the differences between two aggregated utilities with different policies are of importance, we can neglect the constant C from now on.

When we introduce a carbon tax which increases the costs of greenhouse-gas-intense systems to incentivize investments into the lower-emission technologies, the relative annual costs of the different heating systems change. This leads to different investment decisions. The introduction of such policies, which are not lump-sum, cause welfare losses even if the tax revenues are redistributed lump-sum. The households that have to modernize their systems are elastic but not completely elastic as presented in the previous section. For

[8]Analyzing the development of the German heat market over the last 60 years indicates that this is a realistic assumption and that changes resulting from the cost advantages of new heating systems take place only inertially and based on the number of heating systems of that type that are already installed BDH (2010); IWU / BEI (2010). The inertia of the heating system stock results from the long life spans of the heating systems and the fact that heaters are only exchanged when they are broken. Adoption rates of heating systems that already have a large market share are much higher. The proportional substitution pattern of conditional logit models is often criticized. In the case of the homogeneous good heat, it seems however to be appropriate. See for instance Train (2003) for a detailed discussion of the substitution patterns of logit models.

simplification, we assume that the supply function is completely elastic.[9] Then, the welfare loss, i.e. the excess burden, is the difference between the tax revenue and the aggregated compensating variation over all households. The compensated variation of the introduction of a tax indicates how much the government needs to pay the households to compensate the resulting price increase and keep their original utility level. For a subsidy, the compensating variation reflects the willingness to pay of the households to keep the subsidy. Therefore, for both cases, the tax revenue, which could be redistributed to the respective households and the subsidy expenditure of the government which could be collected from consumers via a lump-sum tax, must be compared with the respective compensating variation.

The compensating variation CV_n is determined for each period y by an equation based on McFadden (1999) which is a generalization of the compensating variation of logit models introduced by Small and Rosen (1981).[10]

To determine the difference in consumer surpluses of the two scenarios with and without policy measures, we get:

$$\int_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} P_{n,j} dV_{n,j} = \left[\ln \sum_i \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_j z_n}}{\beta} \right]_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} \tag{12}$$

The amount of money that is needed to keep the original utility level and compensate for the additional costs CV_n caused of the policy measures is then computed as follows:

$$\ln \sum_i \frac{e^{\alpha_j + \beta (c_{n,j}^{\text{policy}} - CV_n) + \gamma_j z_n}}{\beta} = \ln \sum_i \frac{e^{\alpha_i + \beta c_{n,j}^{\text{no policy}} + \gamma_j z_n}}{\beta} \tag{13}$$

where $c_{n,j}^{\text{policy}}$ indicates the respective total annual heating costs of household n with heating system j including a tax or subsidy and $c_{n,j}^{\text{no policy}}$ describes these costs without any policy measures.

To compute the compensating variation per dwelling type n the formula by Small and Rosen (1981) can be

[9] This assumptions leads to an underestimation of the excess burden. It means that the investment costs of heating systems and energy prices are not influenced by demand changes of the residential heating sector. We assume that the residential sector demand is too small to have an impact on energy prices. The producers of heating systems in Germany sell all types of heaters. Thus, they do not depend on a specific system and would adapt their product composition according to the changing demand conditions.

[10] Tra (2010) provides an application of this discrete choice equilibrium framework to the valuation of environmental changes.

applied[11]:

$$CV_n = \frac{1}{\beta} \left[ln \sum_j exp(V_{n,j}^{\text{policy}}) - ln \sum_j exp(V_{n,j}^{\text{no policy}}) \right] \tag{14}$$

We have to account for the number of households belonging to the same group with the same building characteristics (H_n) which have to install a new heating system. Thus, the aggregated compensating variation is:

$$CV = \sum_{n=1}^{N} H_n CV_n \tag{15}$$

Finally, we define the excess burden EB for each period y following Diamond and McFadden (1974):

$$EB^{tax} = CV^{tax} - T \tag{16}$$

where T indicates the overall tax income in this period with:

$$T = \sum_{n \in N, j \in J} H_n P_{n,j} T_j \tag{17}$$

We consider a carbon tax T_j which equals a carbon tax τ in Euro per tons greenhouse-gas-equivalent times a conversion factor that converts τ into T_j accounting for the greenhouse gas emissions of the different systems.[12]

The excess burden of a subsidy is determined similarly:

$$EB^{sub} = S - CV^{sub} \tag{18}$$

[11]See the Appendix for a more detailed derivation. This approach assumes a constant marginal utility of income denoted by $\frac{1}{\beta}$. Torres et al. (2011) investigate the sensitivity of mistaken assumptions about the marginal utility of income and their impacts on the welfare measures in Monte Carlo experiments. They find that mistaken assumptions about the marginal utility of income can amplify misspecification of the utility function. However, throughout all misspecification cases analyzed, they find an underestimation of the compensating variation (referred to as 'compensating surplus' in their paper). Thus, the analysis conducted in this paper assuming a constant marginal utility of income is conservative and might even underestimate the compensating variation (and excess burden).

[12]In our heat market microsimulation model, T_j the conversion factor is determined by the total heat demand TD_n of a household, the annual use efficiency of a heat system AE_j and the greenhouse gas emissions of the different energy carriers.

with

$$S = \sum_{n \in N, j \in J} H_n P_{n,j} S_j \tag{19}$$

If we assume behavioral misperception to be the cause for the household choices, the compensating variation based on utility might not be an adequate measure.[13] Therefore, we also compute total heating system cost differences that result from the introduction of greenhouse gas abatement policies. We take the total annual heating costs over all households and heating systems:

$$c = \sum_{n \in N, j \in J} H_n P_{n,j} c_{n,j} \tag{20}$$

In case of a carbon tax, the total heating system cost differences (CD) are the following:

$$CD^{tax} = (c^{\text{policy}} - c^{\text{no policy}}) - T \tag{21}$$

Again, we assume that the tax income is redistributed lump-sum. For a subsidy we get:

$$CD^{sub} = S - (c^{\text{no policy}} - c^{\text{policy}}) \tag{22}$$

Microeconomic greenhouse gas abatement curve

The excess burden EB changes with different tax rates T_j (equivalently for changes in the subsidy levels S_j). dEB covers the changes in welfare losses of an additional unit increase of the tax rate (or subsidy):

$$dEB^{\text{tax}} = \sum_{n \in N, j \in J} \left[\left(\underbrace{\frac{\partial EB}{\partial CV_n}}_{(+)} \underbrace{\frac{\partial CV_n}{\partial V_{n,j}^{\text{policy}}}}_{(-)} \underbrace{\frac{\partial V_{n,j}^{\text{policy}}}{\partial c_{n,j}}}_{(-)} \underbrace{\frac{\partial c_{n,j}}{\partial T_j}}_{(+)} - \underbrace{\frac{\partial T}{\partial T_j}}_{(+/-)} \right) dT_j \right] \tag{23}$$

The signs in brackets below the derivatives indicate their direction such that (+) indicates a positive and

[13]The utility maximizing approach to model the diffusion process is still appropriate as long as the misperception and household preferences cannot be affected by public policies. However, in this case the evaluation of the compensating variation does not reflect real consumer losses and society's costs.

$(-)$ a negative derivative.

$$\frac{\partial T}{\partial T_j} = \sum_{n\in N, j\in J}\left[\underbrace{H_n P_{n,j}}_{(+)} + \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,j}}\frac{\partial c_{n,j}}{\partial T_j} H_n T_j}_{(-)}\right] \tag{24}$$

The first part of the equation indicates the positive impact of the increasing tax rate on the total tax income T whereas the second part displays the negative impact of the decreasing tax base. Hence, $\frac{\partial T}{\partial t_j}$ is positive for the increasing part of the Laffer curve and decreasing for the decreasing part.
$\frac{\partial T}{\partial t_j} < \frac{\partial EB}{\partial CV_n}\frac{\partial CV_n}{\partial V_{n,j}^{\text{policy}}}\frac{\partial V_{n,j}^{\text{policy}}}{\partial c_{n,j}}\frac{\partial c_{n,j}}{\partial t_j}$ (see Auerbach and Feldstein (1985)). Thus, $dEB > 0$ when the tax rates are increasing ($dt_j > 0$).
For the change of total subsidy spending in S_j, we would have:

$$\frac{\partial S}{\partial S_j} = \sum_{n\in N, j\in J}\left[\underbrace{H_n P_{n,j}}_{(+)} + \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,j}}\frac{\partial c_{n,j}}{\partial S_j} H_n S_j}_{(+)}\right] \tag{25}$$

as the subsidy increases the costs decrease ($\frac{\partial c_{n,j}}{\partial s_j} < 0$) and the installation rate $P_{n,j}$ of the technology j increases through decreasing costs. Adapting equation 23 accounting for equation 18 we would get $dEB^{\text{sub}} > 0$ for $dS_j > 0$.

In the case of behavioral misperceptions, the changes in the total annual heating costs might be more appropriate to be considered than dEB:

$$dCD^{\text{tax}} = \sum_{n\in N, j\in J}\left[\left(\underbrace{\frac{\partial c_{n,j}}{\partial t_j}}_{(+)} - \underbrace{\frac{\partial T}{\partial T_j}}_{(+/-)}\right) dt_j\right] \tag{26}$$

The amount of greenhouse gas emissions $CO2_{n,j}$ that is consumed by household n who installs a new technology is determined by the proportion of installations $P_{n,j}$.

$$CO2_{n,j} = f(P_{n,j}) \tag{27}$$

where $f(P_{n,j})$ is a linear function that transfers the energy consumed by the chosen technology into greenhouse gas emissions. Besides the new technologies, the technology stock (i.e. the currently installed heating systems) ST also emits greenhouse gas. Thus, the aggregated greenhouse gas emissions over all households sum up to:

$$CO2 = \sum_{n,j} f(P_{n,j}) + ST \tag{28}$$

We analyze the impact of a carbon tax and investment subsidies on the diffusion process and on greenhouse gas abatement. We assume that the emissions of the stock are not targeted by the policies. Introducing a new policy $T_j, T_i \quad \forall i \neq j$ (or $S_j, S_i \quad \forall i \neq j$) thus leads to the following change of total greenhouse gas emissions:

$$dCO2 = \sum_{n,j} \left[\left(\underbrace{\frac{\partial f(P_{n,j})}{\partial P_{n,j}}}_{(+)} \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,j}}}_{(-)} \underbrace{\frac{\partial c_{n,j}}{\partial T_j}}_{(+)} \right) dT_j + \sum_i \left(\underbrace{\frac{\partial f(P_{n,j})}{\partial P_{n,j}}}_{(+)} \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,i}}}_{(+)} \underbrace{\frac{\partial c_{n,i}}{\partial T_i}}_{(+)} \right) dT_i \right] \tag{29}$$

and equivalently for S_j, S_i with $\frac{\partial c_{n,j}}{\partial S_j} < 0$ and $\frac{\partial c_{n,i}}{\partial S_i} < 0 \quad \forall i \neq j$.

The greenhouse gas abatement $-dCO2$ is increasing with an increasing tax rate $dT_j > 0$ (or with a decreasing subsidy $dS_j < 0$) of the carbon-intense system j. The greenhouse gas abatement $dCO2$ is decreasing with the increasing tax rates $dT_i > 0$ (or the decreasing subsidy $dS_i < 0$) of the alternatives i. Setting a Pivogian tax τ with $\frac{dT_i}{dT_j}$ being constant would therefore lead to $-dCO2 < 0$.

$\frac{\partial f(P_{n,j})}{\partial P_{n,j}}$, $\frac{\partial c_{n,j}}{\partial T_j}$ and $\frac{\partial c_{n,i}}{\partial T_i}$ are constants due to the respective linear relations. Thus, the changes in the total greenhouse gas emission level are determined by the impact of the cost changes on the diffusion of technologies $\frac{\partial P_{n,j}}{\partial c_{n,j}} < 0$ and $\frac{\partial P_{n,j}}{\partial c_{n,i}} > 0$.

The marginal excess burden dEB and the marginal greenhouse gas abatement $dCO2$ of introducing abatement policies enable to display a microeconomic greenhouse gas abatement curve that accounts for the reaction of households and the resulting diffusion process of technologies as well as marginal welfare losses. In case of behavioral misperceptions dCD might be considered instead of dEB.

4. Data and Methodology

4.1. Microsimulation using DIscrHEat

We developed the model DIscrHEat (DIscrete choice HEat market simulation model) which is a dynamic simulation model for the German heat market of private households. It simulates the development of installed heating systems and insulation levels of German dwellings in five-year intervals until 2030. Starting point of the model calculations is a detailed overview of the current German building stock of private households in 2010. We distinguish single and multiple dwellings and six vintage classes. Each of those building classes has an average net dwelling area and a specific heat energy demand (kWh/m^2a). Additionally, we include data on the distribution of heating systems in each building class.

To simulate the future development of the German building stock (i.e. the installed heating technologies and the buildings' insulation level), DIscrHEat accounts for new buildings and demolitions. Furthermore, we assume that a certain percentage of buildings has to install a new heating system. Those modernization rates are given exogenously. IWU / BEI (2010) show that in Germany, investments into new heaters mostly take place when mendings or replacements need to be done. Therefore, we assume that heater replacements only take place according to empirical rates of the last years based on IWU / BEI (2010).

The household's decision for a new heating technology is modeled by the approach presented in Section 3 which is included in DIscrHEat. The econometric model (alternative specific conditional logit model) estimates the household's choice behavior by using data on the actual heating choice in 2010 and the according cost data of different heating systems. Using this approach allows to take into account not only the observable costs (investment costs, operating costs and fuel costs) but as well non-observable influences (switching costs or preferences) on the household's decision based on empirical data. (See Appendix for the model and estimation results.)

4.2. Policy scenarios

Based on our simulation model results of three greenhouse gas abatement policies, we analyze the diffusion process of newly installed heating systems until 2030. We simulate a scenario without any policies as reference. In a first policy scenario, we introduce a Pigovian carbon tax as it is the first best policy measure if households are utility maximizing. We increase the carbon tax gradually to achieve higher levels of greenhouse gas abatement.[14] We consider a carbon tax t_j in $Euro/kWh$ which equals a carbon tax τ in Euro per tons CO_2-equivalent times the conversion factor CF_j that converts τ into t_j accounting for the amount of CO_2-equivalents in the different energy carriers.[15] In case of a carbon tax all households of the stock that have a heat pump, a gas or an oil heater are thus affected by such a tax and not only the households that have to make the decision on their heating system, i.e. have to modernize it. However, we assume that the households of the building stock that do not have to change their heating system due to

[14]For the assumed emissions of the energy carriers, see Table A.3. We assume that no tax is levied on biomass.
[15]See Table A.3 in the Appendix.

break-down are inelastic to price changes. They neither change their heating system as a result of the tax nor do they change their energy consumption behavior for heating. Thus, their compensating variation is equal to the tax revenue that they generate. In terms of the welfare changes of the introduction of a tax or subsidy only the households who modernize their heating system are relevant.

In addition, we simulate two different subsidy regimes, which both provide subsidies on newly installed heating systems reducing the investment costs of the respective systems. For the first subsidy scenario (subsidy I), we implement a simplified version of the German subsidy system with subsidies on heat pump and biomass heaters. Thereby, subsidies on biomass are significantly larger. The second subsidy scenario (subsidy II) is a hypothetical policy scenario. It provides the same level of subsidies on heat pumps as on biomass heaters and additionally a low subsidy on gas heating systems. We choose this parameterization subsidizing heat pumps and natural gas heaters relatively more than in the German system because marginal abatement costs of biomass heaters are the highest. Contrarily, biomass heaters are highly subsidized in the German system. Like this we can generate a subsidy based greenhouse gas abatement curve that generates lower welfare losses for the first major part of abatement units (see Table A.4 for the subsidy levels). For both subsidy scenarios we increase these subsidies proportionally to effectuate higher greenhouse gas abatement.

Since the heat market and in particular the installation of heating technologies only changes inertially, we focus on the total modeling period and aggregate all greenhouse gas emission reductions until 2030. We compute the final values of the tax income and subsidy expenses and excess burdens in 2030 based on an interest rate of 6% that has been applied throughout the model.

5. Results

5.1. Greenhouse gas abatement policies and diffusion of heating systems

To evaluate the three policy scenarios, we first investigate the diffusion process of the newly installed heating systems in this section. Figure 1 presents the mechanism of our simulation approach exemplarily for the carbon tax: in each policy scenario we increase taxes and subsidies proportionally which leads to different amounts of greenhouse gas abatement. Until 2030, about 300 million tons of greenhouse gas abatement are already achieved in the reference scenario without any policies. The accumulated tons of CO_2 abatement correspond to a decrease from 134 million tons greenhouse gas emissions in 2010 to 105 million tons in 2030 in the reference scenario without policy measures. These reductions are achieved because of the assumed increases in annual use efficiencies of the heating systems over time, the diffusion of the recent non-fossil heating technologies heat pump and biomass, the demolition of old insufficiently insulated buildings and the construction of well-insulated new buildings. Additional greenhouse gas abatement then requires policy intervention. The additional greenhouse gas avoidance achieved by policy measures is slightly increasing with the proportional increase of the tax rate (as in Figure 1) or a subsidy. At levels between 700 and 800 million tons of accumulated CO_2-equivalent (CO_2-eq.) abatement no additional volumes can be reduced. This corresponds to emissions between 64 and 56 million CO_2-eq. in 2030 in comparison to 104 million tons in the reference scenario, i.e. a maximum decrease by 39% to 47%. A carbon tax rate of 100 Euro per tons CO_2-equivalent (t CO_2-eq.) leads to an accumulated greenhouse gas abatement of about 330 million tons until 2030 (or a level of 102 million tons in 2030). 30 million additional tons of accumulated greenhouse gas abatement are therefore achieved by the carbon tax of 100 Euro per t CO_2-eq. A 420 Euro per t CO_2-eq. carbon tax results in an additional reduction of accumulated 200 million t CO_2-eq. until 2030 (see Figure 1).

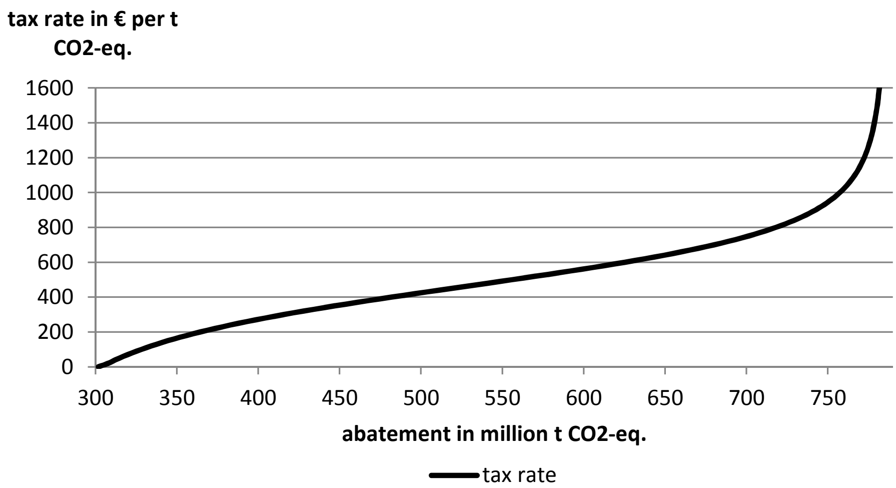

Figure 1: Tax rate, subsidy level and resulting greenhouse gas abatement

Figure 2 presents the effects on the government's budget of introducing all three different policies. For abatement levels above 500 million tons of accumulated CO_2-eq. expenses for the subsidies increase over-proportionally and are significantly higher than the tax revenue that is generated by a carbon tax. At about the same abatement level, the tax revenue starts to decrease indicating the falling part of the Laffer curve. This is where the shrinking tax base, i.e. mainly fossil heating systems disappearing in the building stock, reduces the revenue more than the increasing tax rate adds to the revenue.

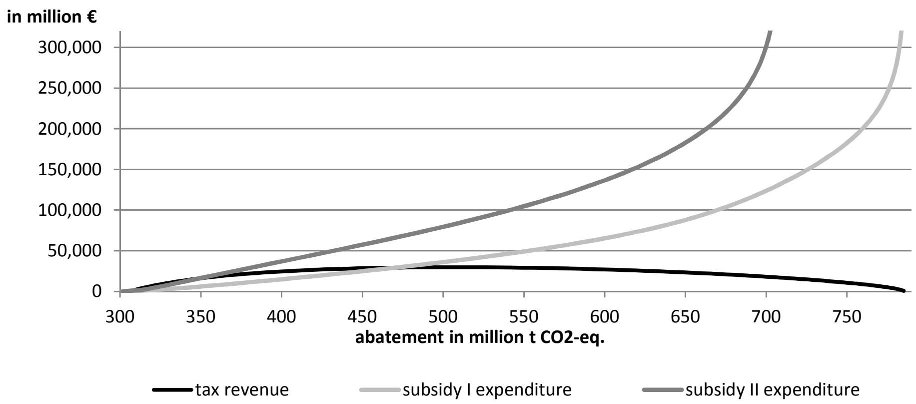

Figure 2: Tax revenue and subsidy expenditure

The diffusion of heating systems and the resulting accumulated amounts of greenhouse gas abatement until 2030 in the three policy scenarios are illustrated in Figure 3. The increasing greenhouse gas reduction amounts thereby result from increasing taxes or subsidies. The high subsidy on the investment costs of biomass heaters in comparison to the subsidy on investments into heat pumps leads to lower installation rates of heat pumps in the subsidy I scenario compared to the tax scenario. The diffusion resulting from the Pigovian tax indicates that heat pumps would be more greenhouse gas abatement cost efficient than biomass heaters for a further reduction of CO_2-eq. of 300 million tons to 550 million tons of greenhouse gas abatement. The subsidy II scenario causes a slightly slower reduction of gas heatings and keeps heat pumps and not only biomass heaters in the market. This is a result of the constant relative subsidy levels for heat pumps and biomass heatings. In this scenario 709 million tons of accumulated greenhouse gas abatement is the maximum that could be achieved because for additional reductions of CO_2-eq. biomass heaters need to be installed instead of heat pumps. In the tax and subsidy I scenario this abatement limit is at accumulated 786 million tons CO_2-eq.[16] The abatement level is higher as all installations of the greenhouse-gas-emitting heating systems oil, gas and heat pump are completely phased out in favor of biomass heaters.

[16]Please note that very high tax and subsidy levels, especially on the downward-sloping part of the Laffer curve, would not be politically implementable because of their government budget effect. Moreover, such high relative cost changes would probably change household behavior and make them install new heating systems before they are broken.

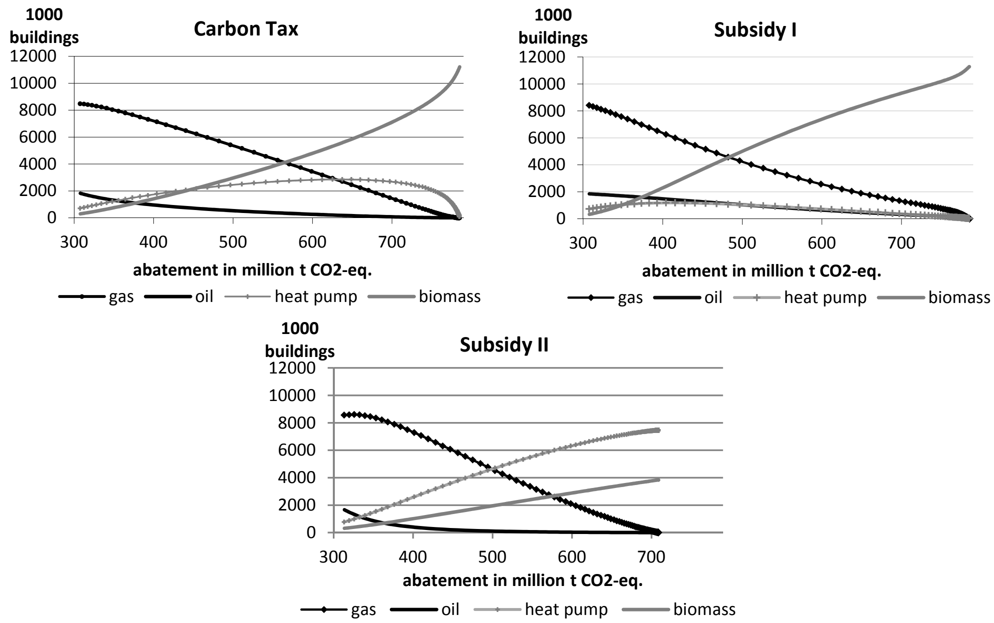

Figure 3: Installed heating systems in 2030 depending on CO_2 reduction and policy measures

5.2. Welfare analysis

In this section, we compare different welfare measures of the three policies in relation to the accumulated greenhouse gas abatement. We compute the accumulated excess burden and heating system cost differences over time, i.e. their net future values, given a discount rate of 6%.[17]

Figure 4 presents the different accumulated welfare measures, i.e. the excess burden and (total) heating system cost differences of the three policy measures. The excess burden is thereby always significantly larger than the heating system cost difference and increases much stronger.

The carbon tax thereby leads to a significantly lower excess burden for all greenhouse gas reductions than the subsidies on investments and is therefore the more efficient policy. If we cannot observe all costs and impacts determining the heating system choice of households, the determination of an investment subsidy that is equivalent to a Pigovian carbon tax is impossible and thus always leads to larger distortions on the household choice. Thus, a subsidy on the heating investment causes a higher excess burden than a carbon tax as it affects the price of the "bad" greenhouse gas directly. We could therefore identify the first best carbon tax as the lower bound for CO2 abatement. Assuming that administration costs would be the same or even higher, other policy measures would lead to higher distortions and welfare costs. However, in case of an energy efficiency gap, Allcott and Greenstone (2012) point out that if investment inefficiencies exist,

[17]Please note that the formulae presented in the previous section refer to the excess burden and heating system cost differences for one period.

subsidies for energy efficient capital stock might have greater benefits than costs. Applied to the public good of greenhouse gas abatement in our case, this could mean that in case of financing constraints, a subsidy as a second best policy could help to reduce this problem and get households to invest in less CO2-intense heating systems. Thus, in reality welfare losses of optimal greenhouse gas abatement policies might lay somewhere between the first best Pigovian tax and the subsidy curve.

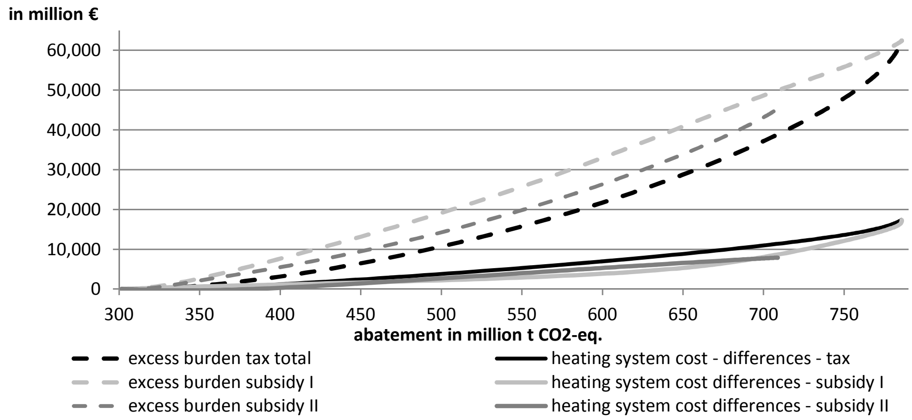

Figure 4: Tax, subsidy and excess burdens depending on CO_2 reduction based

The accumulated heating system cost differences are significantly lower than the excess burdens of all policies. These curves are still based on the diffusion process of the heating systems accounting for household behavior as before but they neglect the losses in consumer utility and focus on pure heating system costs spent. Technology based approaches to determine greenhouse gas abatement curves would neglect household behavior, which leads to even lower plain technology costs. However, a comparison of the curves in Figure 4 already shows, that a plain heating system cost consideration underestimates costs that incur for households and thus society. The cost differences caused by the subsidies are even below the carbon tax.

We further analyze different welfare measures relative to the greenhouse gas abatement level achieved by a Pigovian carbon tax and subsidies on heating system investments to investigate the marginal costs of greenhouse gas abatement. We define the following measures based on Auerbach and Feldstein (1985); Baumol (1972); Mayshar (1990):

- The average costs of public funds in Figure 5 equal the compensating variation of a policy measure relative to the tax revenue T generated: $ACPF = \frac{CV}{T}$. $1 - ACPF$ thus indicates the level of excess burden caused in percent of tax revenue.
- The marginal costs of public funds are the marginal compensating variation per marginal additional

tax revenue T generated: $MCPF = \frac{\Delta CV}{\Delta T}$. $MCPF$ measures the additional welfare loss in raising the total tax income. $1 - MCPF$ thus indicates the marginal level of excess burden caused in percent of an additional tax revenue unit. The different levels of $MCPF$ for different CO_2 abatement levels are shown in Figure 5.

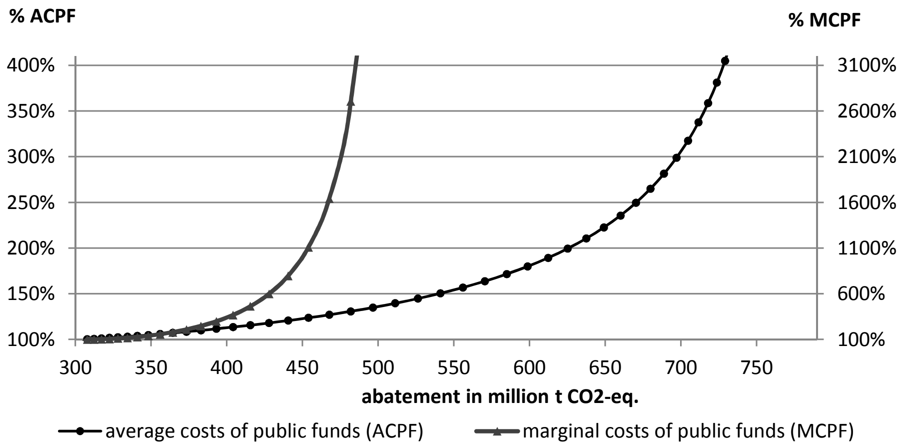

Figure 5: Marginal and average cost of public funds per CO_2 abatement level

The ACPF are increasing slightly whereas the MCPF first increase slowly, but getting closer to an abatement level of 450 million t CO_2-eq., the MCPF increases significantly. At this abatement level, the slope of the tax revenue curve is already close to zero in Figure 4 indicating that the tax base, i.e. mainly the oil and gas heaters, is decreasing significantly. This is also shown in Figure 3. Further greenhouse gas abatement is thus very costly for society because large amounts have already been reduced and additional welfare losses are comparatively high relative to the additional tax revenue generated. Up to a level of 430 million t of accumulated CO_2-eq. abatement, the MCPF remains below 1500% and the ACPF below approximately 120%. Thus, at this point the excess burden of an additional accumulated greenhouse gas reduction of 130 million t CO_2-eq. amounts to approximately 20% of the total tax revenue generated and the generation of a marginal tax income unit causes additional welfare losses of 1500% of the additional tax revenue generated. In summary, accounting for the quantity effects or the decreasing tax base of the carbon tax, i.e. the decreasing number of oil and gas heaters, the MCPF indicate that the additional welfare losses relative to tax revenue generated increase significantly for accumulated abatement levels of 450 t CO_2-eq. until 2030 or total annual greenhouse gas emissions of 92 million tons in 2030. Hence, referring to Figue 1 we can conclude that tax rates above 350 per t CO_2-eq. cause immense marginal costs of public funds and thus seem politically rather unrealistic.

5.3. *Welfare-based greenhouse gas abatement curves*

For the derivation of greenhouse gas abatement curves we use the marginal excess burden for different greenhouse gas abatement amounts for the three policy measures. The results are presented in Figure 6. To derive a greenhouse gas abatement curve based on welfare losses in our partial analysis, we compute the marginal excess burden per additional unit of greenhouse gas reduction: $MEB = \frac{dEB}{-dCO2}$. In Figure 6, per greenhouse gas abatement level $-dCO2$ on the abscissa an additional unit of abatement $-dCO2$ would cause an additional excess burden of MEB. The marginal excess burden of the carbon tax is significantly lower than the marginal excess burden of the subsidy throughout all realistic abatement levels up to 450 million t CO_2-eq. The MEB of subsidy I is decreasing at very high abatement levels because multiple dwellings mainly start switching their heating systems at very high subsidy levels in this policy regime.

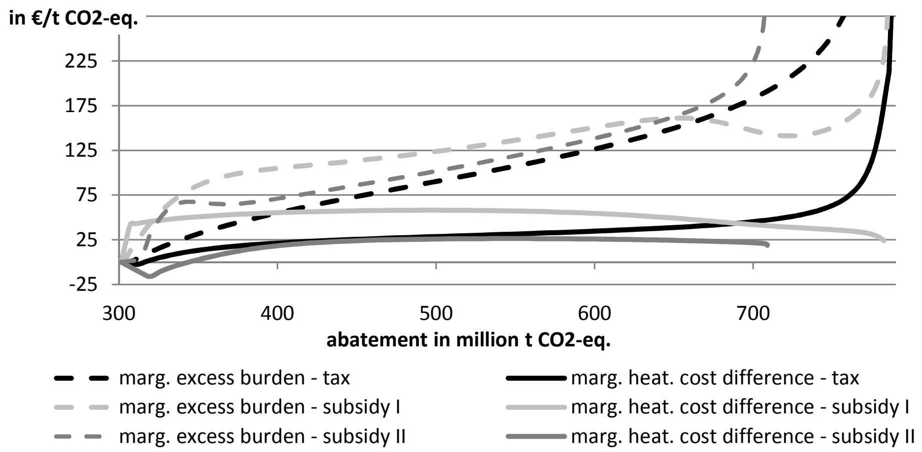

Figure 6: Marginal excess burden of greenhouse gas reduction

The marginal cost difference curves ($MCD = \frac{dCD}{-dCO2}$), which include solely the monetary heating system costs instead of the utility, are also displayed in Figure 6. These marginal cost difference curves reflect the additional heating system costs of a unit of greenhouse gas reduction at the different abatement levels already achieved. The curves indicate that the cost based curves are again significantly below the welfare loss based curves. These marginal heating system cost differences of subsidy I are also significantly higher than those of a carbon tax (for abatement levels up to 700 million t CO_2-eq.). Contrarily, the marginal cost difference of subsidy II are lower indicating that in case of behavioral misperceptions, for which a utility-based measure is not appropriate, subsidies might be effective. However, Figure 2 indicates that such a policy requires a large budget to finance the subsidy expenses. A policy that changes household behavior could then be more appropriate.

In general, the welfare based greenhouse gas abatement curve might overestimate the abatement costs assuming that households do not change their behavioral patterns until 2030. If one assumes that the households' cost elasticities might change over time and that more households might switch to a less carbon intense heating system over time bearing less non-observed costs, the abatement curve might be somewhere between the cost-based and utility-based abatement curves. However, in comparison to pure technology based curves, these curves account for households' reactions to policy measures and policy costs that society would have to bear.

6. Conclusion

Analytically, we derive a welfare based greenhouse gas abatement curve, thereby taking into account household behavior and cost effects of policy measures. We implement the theory into the behavioral micro-simulation heat market model DIscrHEat and use the model to derive an abatement curve based on household preferences and welfare losses for the German residential heating market: based on a discrete choice estimation of the heating system choice of households in 2010, we simulate the diffusion of heating systems until 2030 with and without policy measures to finally derive the compensating variation, excess burden and heating system cost differences in relation to greenhouse gas abatement. In comparison to technology-based abatement curves, this approach takes household investment behavior in heating technologies into account as well as welfare costs of policy measures.

Our microeconomic analysis provides a partial analysis of welfare based greenhouse gas abatement costs in the context of optimal abatement strategies. Analyzing these costs and options of greenhouse gas abatement is of major importance in the residential heat market and also holds for other sectors, where the behavior of economic agents affects the greenhouse gas reduction potential and the implied welfare costs. Implementing certain policies to give incentives for greenhouse gas reduction needs to account for the behavior of economic agents whose elasticities determine the welfare costs and thus the costs society would have to bear in order to achieve certain abatement objectives.

Based on our model results for the German residential heating market we conclude that a carbon tax is more efficient than subsidies on heating system investments in most cases. A subsidy on investments might cause lower abatement costs in case of behavioral misperceptions, but this policy requires very high subsidies (and lump-sum taxes) and precise information on household investment behavior into heating systems. Hence, such a policy seems rather not implementable in reality. The subsidy regime currently implemented by the German government that subsidizes expensive biomass heaters to a large extent reflects a suboptimal design: For the first affordable section of greenhouse gas abatement units, the curves of this policy regime run above carbon tax curves and the alternative subsidy regime curves. The alternative subsidy regime promotes heat pumps and natural gas systems more than the German regime. In summary, regarding policies that change heating system choices through relative costs, a carbon tax is optimal. However, if financing constraints for households exist, subsidies on new heating system installations might be reasonable.

In our model, household preferences and cost elasticities remain constant over time and the policy measures that we introduce are assumed to not affect the preferences. There are alternative policy measures that might change the household behavior over time and might impact abatement curves. These could be information campaigns or letters sent to households that compare their energy behavior with others[18]. The evaluation of the greenhouse gas abatement potential and costs of such policy measures remains open for further research.

The partial analysis of the paper does not cover additional welfare effects of the policy measures caused by cutting other taxes at the same time (see the analyses of the double dividend hypothesis for Bovenberg and de Mooij (1994); Goulder (1995) and Fullerton and Metcalf (1998)). In addition, environmental policies might have redistributive effects which might need to be included in the welfare analysis of different policy measures if equity or equality are highly valued by society. (See Cremer et al. (2003) and Llavador et al. (2011)). This type of analyses are beyond the scope of our paper.

The results of our paper have implications to policy makers: Understanding how households react to different policies to derive microeconomic greenhouse gas abatement curves is crucial for developing targeted policies and for achieving abatement objectives.

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[18] Allcott (2011) evaluates such a program for the electricity use of households and finds a significant decrease in energy consumption.

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Appendix A. Assumptions

Appendix A.1. Data

The estimation of the discrete choice model is based on data on the distribution of energy carriers chosen by a number of building type categories in 2010, characteristics of these building types and the heating system costs. The number of buildings which have to install a new heating system per model period is derived from the dwelling stock based on exogenous modernization rates. The dwelling stock comprises six different vintage classes, differentiates between single/double and multiple dwellings and three different insulation levels (heat demand levels) per house type vintage class combination. Due to a lack of data for the diffusion of energy carriers per insulation level, we include the average heat demand per dwelling category in our discrete choice estimation. However, we account for the different insulations in our simulation model. Thus, our data comprises twelve different representative dwelling types with different heat demand, heating system costs and distributions of heating systems chosen in 2010. Out of this aggregated data, we generate our data set which represents the number of buildings that changed their heating system in 2010 differentiated by dwelling type with the respective characteristics. We assume that the total annual heating costs $TC_{n,j}$ are a major driver for the representative household n to decide on the investment into a heating system using the energy carrier j.

We define the total annual heating costs as follows:

$$TC_{n,j} = AF \cdot (IC_{n,j} - S_{n,j}) + OC_{n,j} + EC_{n,j} \tag{A.1}$$

where AF is the annuity factor, $e_{n,j}$ the total investment costs of a heating system of energy carrier j, $OC_{n,j}$ are the annual operating costs and $S_{n,j}$ the subsidy paid by the German government. The current German policy system to support the diffusion of non-fossil heating systems is mainly based on subsidies and does not apply any extra taxes on the 'bad' carbon. $EC_{n,j}$ represent the energy consumption costs which are defined as:

$$EC_{n,j} = p_j \cdot (TD_n / AE_j) \tag{A.2}$$

p_j is the price of the consumed energy carrier, TD_n the total heat demand of dwelling, and AE_j the annual use efficiency of a heating system. (See Tables A.1 and A.2 for the cost and price assumptions.) The energy consumptions costs are determined by the amount of final energy that a house type consumed times the fuel price.[19] The amount of final energy consumed depends on the house type's heat demand, the heating system installed and the corresponding annual use efficiency of the system in 2010. A fixed interest rate of 6% and an assumed household's planning horizon of 15 years determine the annuity factor. For the data sources, see the follwoing tables in the Appendix. An overview of all sources is provided in Table A.1. The costs included in the discrete choice model equal the annual costs per demanded heat energy unit.

Based on the tax rate T_j presented in Section 3, we introduce a tax $t_j = T_j \frac{AE_j}{TD_n}$ and $t_j CF_j = \tau$. τ is the carbon tax in Euro per t CO_2-eq. and CF_j converts the carbon tax into an energy carrier specific tax rate accounting for the amount of greenhouse gas emissions listed in Table A.3. Biomass is not taxed.
Introducing a carbon tax t_j in $Euro/kWh$ for oil, gas and power would lead to the following total annual heating costs TC:

$$TC_{n,j} = AF \cdot IC_{n,j} + OC_{n,j} + (p_j + t_j)\,(TD_n/AE_j) \tag{A.3}$$

and introducing a lump-sum subsidy $S_{n,j}$ on non-fossil fuel heating systems biomass and heat pumps would result in:

$$TC_{n,j} = AF \cdot (IC_{n,j} - S_{n,j}) + OC_{n,j} + p_j \cdot (TD_n/AE_j) \tag{A.4}$$

In the case of a carbon tax being introduced all households of the stock that have a heat pump, a gas or an oil heater are thus affected by such a tax and not only the households that have to make the decision on their heating system, i.e. have to modernize it. However, we assume that the households of the building stock that do not have to change their heating system due to break-down are inelastic to price changes. They neither change their heating system as a result of the tax nor do they change their energy consumption behavior for heating. Thus, their compensating variation is equal to the tax revenue that they generate. In terms of the welfare changes of the introduction of a tax or subsidy only the households who modernize their heating system are relevant.

[19] We assume households to not have perfect foresight and that they have bounded rationality. Hence, only the energy costs of the current period are included in their considerations and future energy prices are not accounted for.

Table A.1: Data and sources - overview

Input data	Specification of parameters	Sources
dwelling stock	in 2005	Destatis (2008),Destatis (2010b)
	extrapolation until 2010	IWU / BEI (2010)
	new buildings and demolitions	Destatis (2010c),Destatis (2010a)
costs	capital costs	
	except for micro chp	IE Leipzig (2009)
	micro chp	own assumptions
distribution of new heaters installed in 2010	distribution of decentral heating systems	BDH (2010)
	distribution in new buildings	Destatis (2010b)
	distribution in buildings with different construction years	IWU / BEI (2010)
greenhouse gas emissions	emissions of different energy carriers	Öko-Institut (2011)
modernization rates for heating systems and insulation	rates for dwellings with different construction years	IWU / BEI (2010)

Table A.2: Energy prices in Euro per kilowatt hour

Energy prices	2010	2015	2020	2025	2030
biomass	0.05	0.05	0.06	0.07	0.07
natural gas	0.06	0.07	0.07	0.08	0.09
heating oil	0.08	0.09	0.10	0.11	0.12
electricity	0.20	0.22	0.23	0.23	0.23

Own assumptions.
In addition, an annual fixed charge of 120 has to be paid for natural gas.

Table A.3: Greenhouse gas emissions of energy carriers

Energy carrier	g CO_2-eq./kWh
biomass	26
natural gas	242
heating oil	324
electricity	350

Based on Öko-Institut (2011).

Table A.4: Subsidies on heating system investment in Euro

Heating system	single dwelling	multi dwelling
	subsidy I	subsidy I
biomass	2500	2500
heat pump	900	1200
	subsidy II	subsidy II
gas	500	500
biomass	900	1200
heat pump	900	1200

Table A.5: Dwelling stock - number of buildings (1000)

dwelling type	construction year	average dwelling area [m^2]	number of buildings (1000)	heating systems							insulation level			
				district heating	gas	electric-city	heating oil	biomass	heat pump	total	no	low	average	total
single	1900 - 1918	135	1988	39	935	144	618	146	106	1988	60	1272	656	1988
single	1919 - 1948	129	1960	45	1062	96	618	78	60	1960	39	1313	608	1960
single	1949 - 1978	141	5522	157	2169	223	2670	169	134	5522	359	4072	1090	5522
single	1979 - 1990	151	1939	43	934	75	763	66	58	1939	738	1073	128	1939
single	1991 - 1995	149	592	18	364	1	185	12	12	592	473	104	15	592
single	1996 - 2000	147	926	43	639	9	196	23	16	926	787	139	0	926
single	2001 - 2004	148	593	30	420	8	85	30	20	593	545	48	0	593
single	2005 - 2010	144	516	24	396	7	47	39	4	516	490	26	0	516
multi	1900 - 1918	430	399	41	269	13	62	8	6	399	8	243	148	399
multi	1919 - 1948	430	353	56	225	11	51	6	4	353	7	236	109	353
multi	1949 - 1978	430	1537	377	709	37	382	17	15	1537	85	1062	390	1537
multi	1979 - 1990	430	402	138	176	11	71	3	4	402	171	193	38	402
multi	1991 - 1995	430	137	18	93	0	24	0	1	137	109	23	5	137
multi	1996 - 2000	430	149	26	101	0	21	0	0	149	131	18	0	149
multi	2001 - 2004	430	60	10	46	0	5	0	0	60	56	4	0	60
multi	2005 - 2010	430	46	6	37	0	3	0	0	46	45	1	0	46

Based on Destatis (2008), Walberg et al. (2011), Destatis (2010b).

Table A.6: Capital cost assumptions of heating systems in single dwellings

		capital costs [Euro]					operating costs [Euro/a]	annual use efficiency				
		2010	**2015**	**2020**	**2025**	**2030**	**2010 to 2030**	**2010**	**2015**	**2020**	**2025**	**2030**
energy carrier i	**single dwelling (stock) [142 m^2]**											
gas	gas condensing boiler	6426	6426	6426	6426	6426	117	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	8806	8806	8806	8806	8806	205	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	17017	17017	17017	17017	17017	340	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	13195	13195	13063	12932	12803	50	3.7	3.75	3.80	3.85	3.90
	single dwelling (new) [144 m^2]											
gas	gas condensing boiler	9817.5	9621	9429	9240	9055	147	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	12197.5	11954	11714	11480	11251	235	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	17017	17017	17017	17017	17017	340	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	13195	13195	13063	12932	12803	50	3.7	3.75	3.80	3.85	3.90

Based on IE Leipzig (2009).

Table A.7: Capital cost assumptions of heating systems in multiple dwellings

		capital costs [Euro]					operating costs [Euro/a]	annual use efficiency				
		2010	**2015**	**2020**	**2025**	**2030**	**2010 to 2030**	**2010**	**2015**	**2020**	**2025**	**2030**
	multi dwelling (stock) [430 m^2]											
gas	gas condensing boiler	9520	9520	9520	9520	9520	120	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	15232	15232	15232	15232	15232	210	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	24514	24514	24514	24514	24514	400	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	25130	25130	25130	25130	25130	50	3.7	3.75	3.80	3.85	3.90
	multi dwelling (new) [430 m^2]											
gas	gas condensing boiler	15351	15044	14743	14448	14159	120	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	21063	20642	20229	19824	19428	240	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	24514	24514	24514	24514	24514	400	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	25130	34165	33823	33485	33150	50	3.7	3.75	3.80	3.85	3.90

Based on IE Leipzig (2009).

Table A.8: Heat demand per insulation level

in (kWh/m²a)		no	low	average
single	1900 - 1918	227	197	167
single	1919 - 1948	238	209	175
single	1949 - 1978	222	200	166
single	1979 - 1990	161	152	125
single	1991 - 1995	132	123	111
single	1996 - 2000	116	106	
single	2001 - 2004	99	97	
single	2005 - 2010	92	85	
multi	1900 - 1918	189	163	140
multi	1919 - 1948	194	166	143
multi	1949 - 1978	178	157	138
multi	1979 - 1990	136	125	110
multi	1991 - 1995	121	113	104
multi	1996 - 2000	116	108	
multi	2001 - 2004	105	104	
multi	2005 - 2010	96	90	

Table A.9: Modernization rates

dwelling construction year	2010	2015	2020	2025	2030
1900 - 1918	3.3%	3.3%	3.3%	3.3%	3.3%
1919 - 1948	3.3%	3.3%	3.3%	3.3%	3.3%
1949 - 1978	3.3%	3.3%	3.3%	3.3%	3.3%
1979 - 1990	2.3%	2.3%	2.3%	2.3%	2.3%
1991 - 1995	2.3%	2.3%	2.3%	2.3%	2.3%
1996 - 2000	0.0%	2.3%	2.3%	2.3%	2.3%
2001 - 2004	0.0%	0.0%	2.3%	2.3%	2.3%
2005 - 2010	0.0%	0.0%	0.0%	2.3%	2.3%

Based on IWU / BEI (2010).

Table A.10: Distribution of new heaters installed in 2010

	gas	oil	biomass	heatpump
single dwelling				
year of construction				
until 1918	7.9308%	2.6599%	0.5342%	0.6976%
1919 - 1948	7.7124%	2.5866%	0.5194%	0.6784%
1949 - 1978	21.3081%	7.1464%	1.4351%	1.8744%
1979 - 1990	5.6628%	1.1024%	0.2410%	0.8156%
1991 - 1995	1.7252%	0.3359%	0.0734%	0.2485%
new building (since 2005)	9.9751%	0.6252%	1.4881%	5.7876%
multi dwelling				
year of construction				
until 1918	1.6996%	0.5256%	0.1056%	0.0055%
1919 - 1948	1.4807%	0.4579%	0.0920%	0.0048%
1949 - 1978	6.4123%	1.9832%	0.3983%	0.0209%
1979 - 1990	1.3330%	0.2280%	0.0498%	0.0068%
1991 - 1995	0.4531%	0.0775%	0.0169%	0.0023%
new building (since 2005)	1.0790%	0.0418%	0.1242%	0.2372%

Based on BDH (2010),Destatis (2010b),IWU / BEI (2010)

Appendix B. Discrete choice model - welfare measurement and tests

Figure B.7 presents the structure of newly installed heating systems in Germany in 2010 across different dwelling types and their total annual heating costs in Euro. The groups contain dwellings of the same type with the same year of construction, house type (single/double or multiple and average insulation status/heat demand). The frequency of each group in the sample is indicated by the area of the circles[20]. Analyzing these heating system choices leads to the assumptions that the annual costs of a heating system might have an impact on the households' heating system choices but are not their only driver. In addition, the heating system choice differs systematically across the different dwelling types and the buildings' vintage class.

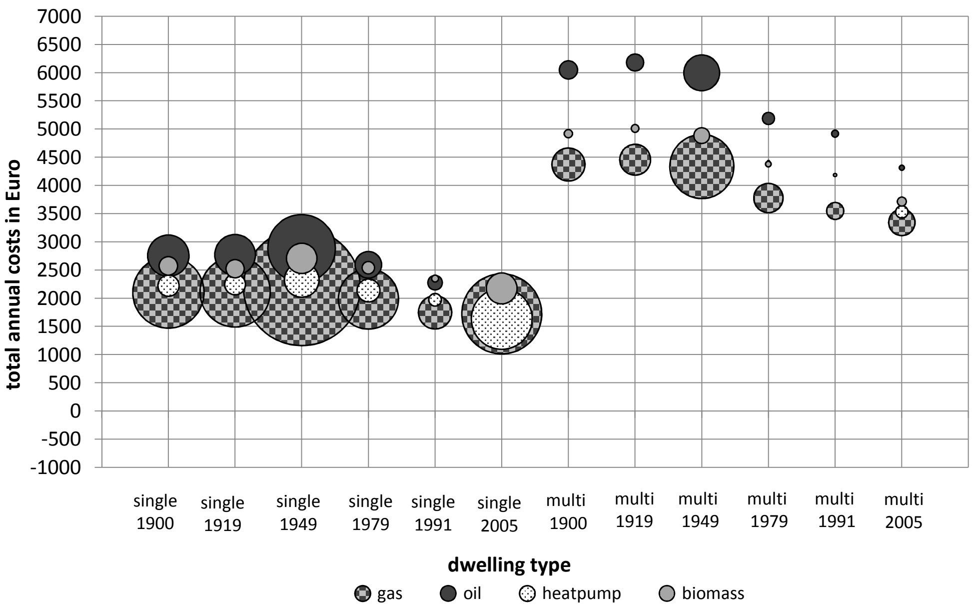

Figure B.7: Data: Costs and frequency of energy carriers installed in different dwellings in 2010

Using this data, we estimate a discrete choice model to identify the effects of the annual costs and further building characteristics that have an impact on the heating choice of a household.We thus assume that the probability $P_{n,j}$ that a representative household n adopts a heating system characterized by the energy carrier j is a function of the annual heating system costs and some building characteristics z_n: $P_{n,j} = f(c_{n,j}, z_n)$. We use the annual heating costs per unit of heat demand in kilowatt hour (kWh) $c_{n,j}$ because we are interested in a normalized impact of costs on the choice of a heating system irrespective of the different

[20]Please note that the group with the construction period 1949 – 1978 includes so many buildings because it covers the longest time period. There was no further differentiation of construction periods in the data. In the two vintage classes 1996–2000 and 2001–2004 there were almost no newly installed heating systems in 2010 because of the 15-year lifetime of heating systems on average in Germany.

dwellings' total heat demand. Considering the total annual costs per unit, we can make them comparable for all buildings. We further assume that all households having the same building characteristics as n behave accordingly.

The normalized costs $c_{n,j}$, i.e. total annual costs divided by the total annual heat demand of the dwelling (the dwelling size times the specific heat demand in kWh/m^2a) are included in the model to estimate an overall cost impact. We additionally define alternative specific, i.e. energy carrier based, variables that could have an impact on the choice of a specific energy carrier based heating system. According to Figure 1, we assume the probability of installing a specific heating system to be different in single and double than in multiple dwellings and in buildings stemming from different vintage classes. Therefore, we include the dummy variable 'single' $z_{1,n}$, with 1 for single and double and 0 for multiple dwellings and the variable 'heat demand' $z_{2,n}$, serving as a proxy for the vintage class[21]. α_j are the alternative-specific constants. β represents the impact of total annual heating cost per kilowatt hour (kWh) $c_{n,j}$. $\gamma_{1,j}, \gamma_{2,j}$ identify the effects of the alternative-specific variables.

The indirect utility of household n that can be for the chosen heating system j is:

$$V_{n,j} = \alpha_j + \beta c_{n,j} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n} \tag{B.1}$$

with the choice probability being:

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} = \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{\sum_i e^{\alpha_i + \beta c_{n,i} + \gamma_{1,i} z_{1,n} + \gamma_{2,i} z_{2,n}}} \tag{B.2}$$

As only the differences of the utilities are of importance for the estimation of the impacts, we define as base alternative 'gas' for which $\gamma_{1,\text{gas}}, \gamma_{2,\text{gas}} = 0$.

Table B.11 presents the summary statistics and Table B.12 the results of our discrete choice estimation. The cost impact is significant at a 10%-level and as expected the cost impact is strongly negative. All alternative specific constants are significant at a 1%-level and have a negative impact. Only the biomass constant is not significant. The negative impact of the alternative specific constants indicates that the probability to choose either a heat pump, a biomass or oil heater is less probable than choosing a gas-fueled heating system. This seems realistic because the market share of gas heaters in Germany is above 50% since the last years and households tend to have a preference for well-established systems.

[21] By tendency, newer buildings c.p. have a lower heat demand.

Table B.11: Summary statistics

		Mean	Std. dev.	Min.	Max.
choice					
	biomass	0.0507	0.2194	0	1
	heat pump	0.1042	0.3056	0	1
	gas	0.6681	0.4710	0	1
	oil	0.1770	0.3817	0	1
costs	over all alternatives	0.1336	0.0315	0.0870	0.2155
	biomass	0.1437	0.0362	0.0977	0.2155
	heat pump	0.1222	0.0200	0.0985	0.1624
	gas	0.1172	0.0264	0.0870	0.1711
	oil	0.1514	0.0273	0.1206	0.2072
single		0.8313	0.3745	0	1
heat demand		122.3183	29.5189	70	149.2417

Table B.12: Estimation results

Number of observations = 11052   Wald chi2(7) = 303.59
Number of cases = 2763
Log likelihood = -2471.1913   Prob > chi2 = 0.0000

choice	coef.	std. err.	z	P> |z|
heating system				
costs	-26.7651	15.7391	-1.70	0.089
biomass				
single	1.0193	0.4400	2.32	0.021
heat demand	-0.0167	0.0051	-3.30	0.001
constant	-0.7025	0.7290	-0.96	0.335
gas	(base alternative)			
heat pump				
single	1.9561	0.4129	4.74	0.000
heat demand	-0.0203	0.0037	-5.44	0.000
constant	-1.3075	0.4355	-3.00	0.003
oil				
single	-0.4750	0.1514	-3.14	0.002
heat demand	0.0202	0.0028	7.17	0.000
constant	-2.6533	0.6660	-3.98	0.000

However, our results show that solely the heating system costs are not the only driver of a household's heating system choice. Otherwise every household would have chosen the cost optimal gas based heating system. There might be additional costs a household has to face when deciding on a heating system that cannot easily be observed or quantified. Amongst other these could be switching costs, financing or infrastructure costs. Moreover, there might be further impacts on the heating choice of households in addition to costs that cannot be observed. We are not able to identify the reasons for the household heating choice structure. There might be financing constraints such that a household does not get a credit at all. Behavioral misperceptions might also be a reason. In this case households do not put enough weight on annual heating system costs and therefore have a preference for certain heating systems.

However, some indirect relations such as income effects are mirrored through building characteristics:[22] For instance, one could assume that households with a higher income spend more on insulation and thus live rather in dwellings with lower heat demand or they live rather in single and double than multiple dwellings than households with lower income. The differentiation between single/double and multiple dwellings also serves as a proxy for the tenure status. Moreover, the inclusion of income or a tenure status in the model might not even improve the model because the heating system decision is often made by the builder, which is not necessarily the owner of a building. The precise impact of such non-observable variables cannot be defined in the model but is included indirectly via the building characteristics proxies. We could thus not identify if the effect of $z_{1,n}$ is an income effect or driven by the 'tenure status' or even other causes. This is not of importance for our approach which focuses on cost elasticities to derive a welfare-based greenhouse gas abatement curve.

Including just dwelling characteristics in our model, we only cover systematic differences of heating system installations in our model, which however mainly explain the diffusion of heating systems (see also Braun (2010)). These serve as proxies for the unobservable costs or other impacts that vary across dwelling types. The results in Table B.12 show that the choice probability of non-fossil heating systems biomass and heat pumps is higher in buildings with better insulation and thus lower heat demand, which usually belong to younger vintage classes. The choice probability of these heating systems is also significantly higher for single and double dwellings than for multiple dwellings.

Later works on random utility models of discrete choice or mixed logit models (McFadden and Train (2000), Train (2003)) or the approach presented by Berry et al. (1995); Berry (1994) and others point out that the approaches presented in McFadden (1974, 1976) neglect product heterogeneity. We assume, that this might be true for products such as cars but is not valid in the case of heating systems installations since the product heat energy is a rather homogeneous good. In addition, especially the approach of Berry et al. (1995) accounts for price endogeneity and price formation on the market level by demand and supply. Our analysis sets its focus on energy consumption neglecting supply and is thus a partial analysis of the residential heat market. Further, we do not deal with price endogeneity as we assume that energy prices are not determined by the residential energy demand: the price of oil and gas is influenced by global supply and demand effects and other sectors such as power generation, transport or industry sectors rather than private households' heat demand. We also assume the price of biomass to be exogenous because the final biomass

[22] Based on Eurostat (2007) data, average gross household income in single and double dwellings in 2007 was about 51500 Euros and in multiple dwellings about 36000 Euros. 87% of households living in single dwellings were owners and only 26% in multiple dwellings.

consumption of the residential sector accounted for 16% of German and only 3% of the European primary biomass production and there is still a significant unused biomass potential AGEB (2011); Eurostat (2011); European Commission (2007). Another often mentioned problem with the presented approach is the Independence of Irrelevant Alternatives (IIA) assumption, which we test for (see the las section of the Appendix).

Computation of the compensating variation

Small and Rosen (1981) introduce a methodology to determine the aggregated compensating variation for discrete choice models and overcome the difficulty of the demand function aggregation and the discontinuity of the demand functions. We apply a generalization of this approach to determine the compensating variation CV_n of the representative household n based on McFadden (1999) associated with a movement of $V_{n,j}$ resulting from introducing a policy.

We have the distribution of the energy carriers j chosen based on the following:

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} \tag{B.3}$$

To compute the consumer surplus based on the utility in the no-policy case and the policy case we get:

$$\int_0^{V_{n,j}^{\text{no policy}}} P_{n,j} dV_{n,j} \tag{B.4}$$

and

$$\int_0^{V_{n,j}^{\text{policy}}} P_{n,j} dV_{n,j} \tag{B.5}$$

Thus, for the difference in consumer surpluses of the two scenarios we get:

$$\int_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} P_{n,j} dV_{n,j} = \left[\ln \sum_i \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{\beta} \right]_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} \tag{B.6}$$

To compute the compensating variation of household n CV_n, we need to find the amount of money $\frac{CV_n}{TD_n}$ that compensates the additional 'per heat unit' costs caused by the policy measures to keep the utility at the 'without policy' level. Thus, the following equation based on McFadden (1999) must hold for the compensating variation CV_n of household n for each period y:

$$\ln \sum_j \frac{e^{\alpha_j + \beta(c_{n,j}^{\text{policy}} - \frac{CV_n}{TD_n}) + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{\beta} = \ln \sum_i \frac{e^{\alpha_i + \beta c_{n,j}^{\text{no policy}} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{\beta} \tag{B.7}$$

We have a constant β over all alternatives, so the formula by Small and Rosen (1981) to compute the compensating variation in our logit model can easily be derived:

$$CV_n = \frac{TD_n}{\beta} \quad \left[ln \sum_j exp(V_{n,j}^{\text{policy}}) - ln \sum_j exp(V_{n,j}^{\text{no policy}}) \right] \tag{B.8}$$

where the difference in brackets just measures the change in utility per heating unit as $c_{n,i}$ are per heating unit costs. TD_n is the total annual heat demand of group n and transfers the utility per kWh/a into the overall all utility of a household with a respective heating demand. The division by β translates the utility into monetary units. This formula by Small and Rosen (1981) depends on certain assumptions: the goods considered are normal goods, the representatives in each group (households with the same dwelling characteristics) are identical with regard to their income, the marginal utility of income β is approximately independent of all costs and other parameters in the model, income effects from changes of the households' characteristics are negligible, i.e. the compensated demand function can adequately be approximated by the Marshallian demand function.

Hausman-McFadden (1984) Test

We conduct tests of Hausman and McFadden (1984) to make sure the Independence of Irrelevant Alternatives (IIA) assumption holds. We therefore reestimate the model presented in Table B.12 by dropping different alternatives i. For instance one could assume that the choice of a heating technology depends rather on fossil versus non-fossil fuels than on the different energy carriers presented. Thus, we first drop the alternative *biomass*, *oil*, and *heatpump* in separate tests, and then both *biomass* and *oil* and both *oil* and *heatpump*. We compare these estimators with those of our basic model.

Under H0 the difference in the coefficients is not systematic. The test statistic is the following:

$$t = (b - \beta)'(\Omega_b - \Omega_\beta)^{-1}(b - \beta) \tag{B.9}$$

$$\text{with } t \sim \chi^2(1)$$

b is the cost coefficient of the reduced estimations dropping alternatives and Ω_b and Ω_β are the respective estimated covariance matrices.

We get:

Table B.13: Hausman-McFadden test of IIA

	b	β	T	Prob(T>t)
cost coeff. drop biomass	-31.97016	-26.76507	0.83	0.3633
cost coeff. drop oil	-26.06515	-26.76507	0.04	0.8399
cost coeff. drop heat pump	-3.358324	-26.76507	0.28	0.5969
cost coeff. drop biomass and oil	-32.64896	-26.76507	0.66	0.4167
cost coeff. drop heat pump and oil	-19.15256	-26.76507	0.03	0.8693

The results show that IIA cannot be rejected.