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Chair for Management Science
and Energy Economics

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EWL Working Paper No. [01/15]

**INDIVIDUAL CHOICE IN A RESIDENTIAL BUILDING & HEATING
MODEL – AN APPLICATION CASE FOR GERMANY**

by

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and

Christoph Weber

03.02.2015

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Abstract

In Germany and other Central and Northern European countries, energy demand for space heating dominates the energy demand of households. In line with European and national energy efficiency and emission reduction objectives, policy makers have identified the residential building sector potentials for the achieving of reduction targets. This paper presents an extended logit model approach for the residential heating market with special regard to the development of the built environment and the heating system choice. A policy as usual scenario for Germany is calculated as an application example to evaluate the likeliness of target achievement for the heating market, its energy demand and associated emissions.

Keywords : Discrete Choice ; Heating Market ; Policy Evaluation

JEL-Classification : Q42, Q48

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Individual choice in a residential building & heating model – An application case for Germany

Abstract

In Germany and other Central and Northern European countries, energy demand for space heating dominates the energy demand of households. In line with European and national energy efficiency and emission reduction objectives, policy makers have identified the residential building sector potentials for the achieving of reduction targets. This paper presents an extended logit model approach for the residential heating market with special regard to the development of the built environment and the heating system choice. A policy as usual scenario for Germany is calculated as an application example to evaluate the likeliness of target achievement for the heating market, its energy demand and associated emissions.

1 Introduction

Driven by climate change, rising energy prices and import dependency; demand-and CO₂-reduction objectives are high on the political agenda. Following the European climate and energy package (Council of the European Union, 2008) efficiency and reduction targets were formulated at a European level and transferred into national regulation. The building sector is responsible for 40% of the European final energy demand and related CO₂ emissions (Economidou et. al., 2011), thus can make an important contribution to reduction targets (Energy Efficiency Plan, 2011). In Germany, the energy concept (BMW_i, 2010) and the energy package decisions (BMU, 2011) form the so called “Energiewende”, the political guideline to transform the energy system towards renewables and energy efficiency. Similar to the European understanding the energy concept states that the building sector is a central key for the modernisation of the energy supply and for the attainment of climate protection goals.

In official statistics, residential buildings are often included in the household sector, that was responsible for the majority of the German final energy consumption in 2010 (households 29%, industry 28%, transport 28%, commerce, trade & services 15%) Within the household sector, the heating energy demand is by far dominating all other appliances and holds for nearly 75% of the final energy demand (BMU, 2012). If the sometimes technically combined demand for tap water heating is added, more than 86% of the energy consumption of households can be explained by those two appliances (BMW_i, 2012). The heating market in Germany and other European countries is dominated by fossil fuels, leading to considerable CO₂ emissions (Lücke, 2012). Thus heating energy demand became focal point in European and national regulation (Directive 2010/31/EU, 2010; Point E in BMW_i, 2010). In Germany, a “climate-neutral building stock” should be achieved until 2050. It is defined as an 80% demand reduction while covering the remaining energy demand predominantly with renewable energies (BMW_i, 2010). More in detail, the energy demand for heating should be reduced by 20% until 2020 while an 80% reduction of primary energy demand should be achieved until 2050, based on 2008 (BMW_i, 2010; BMU, 2010). In line with national CO₂ reduction targets, the household sector and residential buildings are intended to contribute to the 80% reduction target for 2050 that is based on the 1990th emission (BMW_i, 2010).

Against the background of energy demand reduction and decarbonisation, the future development of the residential heating market has been analysed repeatedly in the literature. Schlesinger et. al. (2007) provided the “Energiegipfel”

¹ 2007 with three scenarios on the future energy demand, power generation, and greenhouse gas emissions, concluding that high demand and CO₂ reductions can be attained until 2020 if stimulated by the policymaker – a large fraction of it within the household sector. Other studies and prognosis also find high final energy demand reductions potentials in the residential heating market (Kirchner and Matthes, 2009; Fahl et.al., 2010). Schlesinger et. al. (2010) provided scenarios for the energy concept that all emphasize the role of households and heating energy demand for demand and emission reductions.

Buildings as the constructional environment set the conditions under which heating systems are operated. Thus, the investigation of the heating market requires the analysis of the built environment in a first step. We therefore develop a generic bottom-up model of the residential building stock. Existing literature on the residential building market with respect to heating technologies often has a different approach. The future development of buildings is focused, while the heating market structure is not investigated in detail (Schimschar et al., 2011). Other studies use similar approaches to project the residential building market development and apply existing scenarios (Olonscheck et.al., 2011) or have a European focus rather than a national one (Tuominen, 2012). The development of the heating market as the sum of individual decisions on heating systems has so far not been sufficiently considered and falls short in existing calculated scenarios and analysis. Motivated by this deficit we develop a discrete choice model to consider the individual decisions, which can be classified as a typical example of a discrete choice problem (McFadden, 1974). In our particular case we extended a simple logit model and further develop a multinomial logit towards a nested logit model that helps to deal with the multiple heating system alternatives.

In the field of choice modelling which has first been used for marketing sciences, many contributions have so far dealt with appliances or the residential heating system (RHS) choice in particular. The focus of existing studies on the RHS choice is usually narrower than our two-model approach. Existing studies focus on the parameter estimation to test for the various factors influencing the RHS decision. Dubin and McFadden, pioneers in the field of decision modelling first introduced a logistic choice model to analyse heating appliance, using a subsample data of 313 households (Dubin, McFadden, 1984). Nested logit models were developed early (Williams, 1977; Daly, Zachary, 1979; McFadden, 1979; Ben-Akiva, Lerman, 1979) but for the first time estimated in an energy study on data from the Pacific Northwest region to suggest marketing strategies to RHS producers (Dubin, 1982). Another contribution by Kasanen and Lakshmanan (1989) was not only restricted to certain building types and owner structures but also to a limited number of heating technologies. Their contribution expanded the traditional approach by introducing a diffusion effect on choices to test for the hypothesis of innovation diffusion (Rogers, 1962). For Germany, where such research is comparatively rare, contributions are either based on newly built one- and two-family houses (Michelsen, Madlener, 2012), investigate the differences in decision making (Braun, 2012) or have a rather different focus (Dieckhöner, Hecking, 2012). Apart from dwelling features and other parameters, dealt with in the building model, the perception of the RHS economics is generally found to be the most influencing independent variable on the RHS choice (Vaage, 2000).

¹ The so called “Energiegipfel” in 2007 was the starting point for the German energy policy of the following years (IEKP), resulting in the energy concept (2010) and the decisions on the “Energiewende” in 2011 <http://www.bmu.de/energiewende/downloads/doc/47467.php>

The Main objective of this article is to present our combined building and heating market model. In addition to the model presentation, we calculate one policy as usual (PAU) scenario for Germany to evaluate if the achievement of political targets for the heating market is likely or not. The combination of a bottom-up building model with a nested logit model represents a considerable extension to the existing heating market investigations. Therefore our analysis expands existing approaches, offering a different perspective on the heating market development until 2050.

The article is organised into four sections. Section 2 gives an overview of the applied methodology, explaining the general approach and going into the details of the residential building model and the heating system choice. Section 3 presents the application of our combined model for the case of Germany and the heating market results. To test for the model's robustness we calculate an additional sensitivity analysis. The findings show, that the targets formulated by the government appear optimistic under the given regulatory framework. Section 4 summarises and gives an outlook to further research needs.

2 Methodology

Section 2.1 elaborates on the rationale for combining a residential building model with a discrete choice approach for RHSs. Section 2.2 presents the details of the residential building model, while the development and background of the choice model follows in Section 2.3.

2.1 General Approach

A thorough understanding of the dynamics behind residential heating energy demand and associated greenhouse gas (GHG) emissions requires detailed information about the two main drivers: building characteristics and heating systems. Residential heating systems are usually chosen so as to meet the size and energetic requirements of the particular building. Hence, buildings need to be modelled in a first step as they provide the technical and economical basis for the operation of RHS. As the development of heating energy demand in buildings and associated CO₂ emissions also depend on the heating technologies, i.e. energy carriers, the development of the heating market as the sum of individual decisions is modelled in the following. This two model approaches (Figure 1) enables us to investigate the heating market development in a comprehensive, holistic manner.

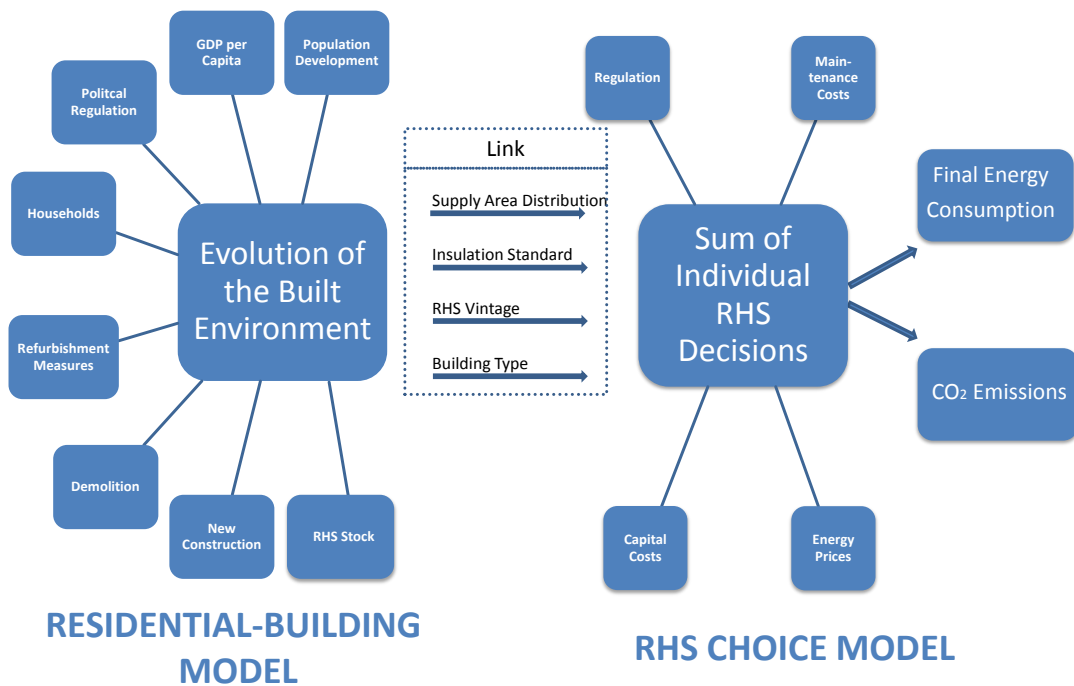


Figure 1 Schematic illustration of the two models, their drivers and dependencies

Buildings are long-lived, durable goods that once erected are not easy to modify in terms of insulation, because additional insulation measures are cost-intensive and therefore present a financial hurdle to many building owners. Still buildings are essential for RHS decisions. While new regulations can be easily adopted for scheduled building projects, the much larger existing building stock poses a challenge to regulations. Thus, new constructions are important but the existing building stock determines the built environment, in particular in Germany where around 90% of the buildings were erected before the first energetic regulation in 1977 (Pietruschka et. al., 2011). Our building model therefore contains detailed data of the existing building stock, needed for calculating the full annual heating costs that later represent the main choice parameter in the choice model. The information of the building market development is incorporated into the second step of investigation, where the RHS market development is modelled based on the choice of households.

2.2 Residential Building Model

The residential building model is designed as a bottom-up model of the built environment. It contains numerous information about the building stock, the types of buildings, their energetic requirements, heating systems and their age structure. Key results of the model are information about the energetic specifications of the buildings as well as the number of newly installed and replaced heating systems. Such information is the input for the next modelling step, the heating system choice. In this section we therefore present the methodology of our bottom-up building model. We calibrate the model to the German residential building market. It could however be applied to any other country.

The German building stock consists of more than 39 million dwellings in approximately 18 million residential buildings, with a vacancy rate of roughly 9% (Federal Statistical Office, 2010). The basic data for modelling is provided by the Institute for Housing and Development (IWU) (Diefenbach et. al., 2010). The IWU building typology data base from 2007 (Diefenbach, Born, 2007) distinguishes 43

different building categories by building type and vintage class². The five building types are: single-family houses, terraced houses, small and large apartment buildings and tower blocks. The ten vintage classes reach from before 1918 until 2010. The structure of the model can be taken from Figure 2.

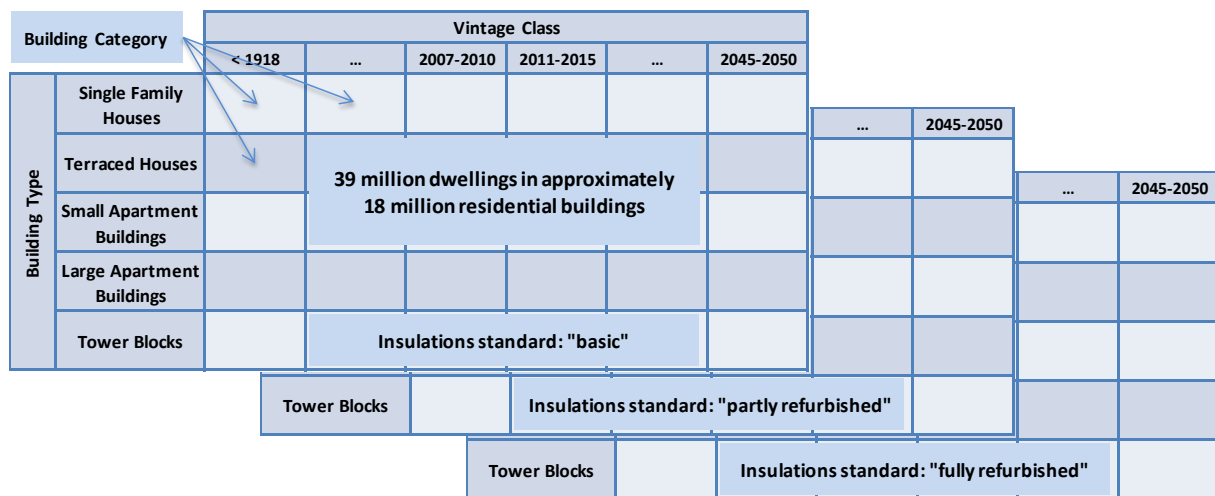


Figure 2 Schematic illustration of the building model

Information on the average number of dwellings per building, the living space, building volume, size and heat demand of each category is added to the model. Micro Census data (Federal Statistical Office, 2010) provides information on the distribution of heating energy used per building type and vintage class. The building typology does not exactly match the periods published by the Micro Census. As the IWU data is more detailed and the basis for the building model, we distribute the heating system data equally to the IWU data to obtain a consistent data set. The data is updated until 2012 using information about newly constructed and torn down buildings from the Statistical Office (Federal Statistical Office, 2011b, 2011c). Further vintage classes are considered in increments of five years until 2050.

Buildings are immobile and bound to their supply area. We therefore differentiate four different types of supply infrastructures:

- gas supply
- district heating supply
- double supply
- no connection to grid bound heating energy

German buildings are distributed to these supply areas, using Micro Census data on the heating energy per building category. Data on the number of dwellings connected to gas and district heating is combined with assumptions and best practice information about the network- or grid density and usual connection rates³. A matching procedure is performed to fit the diverse information on the number of dwellings per building category and their energy supply with the additional supply

² In our model further extended by the insulation standard "basic", "partly refurbished" and "fully refurbished"

³ Data on grid density and connection rates of different network operators was gathered in expert interviews. Additional information was collected through cooperation with the German Association of Energy and Water Industries (bdew) and Energy Data assumptions, published by the Federal Ministry of Economics and Technology. Available at: <http://www.bmwi.de/DE/Themen/Energie/energie-daten.html>

infrastructure information. Even though these supply areas do not form a connected grid in reality, they still form a limit to the households' choice. One can argue that regional climatic differences prevent a useful aggregation of supply areas for the case of a heating market analysis. Yet, Scott et al. (2007) showed that even a 20% change in factors like solar irradiation, wind speed or humidity only slightly changes the building energy demand. As Germany is a country of comparably similar climate conditions and heating degree days, we follow these findings and allow for the simplification to form our supply areas from the sum of all dwellings connected to a certain supply infrastructure in Germany.

In order to generate the input for the following model part, we have to implement the entire residential German building stock by building type, construction age class, heat demand and RHS combined with construction, demolition and refurbishment rates as well as the vintage of the appliance stock.

The future number of dwellings (D) is determined by combining a population forecast until 2050 (Federal Statistical Office, 2006) with the expected average household size (Federal Statistical Office, 2012). The effect of a steady population decline due to senescence, is weakened by the trend towards smaller households with an average of less than 2 persons after 2014 (Federal Statistical Office, 2012). In line with the construction vintages, every time step (t) of our residential building model represents an increment of five years.

$$D_t = \frac{POP_t}{HZ_t} * \rho \quad (1)$$

with

POP_t = Population in year t
 HZ_t = Average household size in year t
 ρ = Reduction factor for dwellings

As a dwelling unit might be occupied by more than one household, the number of households has to be reduced by a factor p . The obtained annual net development (δ_{net}) of dwellings

$$\delta_{net,t} = \left(\frac{D_{t+1}}{D_t} \right) - 1 \quad (2)$$

together with expected data on newly constructed dwellings (δ_{con}), allows us to derive an annual rate of demolition (δ_{dem}), needed to calculate the general dwelling evolution.

$$\delta_{dem,t} = \delta_{con,t} - \delta_{net,t} \quad (3)$$

Furthermore the annual development of the dwellings, i.e. the buildings' growth rate, has to be broken down to the five modelled building types⁴. Unfortunately, market shares and data on the annual construction rates per building are only available for an alternative building classification distinguishing

⁴ In our case, it is broken down to the five building types of the applied building typology. Single Family Houses (SFH), Terraced Houses (TH), Small Apartment Buildings (SAB) and Large Apartment Buildings (LAB) are still supposed to be build, while Tower Blocks (TB) are assumed to be no longer constructed.

buildings types with one, two or multiple dwellings. The following equations show how the aggregated data is apportioned to fit our model. We therefore define $\delta_{con,t}$ as follows:

$$\delta_{con,t} = \delta_{con,t}^{SFH} * \left(\frac{1}{3} m^{SD}\right) + \delta_{con,t}^{TH} * \left(\frac{2}{3} m^{SD} + m^{DD}\right) + \delta_{con,t}^{SAB} * \left(\frac{\frac{2}{3} m^{MD}}{2 * r}\right) + \delta_{con,t}^{LAB} * \left(\frac{\frac{1}{3} m^{MD}}{2 * (1 - r)}\right) + \delta_{con,t}^{TB} \quad (4)$$

with

$$\delta_{con,t}^{SFH} = \frac{\frac{1}{3} s_{con}^{SD} * \delta_{con,t}}{\frac{1}{3} m^{SD}} \quad (5)$$

$$\delta_{con,t}^{TH} = \frac{\left(\frac{2}{3} s_{con}^{SD} + s_{con}^{DD}\right) * \delta_{con,t}}{\frac{2}{3} m^{SD} + m^{DD}} \quad (6)$$

$$\delta_{con,t}^{SAB} = \left(\frac{\frac{2}{3} s_{con}^{MD} * \delta_{con,t}}{\frac{2}{3} m^{MD}}\right) * 2 * r \quad (7)$$

$$\delta_{con,t}^{LAB} = \left(\frac{\frac{1}{3} s_{con}^{MD} * \delta_{con,t}}{\frac{1}{3} m^{MD}}\right) * 2 * (1 - r) \quad (8)$$

$$\delta_{con,t}^{TB} = 0 \quad (9)$$

with

$\delta_{con,t}^{BT}$ = Annual construction rate of dwellings in the each of the modelled building types (BT), with $BT \in \{SFH, TH, SAB, LAB, TB\}$

m^{ABT} = Market share of dwellings in alternative building types (ABT) with a single dwelling, double or multiple dwellings, with $ABT \in \{SD, DD, MD\}$

s_{con}^{ABT} = Average share of newly built dwellings, located in alternative building types with a single dwelling, double dwellings or multiple dwellings

r = Proportion factor for apartment buildings

As tower blocks are no longer constructed, their annual construction rate is set to zero.

The demolition rate per building type ($\delta_{dem,t}^{BT}$) is age dependent and calculated as follows:

$$\delta_{dem,t}^{BT} = \delta_{dem,t} * \frac{\#D_t^{BT}}{\#D_t^{BT} > a_{years}} \quad (10)$$

with

D^{BT} = Dwellings per building type

a_{years} = Age-variable

Since demolition is assumed to be carried out in function of the building age, we proceed in a similar manner for the case of an energetic refurbishment. As a distinction between the different building types is not made for the case of a refurbishment, the annual refurbishment rate for the dwellings older than a_{years} (rr_t^f) is derived as follows:

$$rr_t^f = RR_t^f * \frac{\#D_t}{\#D_t > a_{years}} \quad (11)$$

with

f = Type of refurbishment with $z \in \{\text{partly, full}\}$

RR^z = Global refurbishment rate assumed

In order to calculate the expected living space development - needed to estimate the size of future dwellings - we link the GDP per capita forecast (IMF, 2011), to the previous findings, using the elasticity of demand (η).

$$\eta_{LS,GDP_{cap}} = \frac{\frac{dLS}{LS}}{\frac{dGDP_{cap}}{GDP_{cap}}} = \frac{dLS}{dGDP_{cap}} * \frac{GDP_{cap}}{LS} \quad (12)$$

with

d = Relative change

LS = Living space

GDP_{cap} = Gross domestic product per capita

In an earlier contribution, we have argued that the GDP growth is usually followed by an increase in living space (Bauermann, Weber, 2011). As our study aims to show long term effects on the heating market, we continue in periods of 5 years until 2050.

Beside the refurbishment measures due to the aging of the buildings, we consider the vintage effect on heating systems. Data on the age pattern of existing is used to split existing heating systems into three age classes: new (N), aged (A) and old (O), that are assigned to every building category until 1994. Buildings erected after 1994 are operating on younger heating systems due to their construction age. Equations (13)-(15) show the senescence of the heating systems installed for one time step.

$$N_t = (1 - v) * N_{t-1} \quad (13)$$

$$A_t = v * N_{t-1} + (1 - v) * A_{t-1} \quad (14)$$

$$O_t = v * A_{t-1} + (1 - f) * O_{t-1} \quad (15)$$

with

- v = transition probability between heating vintage classes (50%, given vintage classes contain 10 years and time steps cover 5 years)
- f = replacement rate for old heating systems (75%)

Heating systems up to ten years old are termed “new”, up to 20 years “aged” and beyond that they are termed “old”. As the number of RHS corresponds to heated dwellings, their sum is reduced by torn down and refurbished units, the latter shifted to the calculation equally performed for refurbished buildings.

2.3 Residential Heating System Choice

The RHS choice model represents the second step of our combined model approach. As a discrete choice model, it describes the decision between two or more distinct alternatives, i.e. heating systems in our case. The set of alternatives, called the choice set, that a decision maker may choose from exhibits the three characteristics needed to fit into a discrete choice framework. It is mutually exclusive, exhaustive and finite (Train, 2003). As combined RHS like gas heating with solar thermal support are defined to be one single system, the choice of a certain RHS is mutually exclusive and implies not to choose any other alternative from the choice set. We have considered all heating systems with a considerable market share, leading us to the point that the choice set is exhaustive and that all possible relevant alternatives are included. As final criteria for a discrete choice model to be applied, the number of alternatives in the choice set is finite. All three characteristics are satisfied by definition; hence we formulate a (nested) logit model, the most prominent discrete choice model to assess the RHS choice process (McFadden, 1978; 1981). Fundamental data needed for the simulation of the choice process on RHSs is delivered by the aforementioned residential building model. As a result, the RHS choice model provides a future distribution of RHS-technologies in households and energy carriers used for heating that are needed to calculate heating energy demand and CO₂ emissions of the households. In this section we show the development of our logit model towards a nested logit and the extension compared to existing logit approaches on RHS choice.

As already mentioned, existing studies on RHS decisions either focus on owner decisions or differentiate between renters and owners. This certainly is an important distinction when examining the influence of different variables on the choice process of determined groups. Yet the decision to concentrate on either one or the other group depends on the focus and purpose of the study. This contribution presents our model approach that is designed to follow a broad research question to derive long term generalised conclusions for the heating market. As we focus on long-term effects and estimate parameters from national market data that do not distinguish between landlords and

tenants, we neither distinguish between owner-occupied or rented dwellings and the associated RHS decision. In a detailed short term choice analysis, it is true that the renter probably has only limited influence on the heating system decision of the landlord. Households, as long as they do not own the building, only select the dwelling they want to live in. In a long term perspective, one can argue that a building owner will probably be stronger influenced by the sum of the households' preferences. More precisely, for the sake of a better market position, an owner will be likely to choose a RHS that a potential tenant also prefers (Nesbakken, 2001). This effect is supported by the idea, that the installed RHS in an existing dwelling influences the decision making of a potential renter. The decision maker does consciously decide on the heating system, influencing the future heating system decision of the renter (Braun, 2010). Some authors also include owners and renters into their investigation, following a comparable explanation (Baker et. al., 1989; Vaage, 2000). This could be further discussed in terms of the principal-agent theory, including the problem of asymmetric information between landlords and tenants (Jaffe and Stavins, 1994).

For the main explanatory variable, we follow existing studies and choose full annual heating costs as the main parameter in our choice model. It can be argued that the comparably complex concept of full annual costs does not reflect the peoples' perception of RHS economics. In contrast to the previously mentioned literature, we aim to project the long term development of the heating market and its effects in an integrative approach. Short-term fluctuations of energy prices may influence household decisions, however only for a short period of time. In a long-term perspective, the perception of investment and fuel costs overlap, leading to a general public cost perception of particular RHS. This process is amplified by a higher attention paid to energy related topics due to the generally rising energy price level over the past decade (Frontier Economics, 2010). This demand for information has been satisfied by several heat cost comparisons (Voß, Zech, 2012; Bauermann, Eickholt, Weber, 2010; Ebert, Bohnenschäfer, 2008), that all use full annual costs as key information element. In our long-term investigation, we therefore also use full annual costs as the most suitable figure to cover the long-term perception of different cost parameters among decision makers.

In a discrete choice framework, the probability for a household to opt for a specific RHS is the explained variable. The decision for a heating system depends on the perceived value (V) for the household (i), $i = 1, \dots, n$, that has to select from a finite set of alternatives ($tech$), $tech = 1, \dots, J$. In general, the value of an alternative equals:

$$V_{i,tech} = b'x_{i,tech} + \varepsilon_{i,tech} \quad (16)$$

x stands thereby for a vector of explanatory variables. In our case this includes notably the full annual costs of the heating system $tech$ considered. b describes weights attached to the different explanatory factors and ε the error term. A household i chooses an alternative $tech$ if its value exceeds all other RHS' alternatives. The focus of the following analysis is not on an empirical estimation of the parameters b as in many previous contributions (e.g. Braun 2010 and Michelsen, Madlener, 2012), Yet our focus is on the use of the logit model for future system scenarios. The basic multinomial logit model can thereby be used as starting point. It describes the probability of a household to choose a heating system $tech$ as:

$$Prob(tech|i) = m_{i,tech} = \frac{\exp(b' x_{i,tech})}{1 + \sum_{tech'=1}^J \exp(b' x_{i,tech'})} \quad (17)$$

For the interpretation of the model, the relative log Odds are useful. They are defined as the logarithms of the relative choice probability for an alternative vs. a reference alternative:

$$logOdd_{tech,t} = \log\left(\frac{m_{tech,t}}{m_{ref,t}}\right) \quad (18)$$

with

m_{tech} = Market share of any given technology
 m_{ref} = Market share of a reference technology

The log Odds hence correspond to the logarithm of the ratio (odds) of the market share relative to a the market share of a reference technology. We use as the reference technology as the heating technology with the largest market share in a particular supply area.

Algebraically it can be shown that

$$logOdd_{tech,t} = b' (x_{i,tech} - x_{i,ref}) \quad (199)$$

Yet, in order to get a more realistic description of choice behaviour, the dependence of household choices from previous choices (of other households) has to be taken into account. This can be done by a diffusion term into the multinomial logit model (Rogers, 1962; Kasanen and Lakshmanan, 1989). The diffusion process is used to consider the past period market share development in our model formulation. This describes the observable effect that price differences perceived by the households do not immediately lead to a change in RHS sales numbers. The price-effect is dampened by the influence of past installation numbers, in particular if new technologies are concerned. The more a technology gains market share, the more attention it receives and the more do cheaper prices push future installation numbers. This effect can also be described as the neighbourhood influence, hence the effect that for example the installation of a certain RHS by friends and neighbours positively influences the own choice (Case, 1992).

A further touch of realism is introduced in the model by including not only full cost of heating systems but also typical preferences for some technologies as explanatory variables. Examples of such preferences might be a dislike of oil as dirty fuel and a preference for green technologies.

This leads to the following specification of the extended choice model – the household index I (which corresponds in our case to building types) is dropped thereby for notational convenience.

$$\log\left(\frac{m_{tech,t}}{m_{ref,t}}\right) = \mu \cdot \log\left(\frac{m_{tech,t-1}}{m_{ref,t-1}}\right) + \alpha_{tech} - \alpha_{ref} - \beta \cdot \log\left(\frac{c_{tech,t}}{c_{ref,t}}\right) \quad (20)$$

with

μ	=	<i>Diffusion parameter -, estimate of the last period's installations</i>
m_{tech}	=	<i>Market share of any technology (tech)</i>
m_{ref}	=	<i>Market share of the particular reference technology (ref) – depending on supply area</i>
α_{tech}	=	<i>Preference parameter of any technology – determines market share at equal costs</i>
β	=	<i>cost parameter – determines the influence of perceived cost differences</i>
c	=	<i>full annual costs of heating system</i>

While μ describes the impact of the past relative market share of any given technology, α can be interpreted as the “image” or reputation of a heating system and is assessed individually for each RHS fuel category. Finally β describes the impact of cost differences on household choices. Note that in the specification a positive β corresponds to a reduction of choice probability with increasing costs – as one would expect with usual choice behaviour.

For a detailed parameter estimation, recent, individual long-term household panel data would be needed. Unfortunately such data is not available, that is why parameters are assessed using aggregate time-series of market shares, in-line with our long-term integrative approach. For detailed parameter estimations of RHS choice in Germany, we therefore refer to Braun (2010) and Michelsen, Madlener (2012).

In order to cope with real-world choices, the choice set has to be expanded to a higher number of possible alternatives. For the above mentioned multinomial logit model to be valid, the so-called independence of irrelative alternatives (IIA) has to be assumed (Greene, 1997). It implies that the ratio of probabilities for choosing any two alternatives does not change if a new alternative is introduced. Statistically, a Hausman test can be used to examine the validity of the IIA assumption (Hausman and McFadden, 1984). Intuitively, the introduction of a new alternative which is rather similar to an existing one, should not affect the choice probability of a rather distinct alternative - the classical example is a blue bus added to the choice between red bus and car.

If the IIA assumption does not hold, as is to be expected with the broad variety of heating systems, a nested logit model may be used to overcome that problem. As a result the choice is represented by a two-stage decision tree (cf. Figure 3) is used. The technological progress in the heating market has led to a wide range of available systems that are to a great extent covered by our nested logit model. Different to Kasanen and Lakshmanan (1989), we do not structure our nested logit by organizing it per system type (central vs. non-central) on the first level. In Germany nowadays, central systems are largely dominant, so we rather separate by broad fuel and technology categories on the first decision level (nest). In the lower nest, we then distinguish variants of technologies, e.g. by the share of renewable heating.

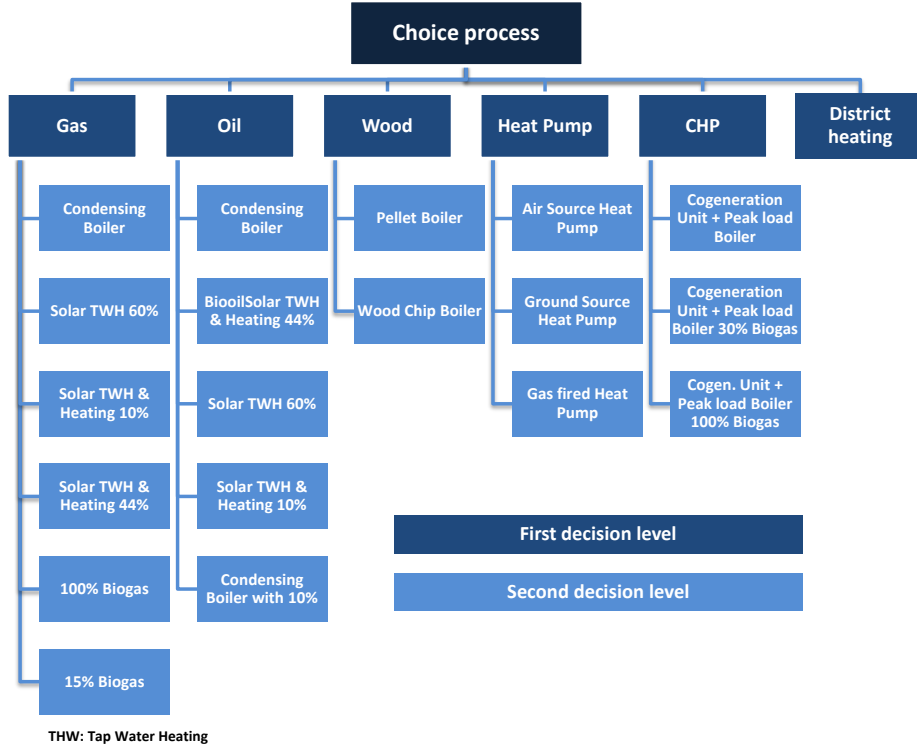


Figure 3 Decision tree and choice set for the nested logit model

By structuring the nested logit by technology and characteristics, a household opts for a general heating technology $gent$ in a first step, while deciding on the specific fuel or technological characteristics $tech$ in a second step. The modelled decision is determined by the choice and costs of the second level alternatives. Yet, the first level decision is connected to the second level decision by the linked equations as follows:

$$\log \left(\frac{m_{tech,t}}{m_{ref,t}} \right) = \mu \cdot \log \left(\frac{m_{tech,t-1}}{m_{ref,t-1}} \right) + \alpha_{tech} - \alpha_{ref} - \beta \cdot \log \left(\frac{c_{tech,t}}{c_{ref,t}} \right) \quad (21)$$

$$\log \left(\frac{m_{gent,t}}{m_{genref,t}} \right) = \mu \cdot \log \left(\frac{m_{gent,t-1}}{m_{genref,t-1}} \right) + \alpha_{gent} - \alpha_{genref} + \gamma \cdot (z_{gent,t} - z_{genref,t}) \quad (22)$$

The parameter z denotes an inclusive value for each general technology with γ as its coefficient. In order to solve the choice problem, we have to proceed in the reverse order, so that the value of the lower nest determines the value of the upper nest. First, market shares, i.e. conditional probabilities of specific fuel or technological characteristics $tech$ within a lower nest have to be calculated, given a choice for a general heating technology l in the higher nest. Second, equation (22) is evaluated providing the log odds for any general heating technology. The key linkage between the lower and the upper nest is the inclusive value z which is in line with the general nested logit approach as:

$$\begin{aligned}
z_{gent,t} &= \ln \sum_{tech \in gent} \exp(\alpha_{tech} - \beta \cdot \log(c_{tech,t})) & (233) \\
&= \log \left(c_{ref,t}^{-\beta} \left(e^{\alpha_{ref}} + \sum_{\substack{tech \in gent \\ tech \neq ref}} \exp \left(\alpha_{tech} - \beta \cdot \log \left(\frac{c_{tech,t}}{c_{ref,t}} \right) \right) \right) \right) \\
&= -\beta \cdot \log \left(c_{ref,t} \left(e^{\alpha_{ref}} + \sum_{\substack{tech \in gent \\ tech \neq ref}} \exp \left(\alpha_{tech} - \beta \cdot \log \left(\frac{c_{tech,t}}{c_{ref,t}} \right) \right) \right)^{\frac{1}{\beta}} \right)
\end{aligned}$$

The third part of the equation provides an intuitive interpretation to the inclusive value. In fact, it corresponds to the (logs of the) cost of the reference technology within the nest, corrected by a term which reflects the benefits of diversity of choice within the nest. Hence the upper level of choice may also be written:

$$\log \left(\frac{m_{gent,t}}{m_{genref,t}} \right) = \mu \cdot \log \left(\frac{m_{gent,t-1}}{m_{genref,t-1}} \right) + \alpha_{gent} - \alpha_{genref} - \gamma \cdot \beta \cdot \log \left(\frac{c_{gent,t}}{c_{genref,t}} \right) \quad (24)$$

Using thereby the representative costs of the general technology $c_{gent,t}$ defined as:

$$c_{gent,t} = c_{ref,t} \left(e^{\alpha_{ref}} + \sum_{\substack{tech \in gent \\ tech \neq ref}} \exp \left(\alpha_{tech} - \beta \cdot \log \left(\frac{c_{tech,t}}{c_{ref,t}} \right) \right) \right)^{\frac{1}{\beta}} \quad (25)$$

By construction, the factor following the cost $c_{ref,t}$ will be smaller than one, at least as long as $\alpha_{ref} \geq 0$. Hence the cost of the generalized technology has the cost of the corresponding reference technology as upper bound. If many alternatives are present at the lower level, the apparent cost at the higher level will decrease – reflecting a higher propensity to choose from an attractive nest.

The inclusive value hence bridges the gap between the two nests. It implies that households' decisions in the higher nest (cf. Figure 3), are taken in awareness of the anticipated maximum utility of the lower nest's decision. To sum up, the probability to choose for one RHS technology category depends on the costs of its lower nest alternatives. Our extended choice model can now be applied on German market data. This is an improvement to existing literature on the heating market development as it covers all

common heating technologies and their leverage effects on market shares among each other by applying a nested logit with a diffusion effect.

3 Application Case

Section 3 shows the application and the results of our linked model approach calibrated for Germany. Section 3.1 presents the main parameters of the German building and heating market as well as assumptions made for our model calibration. Results are presented in 3.2. The final energy demand and CO₂ emission development as well as the results of a sensitivity analysis are shown at the end of this section.

3.1 Context & Data

As shown before, the building stock in Germany includes a wide range of different building types and vintage classes. Furthermore, the location of a building inside a certain supply area restricts the choice set of heating technologies. For example the decision in favour of district heating is only possible in areas with an existing heating grid. The same holds for gas. Hence, the distribution of buildings within the four supply areas in Germany determines the RHS choice set while the building type influences the RHS economics. Large buildings, for example, are more often supplied by district heating than single family houses, because the building corresponds to a larger heat sink and therefore is economically more attractive for district heating (see Figure 4).

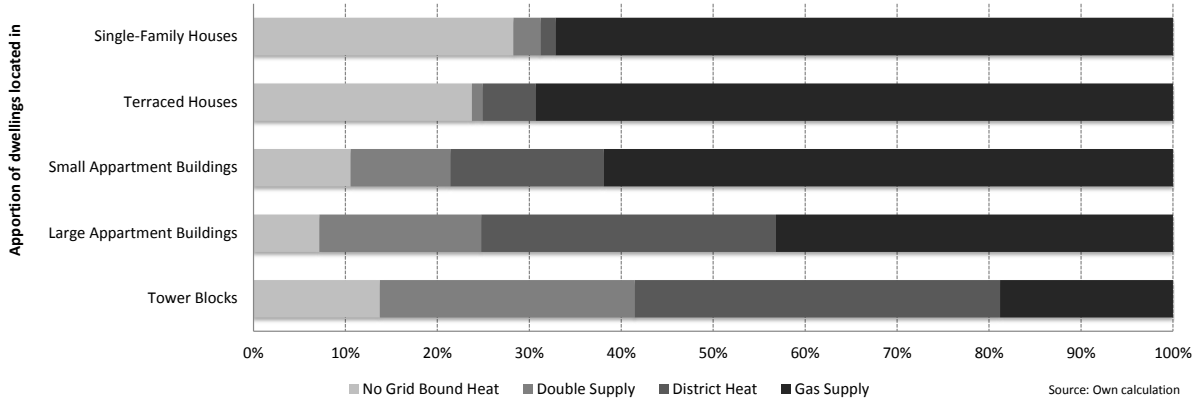


Figure 4 Distribution of dwellings per building type in the four supply areas

We assume that despite the political will to expand district heating supply, no major changes will occur to the distribution of buildings within the network infrastructure until 2050. Newly erected, low energy buildings and energetically refurbished existing buildings reduce grid profitability and increase the share of sunk, fixed costs, leaving only very few options to grid expansion in reality. Grid expansion is therefore not covered by our model, while increased connection rates within existing supply grids are possible, following the households’ choice.

Besides the type of building, it is the buildings’ energetic performance and its future development that significantly determine the RHS economics. Data on the energetic quality of the existing buildings are taken from of the IWU building typology and additional information (Born et. al., 2003). The performance figures of the future building types follow the energy concept as part of the “Energiewende”. These targets as well as observed market developments determine our PAU-scenario configuration. The main regulation to achieve demand reductions in the building market is the Energy

Saving Ordinance (EnEV), last adapted in 2009 (Bundesgesetzblatt, 2009). It formulates building codes and efficiency standards for buildings and will be further tightened to harmonise German standards with the European standard for nearly zero-energy buildings, the new construction standard for 2020 and beyond (Directive 2010/31/EU, 2010). In the public debate, a tightening of the primary energy demand and the insulation standard of the building envelope of about 30% is discussed concerning an announced new ordinance in 2012 or 2013 (BMWi, 2007). A refurbishment roadmap for existing buildings is announced to be set in place, to help owners make their way through the numerous refurbishment measures and to give support to efficient actions (BMU, 2011). Besides new buildings, primarily addressed by the EnEV, the rate of energetic refurbishment should be increased and doubled soon, as it still averages below 1% (BMWi, 2010; Kohler, 2012). Despite the constant emphasises on behalf of the German government and financial support granted for energetic refurbishment measures, recent annual rates remain constantly low or even fall (Biogasrat, 2012). Thus, we only assume a slow increase of refurbishment rates, not exceeding 1.6% of the stock from 2030 on. We further differentiate between partial and full refurbishments (see Table 1):

Table 1 Assumed annual rates of partial and full refurbishment of the building stock

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Partial Refurbishment	0.6%	0.7%	0.8%	0.9%	1.0%	1.0%	1.0%	1.0%	1.0%
Full Refurbishment	0.2%	0.3%	0.4%	0.5%	0.6%	0.6%	0.6%	0.6%	0.6%

Despite a decreasing population, new buildings that meet the living standard of today will still be constructed to replace old, torn down buildings. Based on population and household size forecasts (Federa Statistical Office, 2006), we assume a net growth rate for the number of dwellings in Table 2 (Bauermann, Weber, 2011), that turns negative by 2025.

Table 2 Expected growth rate of the number of dwellings over all building types

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Net development	0.29%	0.73%	0.12%	-0.46%	-1.62%	-1.65%	-3.03%	-3.10%	-3.10%

The number of dwellings is about to diminish by approximately 2 million units, reaching around 37 million in 2050. The rates of construction, demolition and refurbishment are distinguished between the five different building types and construction age classes. Statistics show that proportionally more dwellings are provided in new single family or detached houses than in apartment buildings (Federal Statistical Office, 2011b). Tower blocks are assumed to be no longer built in Germany. Finally, the model calibrated for Germany consists of 18 construction age classes and five building types that cover all residential buildings from the early 20th century until 2050. Tower blocks are an exception as there are only three instead of 18 construction age classes. In sum, the model considers 225 building categories, each with different energetic requirements.

Heating systems have a lifetime that is typically specified to average around 20 years, depending on the particular technology⁵. However, many households and buildings in Germany still have older systems installed. Following market data only 13% of the heating systems installed in 2008 were new

⁵ The 20 years lifetime of heating systems is an average figure, derived from several publications, such as fuel cost comparisons, the VDI Guideline 2067 Part 1 and manufacturer information. Among others, available at: http://www.ie-leipzig.com/IE/Publikationen/Studien/IE_Vollkostenvergleich_2008.12.01.pdf

and younger than 10 years, whereas around 70% were aged, hence between 10 and 24 years, while the remaining 20% were older than 24 years (BDH, 2008, BDH, 2011⁶). Today, the German heating market is dominated by gas heating. Figure 5 shows the market share distribution of RHS for single-family houses and apartment buildings.

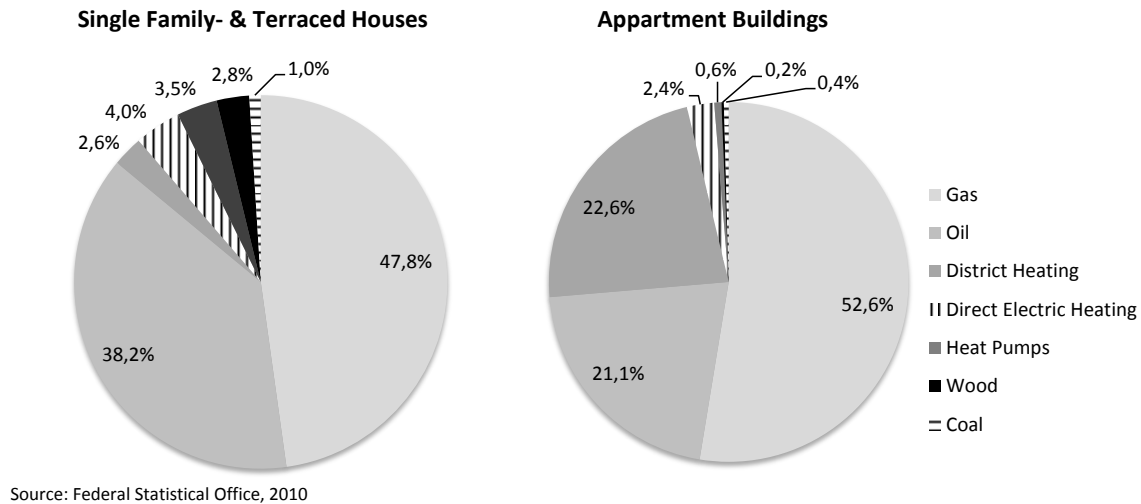


Figure 5 Aggregated market share of heating systems (higher nests) in 2010 by single-family & apartment houses

Corresponding to the distribution of buildings to the supply areas (Figure 4), dwellings in apartment buildings are more often supplied by district heating, while oil is more often used for single family houses. We omit direct electric and coal heating systems from our analysis as they are crowded out of the market by political initiative and represent a niche system of no systemic relevance. In sum, the household choice can be made between 21 different systems shown in Figure 3⁷. These systems represent the vast majority of the German heating market. The latest Act on the Promotion of Renewable Energies in the Heat Sector (Heat Act) prescribes that single gas- or oil-fired heating systems in new buildings are no longer allowed to be installed without the support of renewable energy (Bundesgesetzblatt, 2008). Like in the federal state of Baden-Wuerttemberg we consider biogas and biooil to be an option to satisfy the requirements of the Heat Act and suppose that this will be a nationwide option soon (Landtag von Baden-Württemberg, 2007).

Electricity prices for the time range are derived using the latest version of a stochastic electricity market model (E2M2^s) (Swider and Weber, 2007; Spiecker and Weber, 2011). Energy prices, required to calculate the full annual heating costs, are either taken from E2M2^s as well, or from further publications (Biogasrat, 2012; BMWi, 2012). The wholesale market prices are transformed to retail market prices, adding current taxes, duties, and surcharges. The Renewable Energy charge of 5,2 ct/kWh (Bundesgesetzblatt, 2012), as well as the aforementioned figures are kept constant over the considered period. Inflation adjusted, real energy prices for the final consumer are shown in Table 3.

Table 3 Inflation adjusted household energy price in €/kwh development until 2050

	2010	2020	2030	2040	2050
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⁶ Effizienzstruktur Heizungsanlagenbestand 2011, BDH 2011, sent on request

⁷ Figure shows only 20 systems that can be chosen by the household. District heating represents a final nest, that entails local heating too. Local heating is not considered in detail, as the costs are project individual and determined by the particular heat grid.

Electricity	23.2	28.6	27.6	27.6	27.6
Gas	7.0	7.6	8.1	8.3	8.6
Oil	8.2	10.6	11.3	11.6	11.7
District Heating	7.7	7.8	8.3	8.6	8.9
Biooil	18.5	18.5	18.5	18.5	18.5
Biomethan	15.4	15.4	15.4	15.4	15.4
Pellets	5.8	6.3	7.2	6.7	5.8
Wood Chips	3.9	4.2	4.8	4.5	3.9
EEG Charge	3.6	5.2	5.2	5.2	5.2

The prices for wooden energy carriers are internally calculated by using the elasticity of demand. Electricity prices for heat pump users are 5 ct/kWh below the average energy retail price. The capital- and operation-bound costs for the heating systems are derived from the updated version of our heat cost comparison (Bauermann and Weber, 2010). Subsidies for the installation of heating systems are based on the current German regulation (Bundesanzeiger, 2012)

3.2 Results for the PAU scenario

The results presented in the following are derived under the PAU-scenario assumptions. This scenario is most suitable for this contribution, which focuses on the methodological aspects, offering an additional application case. The PAU-scenario is based on the continuation of recent policy and announced modifications of relevant regulations; it is hence most suitable to answer the question if the achievement of recent political heating market targets is likely or not.

According to the model results, the German households slowly develop towards a more diversified heat supply that is less dominated by fossil fuels. In 2010 fossil fuels largely dominate the RHS stock, since renewable stand-alone systems have been absent from the market until the 1990s. Figure 6 shows the market share development of dwellings with general heating technologies installed⁸.

⁸ Others include direct electric heating and coal heating stoves

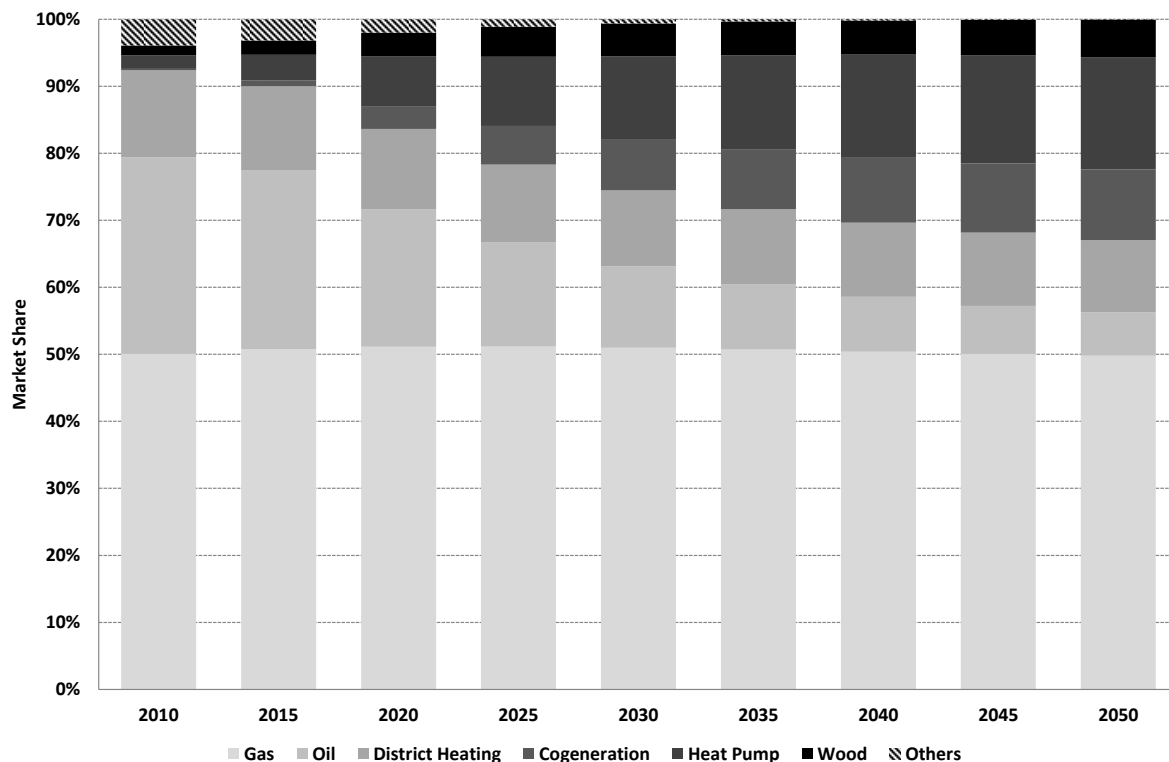


Figure 6 Market share development of dwellings with general heating technologies installed until 2050

At first sight it is striking that there is only little change in the market share of dwellings supplied by gas fired heating systems until 2050, while dwellings equipped with oil fired systems nearly lose 85% of their initial market share. Nevertheless, we find a continuous domination of fossil fired RHS until 2050. Since the households' energy demand is dominated by the demand for heating energy, a "climate-neutral building stock" until 2050 seems to be unattainable under current regulation. Renewable heating systems like wood fired stoves and heat pumps gain market shares until 2050 but remain below 25%. Only little market share losses can be observed for traditional district heating, while cogeneration units appear increasingly attractive to decision makers. The two technologies conjointly cover around 20% of the overall market in 2050.

The PAU-scenario results reveal the shortcoming of recent regulations and subsidies. However, more households opt for renewable heating systems than visible at first sight. The detailed results behind the first-level categories in Figure 6 permit to evaluate the development of the heating market more in detail (Figure 7). Yet they strengthen the perception that recent regulation does not suffice to achieve the stated heating market objectives.

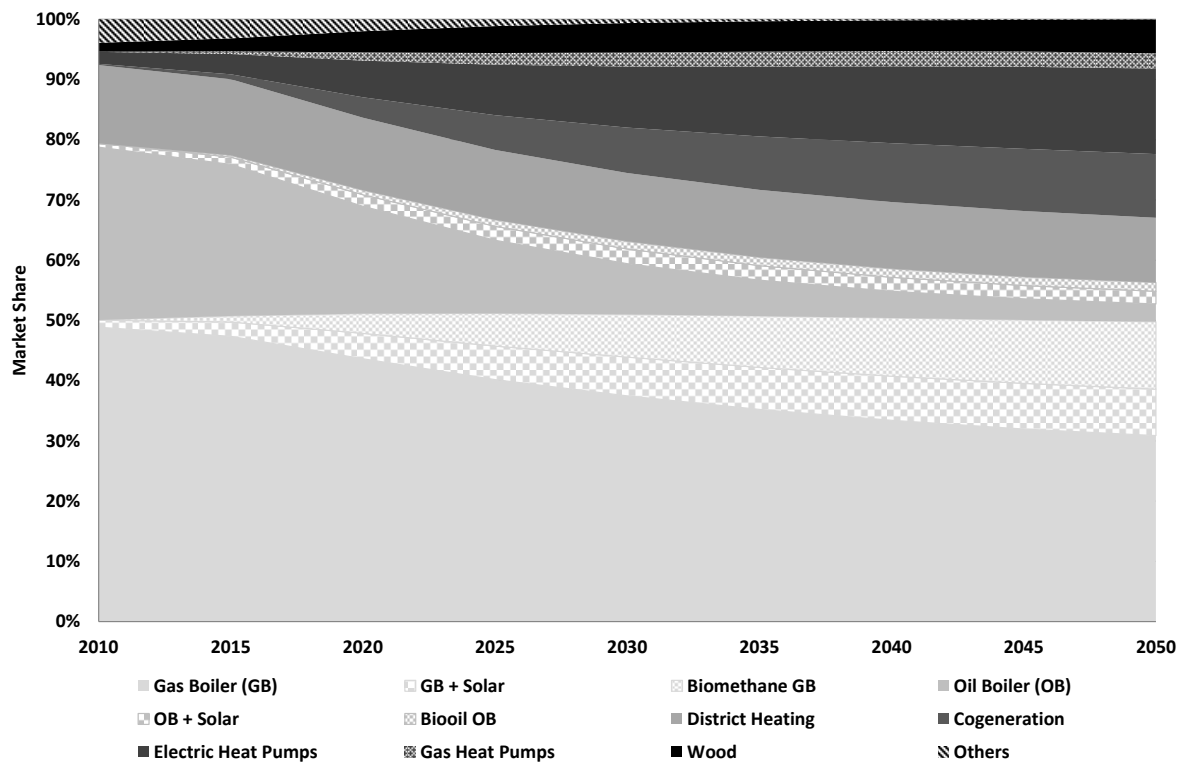


Figure 7 Market share development of dwellings with second level category technologies installed until 2050

The slow shift towards regenerative RHS continues among technologies in the gas nest. Single gas fired RHS lose market shares but remain dominating until 2050 when they still deliver heat for approximately 30% of the households. Combined gas-solar-thermal systems and RHS with biomethane addition constantly increase their market share but stay below 20% of all supplied dwellings in 2050. Oil fired RHS generally lose on the heating market, dropping to only 7% of the total market share in 2050. While single oil fired heating become less relevant, solar-thermal combinations and biooil addition solutions gain market shares. In 2050 oil heating RHS are equally split between regenerative and solely oil fired RHS. Regenerative RHS like heat pumps and wood-fired stoves expand their market share by a factor of more than six, delivering heat to 22% of the households in 2050. Heat pumps become more attractive as they are the choice for nearly 17% of the households in 2050, nearly three times more than wood fired RHS⁹. The evolution of the building market and the regulatory framework also affect the market share of combined heat and power technologies. The ongoing refurbishments of the building stock lead to lower heating energy demand, consequently turning heat grids less profitable. New housing estates with low energetic demand provide little opportunities for district heating supply anyway. However district heating can more or less defend its market position and does not drop below 10% until 2050. The slight downturn of district heating is compensated by smaller cogeneration heating systems that become increasingly attractive until 2050. As district heating is costly for newly erected buildings due to little heat demand, smaller, customized cogeneration units penetrate the market as they do not have to refinance an expensive grid structure.

We find that the continuation of announced and existing regulations and subsidies, represented by the PAU-scenario, does not suffice to incite a heating market dominated by regenerative systems until

⁹ The strong market share increase of heat pumps is to some extent induced by the lower heat pump tariff, that is 5 ct/kWh below the average household price. If the prices were adjusted, as already observed in some regions in Germany, electric heat pumps could only reach around 10% market share – losing 7% points in 2050

2050. Single fossil fired RHS are still permitted to be installed in buildings erected before 2009, which represent the majority of buildings until 2050. As the inertia to turn away from well-known systems is high while alternative systems remain comparatively expensive, a heating market development towards the domination of regenerative energy cannot be expected.

3.3 Sensitivity analysis

Besides the scenario assumptions such as regulation, the parameters of our applied model influence the results. In particular, the parameters b and μ , that describe the strength of the price sensitivity and the role of the diffusion process should be investigated in order to test for the robustness of our model results. A high, absolute value of b corresponds to a high sensitivity towards price differences, while a high value of μ imposes a strong influence of the diffusion process and hence a slower adoption of new technologies.

In order to test for the robustness of our model we vary the parameters b and μ for the PAU-scenario. Figure 8 shows the households’ reaction on the variation of the two parameters in 2050. A low value of b , hence less price sensitivity results in a lower gas share. The total heating costs as criterion for decision making becomes less important. Alternatives to gas are now more frequently chosen or people stick to their existing system even if it is identified to be more expensive. Oil RHS, heat pumps and wood fired boilers benefit from a lower b . Opposing effects occur with a higher b , where even small differences in full costs convince decision makers to opt for the cheaper alternative.

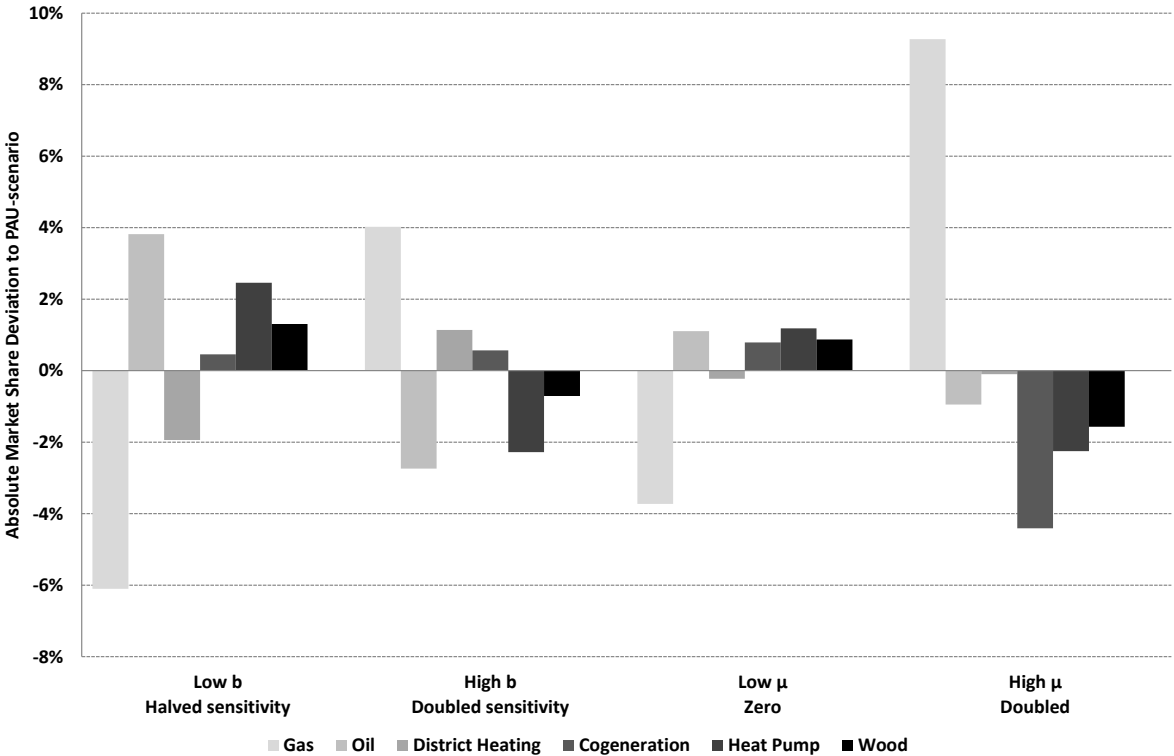


Figure 8 Comparison of market share deviation between the PAU-scenario and altered parameters in 2050

For the parameter μ that determines the strength of the diffusion effect, we chose to eliminate it rather than to lower the value. A decision making analysis without the consideration of a diffusion process leads to market results with a slightly higher share of renewable RHS. If the slowing diffusion effect is eliminated, less inertia towards new technologies results in downwards pressure on the market share of the market leader. The doubled weight of μ results in a higher inertia towards new

heating technologies. The higher appreciation for proven technologies strengthens the gas market shares also on the expense of oil heating systems and leads to more than 9% more households that choose gas fired RHS in 2050.

The impact on market shares is even more obvious at the lower choice level (Figure 7). The dominating single gas boilers still represent the cheapest alternative to many households and serve best to illustrate the effect of the parameter variation. The lower b that leads to 6 percentage points less gas heated dwellings in general has in turn a positive influence on alternative gas systems. While single gas fired RHS loose more than ten percent market share until 2050, solar thermal and biogas combinations profit from a lower price sensitivity. In contrast, if b is higher the little full cost advantage of single gas heating systems makes more households decide in favour of this system. An infinite b would result in a market dominated by the cheapest RHS even if it has only an infinitesimal cost advantage. The variation of μ reveals a comparable effect on the market share of single gas heating boilers. Alternative technologies like heat pumps and biogas/biooil combinations profit from the assumed absence of a diffusion process, as more decision makers are willing to change to an alternative technology. However this is unrealistic, since diffusion processes are characteristic for innovations as already shown by Rogers (1962).

3.4 Impact on energy demand and CO₂ emissions

Besides the share of renewable RHS in the heating market, the demand for heating energy until 2020 and the CO₂ emissions are primarily targeted by policy makers and building regulation. In order to answer the question if the political targets are likely to be achieved under the assumed PAU-scenario, Figure 9 and Figure 10 show the model results for the final energy demand and CO₂ emissions of the residential heating market including the results for the sensitivity analysis. Final heating energy demand and emissions are only little affected by the parameter variation.

The energy consumption for heating in 2020 is targeted to be 20% below the 2008 consumption. Refurbishment measures and the demolition of old, inefficient buildings in the PAU-scenario lead to a constant decrease in final energy demand for heating. Yet, the decrease is too low and the achievement of the 2020 target is delayed as it is only reached between 2025 and 2030.

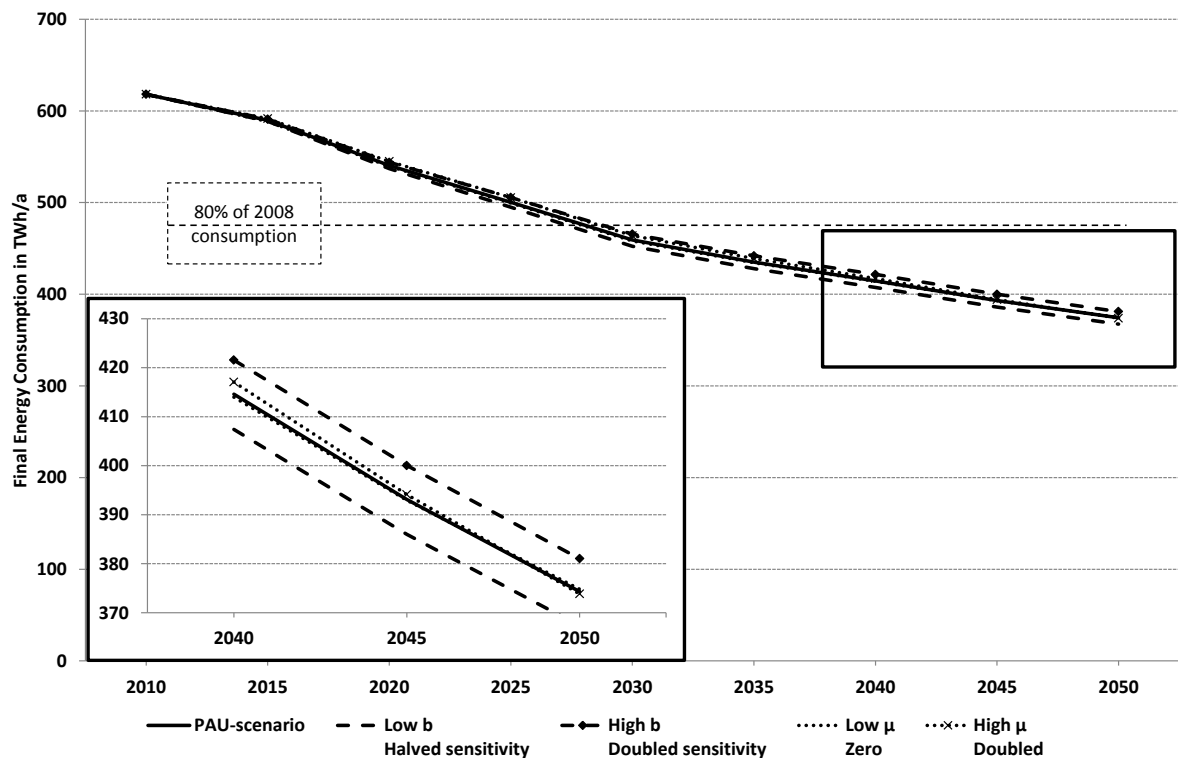


Figure 9 Development of final energy demand for heating until 2050

Nevertheless it should be noted that the 2020 target does not fall out of reach. The regulation in place and in preparation as assumed by the PAU-scenario and the resulting building- and heating markets lead to a steady decline of heating energy demand. A lower price sensitivity would facilitate the target achievement, while the variation of the diffusion process does not affect the results significantly.

The achievement of the CO₂ emission reduction targets can be evaluated by more than one step. The German government aims to achieve emission reductions of 40% until 2020, based on the emissions of 1990. Furthermore 55% should be reached by 2030, 70% by 2040 and at least 80% until 2050 (BMW, 2010). The decreasing heating energy demand leads to less energy consumption and emissions. The share of renewable RHS affects the CO₂ emissions just like a lower heating energy demand, while the energy demand more affected by refurbishment measures. Differences between the PAU-scenario and the parameter variations therefore become more visible in Figure 10.

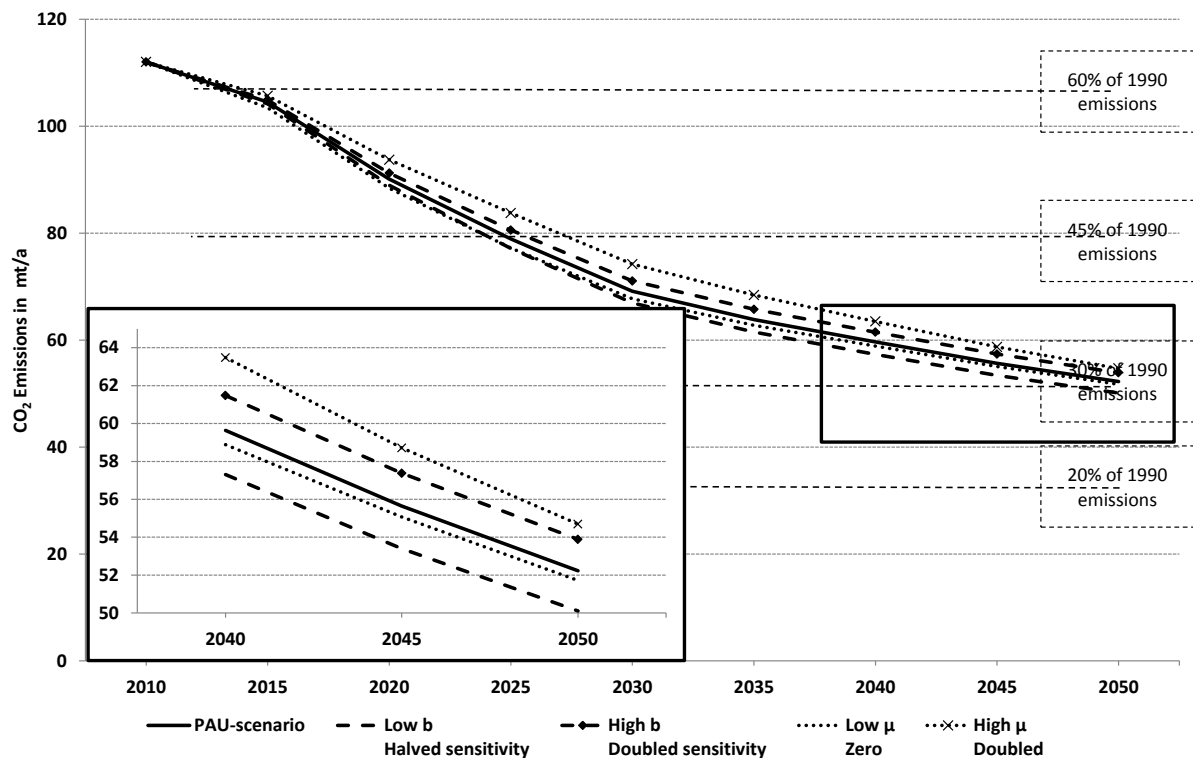


Figure 10 CO₂ emission development comparison between the Base Case and the sensitivity analysis

The heating contributes overproportionally to the 2020 reduction target, as 40% are already reduced by 2015. Further efficiency yields appear more difficult. The early attainment of the 2020 goal can be explained by the reunification effect in Germany. The poor building and insulation quality in the former GDR has led to refurbishment measures during the 90ties and after 2000. For the same reason the 2030 target is also exceeded. Yet these low hanging fruits have been picked and are no longer attainable in the future (Barkholz, Rosenschon, 2012), so that the 70% reduction for 2040 is only reached by 2050. The 80% reduction target for 2050 is clearly missed. Comparable to the energy demand-findings, the targets formulated by the government are not out of reach but appear optimistic in the light of the given regulatory framework. The PAU-scenario does not formulate an obligation for the use of renewable RHS. As future refurbishment yields diminish due to the generally higher future insulation level, renewable RHS become crucial for the attainment of ambitious emission reduction goals. Corresponding to the higher renewable shares, the sensitivity analyses show stronger emission reductions for a low price sensitivity and in absence of the diffusion process. Yet the effects remain limited and even under the optimistic assumptions the 2040 and 2050 objectives are clearly missed.

4 Summary and Conclusion

Space heating accounts for a large fraction of energy demand and associated CO₂ emissions in Germany and other countries with similar climate. Energy prices have been on the rise drawing more attention to residential heating. The development of the residential heating energy demand and emissions is consequently identified to be a key aspect of the German “Energiewende” as well as for European reduction efforts. It is therefore of importance to have methods and models that help to understand the evolution of the residential heating market and allow for the evaluation of political targets and the impact of regulation.

The study's aim was to present an extended approach for the development of the residential heating market and to answer the question if the existing demand and emission reduction goals are likely to be attained under the current and announced regulation. Our combined residential building and heating model connects and extends previous approaches, which either focus on the building market or on the determinants of the RHS decision. By using a nested logit model with a diffusion term, we expand the choice set for households to a total of 21 different heating systems, each considered for every building category of a detailed German building typology. With this combination applied to the policy-as-usual scenario, we deliver a considerable extension to the available literature on the RHS markets and the German market in particular. The results offer a long-term integrated perspective on the future heating market development under given regulation and may be of high interest for policy makers and heating market players.

Following our model results, the attainment of politically desired heating market targets is rather unlikely. Neither the demand reduction until 2020 nor the emission reduction until 2050 will be achieved in time under the current and announced regulation. Yet, these targets are not out of reach. Both are delayed but may be reached at a later point in time. While the energy demand for heating reaches the 2020 target by 2028, emission reductions yields decrease so that the 80% reduction is only reached by 2075¹⁰. In order to make faster progress, the regulation has to be modified and developed further. Our model results suggest the following measures to increase the achievement of objectives.

As long as refurbishment rates remain at today's low level, efficiency potentials cannot be tapped. Beyond the pronouncement of ambitious targets like a doubling of the refurbishment rates, effective measures are needed to actually achieve these targets.

The second crucial point is the future distribution of heating systems and once more the role of the built environment. For now renewable RHS are only mandatory in new constructions, while the lions' share of heating systems is operating in the building stock. The "climate-neutral building stock" cannot be attained under the PAU-scenario, despite some subsidies granted to renewable RHS. As future efficiency yields by refurbishment tend to decrease, renewable RHSs and their market share become increasingly important for the attainment of CO₂ reduction targets. One should therefore consider an obligation for the use of renewable RHS in the case of RHS replacements to achieve climate policy targets. Alternatively also a CO₂ tax may be considered as a first best-instrument according to environmental textbook theory. Furthermore, the realisation of a faster stock-refurbishment could yet significantly put downward pressure in the energy demand. These variations were not focused on in this paper and leave room for further investigation.

So far, our findings lead to the conclusion that the innovation will of decision makers is overestimated and that the decision making process is more rigid than expected by politicians. The model developed here may be used in further studies to assess in detail the impacts of alternative regulations and thus contribute to a realistic assessment of climate policy opportunities and limitations.

¹⁰ Reductions of the final simulation years are extrapolated.

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