Households' dynamic investment in domestic energy efficiency

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Abstract

In this article we study households' incentives to improve their domestic energy efficiency. We develop and estimate a structural dynamic model of households' retrofitting investments. The model explicitly accounts for the dynamic nature of the investment activities, with high cost of investment that occur at the time of retrofitting and with payoffs being realized delayed in time. The model also accounts for changes in household behavior that result from higher efficiency levels after a modernization, by linking the dynamic investment model to a structural model of the household's demand for heating. The model allows us to quantify the expected long-run utility gain and cost from retrofitting investment.

We find that retrofitting investment is very costly, in monetary and non-monetary terms, which leads to low investment rates by households. Once conducted, energy efficiency investment has a substantial impact of reducing domestic energy requirements for heating. Households are found to increase their demand for warmth in reaction to decreases in the energy requirement, hence marginal cost of thermal comfort. Furthermore, simulations of counterfactual policy scenarios show that government subsidy that decrease the investment cost, increases the investment rate, does however little to reduce the household's energy consumption. A household facing higher energy prices, however has more incentive to invest in domestic energy efficiency improvement. An increase in energy price of 10 percent increases the probability of investment substantially and reduces the energy consumption by 6 percent.

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1 Introduction

The European Commission takes strong actions to combat climate change. It has set Europe-wide goals to reduce greenhouse gas emission by 40 % compared to 1990 levels and to realize energy efficiency improvement by 32.5 % until 2030 (European Commission, 2020).[1] Numerous regulatory frameworks and subsidy programs are in place to trigger household investment into energy saving technology as means to meet climate targets. In Germany alone they include mandatory prescriptions for new products, subsidy programs and tax credits for the adoption of energy efficient technology, and information campaigns of different forms and scale.

Many of these programs focus on setting incentives for the retrofitting of domestic housing, for example the modernization of the thermal shell and heating system of dwellings. One reason for the relevance of retrofitting is that residential space heating is a major contributor to the overall energy consumption in the economy. In the European Union households have accounted for roughly 26 % of the total final energy consumption in 2018 of which almost 64 % were used for heating (Eurostat, 2020).

Engineering calculations show, that the energy saving potentials from retrofitting are substantial. Energy demand for residential heating can be reduced by half with the appropriate retrofitting measures (Becchio et al., 2012). In Germany roughly 60 % of gas-fired and 70 % of oil-fired installed heating systems have been more than 20 years old in 2019 (Bundesverband Des Schornsteinfegerhandwerks, 2019). Additionally, only 50.4 % of all dwellings in Germany had received some thermal insulation of the outer walls in 2016 (Cischinsky and Diefenbach, 2018, p. 44) , which further indicates the large potential that could be leveraged, if the necessary investments were conducted.

Households are found to be fairly reluctant to retrofit their homes. The empirical observation that even (seemingly) profitable investments into energy efficiency remain undone, has extensively been discussed in the literature and is commonly referred to as the "Energy Paradox" (Hirst and Brown, 1990; Jaffe and Stavins, 1994; Gerarden et al., 2017). Reasons for the low investment rate are manifold. They include market failures, financial constraints, behavioral

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[1] In September 2020 it proposed to further raise the reduction target to a 55 % reduction of greenhouse gas emissions over 1990 levels until 2030 (European Commission, 2020).

biases in consumers' decision process, and misconceptions about the level and heterogeneity of actual cost and potential savings that households face (see Gerarden et al., 2017).

To assess how effective government policies are to promote investments in energy saving technology, a precise understanding of how they affect households' decision process is required. We contribute to the understanding of households' retrofit decisions by developping a dynamic structural model of their decision to modernise the thermal shell, windows or heating system of the dwelling they inhabit.

In the model, households choose in every period a mean indoor temperature in the dwelling to maximize period utility. The amount of fuel required to produce the desired temperature level depends on the thermal efficiency level of the dwelling. Households invest in energy saving technology to improve the energy efficiency standard and thus the amount of fuel required to heat the dwelling to the desired temperature level. This investment choice has dynamic implications: By improving the domestic energy efficiency, households benefit from savings in energy consumption or from higher thermal consumption levels in the future. Households only invest if the expected resulting gain in lifetime utility, discounted to the current period, exceeds the one-time fixed costs that arise at the time of investment. Using fuel data from "The German Residential Energy Consumption Survey" (**?**) we first estimate the parameters of households' period utility function using a framework developed by Mertesacker (2020a). In a second step, the investment costs are then estimated given the increase in lifetime utility that we calculate based on the estimates of households' preferences for thermal comfort obtained in step 1. Using maximum likelihood the investment cost are chosen such that they rationalize investments observed in the data, given the developed economic model.

The empirical analysis of households' retrofitting decisions using the proposed structural dynamic investment model has a couple of advantages over standard regression analyses, such as logit or probit, that rely on static utility models to estimate the relationship between household and dwelling characteristics and the propensity to invest. First, the lifetime utility gain from investing is derived from a sound economic model of the period utility that households receive from the consumption of thermal comfort. Different to mere engineering estimates of the benefits of modernising the dwelling, our model explicitly accounts for the possibility that households may benefit from increased efficiency levels by reducing their expenditures for thermal heating as well as by increasing the temperature level in their dwelling. While the possibility of households to rebound after an efficiency increase is undesirable from a policy perspective that aims to reduce fuel consumption to mitigate carbon emissions, it increases the potential benefits of investments to households. Our model allows to explicitly consider both effects. Conveniently, the chosen functional form of the period utility function implies that lifetime utility gains can be expressed in monetary values even though they also include non-monetary benefits to households. In our sample, the mean expected increase in lifetime utility that results from investing is $4,368$ euro.

Second, the framework allows to estimate and analyse the benefits and costs of investing separately. Standard regressions of observed investments on household and dwelling characteristics only estimate the net impact of both factors behind the investment decision. In contrast, our model assigns a clear structural interpretation to every estimated parameter. Since investment costs are estimated in relationship to the lifetime benefits of investing, they are also expressed in monetary equivalents, providing an intuitive quantification of all impediments that might hinder more investment to occur. The cost estimates thus provide a convenient alternative to standard calculations of high discount rates to characterize households' low investment activity despite large potential savings that might be realized.

Third, given the estimates of all parameters of the dynamic structural model, we can predict and thus quantify model quantities such as the temperature choice and the associated fuel consumption, the period utility, the expected gain in lifetime utility associated to an investment and the resulting investment probability for every household in the sample. In contrast to estimates of average impacts of covariates on the investment probability, provided by standard regression approaches, this allows a much more detailed study of households' incentives to invest and how these might change if conditions in the economic environment are altered.

Finally, the model allows to explicitly analyse the consequences of different policy scenarios – that are designed to facilitate investments or reduce energy consumption – on households' decisions. Simulating a public policy that aims at reducing households' costs of investing via a direct subsidy, we find that the investment rate is increased, but that this does only little to decrease average fuel consumption. Similar effects are found for a policy that increases the effectiveness of modernisations, e.g., by funding research and development. In contrast, an increase in energy prices, for instance via a tax, creates high energy saving incentives for households. It leads to an increase in the investment rate by 22.1 % and a reduction of households' mean temperature choice by 4.8 %.

In the next section we introduce the theoretical model of households' energy demand and dynamic investment decision. Section 3 describes the data used for the estimation. Section 4 discusses the estimation procedure and empirical results. Section 5 provides concluding remarks.

2 Theoretical model

This section develops a theoretical model of households' dynamic decision to improve their domestic energy efficiency through retrofitting. The model is structured in three steps. First, households decide whether or not to retrofit their home. This can be the insulation of walls, installation of double glazing (two or three glass window panes) or the adoption of a more efficient heating system. The second step describes the impact of these retrofitting measures on the energy required for heating. Dwellings with lower energy requirements are considered more energy efficient. In the third step, the changes in domestic energy efficiency affect households' optimal consumption of thermal warmth and can lead to improvements in households' overall utility level.

In the dynamic model households invest in improvements of their domestic energy efficiency level to maximizes the discounted sum of expected future utility, while taking into account the impact of retrofitting measures on domestic energy requirement and the resulting improvements in their utility level. The next subsections develop the theoretical model for each stage. We first analyse the link between the energy efficiency level, households' consumption of warmth and the utility they receive, before we move to the dynamic retrofit decision.

2.1 Energy efficiency and thermal heat consumption

To model households' consumption of thermal comfort, we make use of a structural empirical model developed by Mertesacker (2020a). The model considers households to consume thermal comfort by choosing a mean indoor temperature in their dwelling. If the temperature level reaches a satiation point of 21 degree Celsius, they enjoy blissful thermal comfort. Deviations from this ideal temperature level create discomfort. To avoid this disutility, households spend parts of their income on the consumption of heating energy. The remaining part of income is spent on the consumption of all other goods. Household i's period utility function is given by

$$u(\tau_{i,t}) = \beta^G \left(Y_{i,t} - p^F_{i,t} \cdot F(\tau_{i,t}, s_{i,t}, m_{i,t})\right) - \boldsymbol{\beta^\tau x^\tau_{i,t}} \cdot (\bar{\tau}_{i,t} - \tau_{i,t})^2. \tag{1}$$

Household i's income in period t is denoted by $Y_{i,t}$. The function $F(\tau_{i,t}, s_{i,t}, m_{i,t})$ determines the amount of heating energy consumed by households, measured in kilowatt hours (kWh), and $p^F_{i,t}$ denotes the energy price per kilowatt hour. The amount of fuel consumed, $F_{i,t}$ depends on households' decision by how many degrees to increase the indoor temperature, $\tau_{i,t}$, on a measure for the efficiency of the dwelling, $s_{i,t}$, and on the size of the living area, $m_{i,t}$, measured in squared metres. The variable $s_{i,t}$ measures the amount of energy in kilowatt hours per square metre required to increase the mean indoor temperature of the dwelling by one degree Celsius over the entire heating period. It is larger for very inefficient dwellings and the smaller the less fuel is required to heat the dwelling to a desired indoor temperature.[2] Thus, the first term of the utility function is the utility level households receive from their available income net heating expenditures.

Depending on the outdoor temperature, the parameter $\bar{\tau}_{i,t}$ denotes the maximal temperature increase households can choose by heating the entire dwelling up to 21 degree Celsius over the entire heating period. It is the difference between the ideal and the outdoor temperature level. The actual temperature increase chosen by households is $\tau_{i,t} \in [0, \bar{\tau}_{i,t}]$. Thus, the second term of the utility function describes their disutility resulting from the deviation between the ideal temperature increase and the actual choice of $\tau_{i,t}$. Additionally, we allow for the thermal disutility to vary by household characteristics stored in the column vector $\boldsymbol{x^\tau_{i,t}}$. The parameters stored in the row vector $\boldsymbol{\beta^\tau}$ indicate how differences in variables in $\boldsymbol{x^\tau_{i,t}}$ affect households' valuation of thermal comfort and will be estimated in the empirical analysis. The heterogeneity in the marginal utiltiy of indoor temperature leads to heterogeneity in temperature choices and

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[2] See Mertesacker (2020b) for a very detailed discussion how the variable $s_{i,t}$ can be obtained from an engineering model and be interpreted.

thus energy consumption.

Overall, households can reduce their thermal discomfort by choosing a temperature increase, $\tau_{i,t}$, that is close to $\bar{\tau}$. This however involves higher spending on fuel consumption.

Following Mertesacker (2020b) and Mertesacker (2020a), we assume that fuel consumption can be related to households' temperature choice by a linear function:

$$F_{i,t} = F(\tau_{i,t}, s_{i,t}, m_{i,t}) = s_{i,t} m_{i,t} \tau_{i,t}. \tag{2}$$

Solving households' period utility maximization problem, the optimal temperature choice can be derived:[3]

$$\tau^*_{i,t}(s_{i,t}) \;\; = \;\; \bar{\tau}_{i,t} - \frac{\beta^G}{2\boldsymbol{\beta^\tau x^\tau_{i,t}}} \cdot p^F_{i,t} s_{i,t} m_{i,t}. \tag{3}$$

Households' optimal temperature increase is a function of the utility function parameters $(\beta^G, \boldsymbol{\beta^\tau})$, dwelling characteristics $(s_{i,t}, m_{i,t})$, the energy price, $p^F_{i,t}$, and household characteristics $\boldsymbol{x^\tau_{i,t}}$. The ratio ${}^{\beta^G}\!/_{\boldsymbol{\beta^\tau x^\tau_{i,t}}}$ indicates households' valuation for thermal comfort relative to other goods. A high valuation of thermal comfort is reflected by small values of ${}^{\beta^G}\!/_{\boldsymbol{\beta^\tau x^\tau_{i,t}}}$, implying the consumption of high temperature levels according to equation (3). Furthermore, as $s_{i,t}$ decreases, the amount of fuel required to increase the room temperature is reduced. This effectively lowers the marginal cost for heating and results in a higher temperature choice. This rebound effect – documented in previous studies (see, e.g., Aydin et al., 2017) – reflects utility maximising behavior and is an important part of the benefits associated to retrofit investments. At the same time it reduces the amount of fuel that is saved through a modernisation. Our model explicitly incorporates both effects.

Inserting the optimal temperature choice, $\tau^*_{i,t}$, into equation (1), it is straight forward to obtain households' utility as a function of the efficiency level, $s_{i,t}$, and other state variables:

$$u(\tau^*_{i,t}(s_{i,t})) \;\; = \;\; \beta^G Y_{i,t} - \beta^G p^F_{i,t} s_{i,t} m_{i,t} \bar{\tau}_i + \frac{(\beta^G p^F_{i,t} s_{i,t} m_{i,t})^2}{4\boldsymbol{\beta^\tau x^\tau_{i,t}}}. \tag{4}$$

Equation (4) allows to directly calculate the period utility households receive given different efficiency levels of the dwelling. It provides the basis to explore the benefits households may

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[3] See Mertesacker (2020a) for a very detailed discussion of the entire theoretical model.

receive from retrofitting their dwellings. In the dynamic estimation we simplify equation (4) by dropping the term $\beta^G Y_{i,t}$, which neither affects households' optimal temperature choice nor their benefits from investing. The resulting period utility $\tilde{u}(\tau^*_{i,t}(s_{i,t}))$ strictly smaller than zero.

To calculate the utility gains associated to actual modernisations, their impact on dwellings' efficiency levels has to be modelled. We model the domesting energy efficiency level to follow a first order Markov process, that can be shifted by retrofitting investments. Using discrete indicators of retrofitting investments, $r_{i,t}$, the evolution process of energy efficiency can be characterized as follows:

$$\begin{aligned} s_{i,t+1} &= g(s_{i,t}, r_{i,t}) + \varepsilon_{i,t} \\ &= \lambda_0 + \lambda_1 s_{i,t} + \lambda_2 s_{i,t}^2 + \lambda_3 s_{i,t}^3 + \lambda_4 r_{i,t} + \varepsilon_{i,t}. \end{aligned} \tag{5}$$

The realized energy efficiency level in period $t+1$ depends on its lagged values, the modernisation activities in the last period and an error term $\varepsilon_{i,t}$. Generally, the energy efficiency level is a combination of several dwelling characteristics, for instance the materials used for construction. While the building can deteriorate over time, the main characteristics do not change vastly and previous energy efficiency levels will generally be carried over to future periods. The parameters $\lambda_1, \lambda_2, \lambda_3$ jointly determine the persistence of the energy efficiency level. If households invest into retrofitting measures, energy requirements for heating can be reduced and the level of $s_{i,t}$ will be shifted by the amount of λ_4. In the empirical model we also distinguish the impact of different retrofitting types and their interaction with the energy efficiency level to capture the heterogeneity in the overall impact. The random term $\varepsilon_{i,t}$ captures the uncertainty in the efficiency process. It allows for households with the same efficiency levels and investment decisions to have different energy efficiency realization in the next period. This can be due to the ability of the construction companies that implement the retrofitting, the products they use and specifics of the dwelling that affect the exploitation of the energy saving potentials. We assume $\varepsilon_{i,t}$ to be i.i.d normally distributed with mean zero and variance σ^2_ε, according to a distribution function $\Omega(0, \sigma^2_\varepsilon)$.

2.2 Households' dynamic investment choice

This section develops households' dynamic investment decision in domestic retrofitting. The majority of the empirical energy literature aims at measuring the correlation between households' investment decisions and their socioeconomic characteristics. We take another approach and model households' optimal investment decision structurally. In our model the investment decision results from a comparison of the long-run benefit from investing and the one-time fixed cost associated to it. Households' long-run benefit from investing is the potential gain in period utility through improved domestic energy efficiency in all future periods. These gains might be achieved through lower total cost for the consumption of indoor temperature or by realising a higher level of thermal comfort in the dwelling. The cost of retrofitting can be interpreted as the sum of all costs households encounter when conducting the energy efficiency improvement. Most obviously, this contains the monetary spending for the installation of retrofitting measures. It however, also includes non-monetary impediments to the investment such as behavioral cost that may arise from the necessity of gathering information about the investment alternatives, the existence of a construction side within the dwelling or other inconveniences related to the installation. In our model, we capture the effect of all costs from retrofitting on households' choice by a variable, $C_{i,t}$, that directly measures the total utility cost encountered by the household. It indicates the total loss in (lifetime) utility associated to an investment discounted to period t when the retrofit decision is made.[4] The investment cost vary across households. Different households work with different construction companies and enjoy different prices for the retrofitting. Households can also have idiosyncratic differences in their behavioral impediments to invest. To allow for the cost heterogeneity, we model the investment cost $C_{i,t}$ as a random draw from an exponential distribution with mean γ, $C_{i,t} \sim \Phi_C^\gamma$.

In each period, t, households observe their energy efficiency level and choose the temperature increase that maximises period utility according to equation (3). Then, they learn their investment cost and make an investment decision $r_{i,t} \in \{0, 1\}$. Note, that even though house-

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[4] Generally, all costs associated to the investment are considered to occur in the period the retrofit decision is made. Households might take out a loan to cover monetary cost of the retrofit, such that payments are apportioned over many periods in the future. The variable $C_{i,t}$ then measures the net present value of the loss in period utility over the repayment period.

holds observe their investment cost in the current period, they remain uncertain about the cost they will face in future periods. In period $t+1$, the new energy efficiency level is realized based on the evolution process stated in equation (5).

Households' value function before observing the investment cost is:[5]

$$\begin{aligned} V(s_{i,t}) = \quad & u(\tau^*_{i,t}(s_{i,t})) + \max_{r_{i,t}} \int_{C_{i,t}} \Big\{ \delta EV(s_{i,t+1}|s_{i,t}, r_{i,t}=1) - C_{i,t}; \\ & \qquad \delta EV(s_{i,t+1}|s_{i,t}, r_{i,t}=0) \Big\} d\Phi^{\gamma}(C), \end{aligned} \tag{6}$$

where δ denotes the discount factor. The term $EV(s_{it+1}|s_{i,t}, r_{i,t})$ denotes households' expected value of future utility given the current energy efficiency level, $s_{i,t}$, and the retrofitting decision, $r_{i,t}$. The expectation about future utility is taken with respect to the realization of $s_{i,t+1}$. That is,

$$EV(s_{i,t+1}|s_{i,t}, r_{i,t}) = \int_{s_{i,t+1}} V(s_{it+1}) d\Omega(s_{i,t+1}|s_{i,t}, r_{i,t}).$$

Households' decision to modernize the dwelling, implies that the evolution process follows a different, more favourable, path than if they decide not to invest. Consequently, the expected stream of future period utilities given that an investment has occurred, $EV(s_{i,t+1}|s_{i,t}, r_{i,t} = 1)$, exceeds the respective expectation without an investment, $EV(s_{i,t+1}|s_{i,t}, r_{i,t} = 0)$. The difference between the two future value streams determines the expected long-run gain of a retrofit investment.

$$\Delta EV(s_{i,t}) = EV(s_{i,t+1}|s_{i,t}, r_{i,t} = 1) - EV(s_{it+1}|s_{i,t}, r_{i,t} = 0).$$

Retrofitting occurs if and only if the expected discounted lifetime utility gain of investing, $\Delta EV(s_{i,t})$, is larger than the investment cost, $C_{i,t}$,

$$r(s_{i,t}) = \begin{cases} 1 & \text{if} \quad \delta \Delta EV(s_{i,t}) > C_{i,t} \\ 0 & \text{else} \end{cases} \tag{7}$$

The expected gain from investing in energy saving technology depends on the current efficiency level of the dwelling and further socioeconomic characteristics such as households' age and size. Differences in $s_{i,t}$ and the variables in the vector $\boldsymbol{x^{\tau}_{i,t}}$ across households result in

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[5] Besides the energy efficiency level, households' value function also depends on other dwelling and household characteristics, which we omit here for notational convenience.

variation in the expected gain from investing. Together with the variation in the cost that households draw in every period, this allows for heterogeneity in households' choices.

Overall, our model endogenizes the retrofitting decision of households and links it to the evolution of energy efficiency and their choice of thermal comfort. The key structural components of the model which we estimate from the data are: (i) parameters of the utility function in equation (4), (ii) parameters of the energy efficiency evolution process stated in equation (5) and (iii) the parameter γ of the investment cost distribution. The model can be estimated using data on households' investment decisions, $r_{i,t}$, fuel consumption, $F_{i,t}$, dwelling characteristics $m_{i,t}$ and $s_{i,t}$ and demographic characteristics $\boldsymbol{x}_{\boldsymbol{i,t}}^{\boldsymbol{\tau}}$. The next sections describe the data, estimation procedure and discuss the results.

3 Data

For the empirical analysis a dataset created by Mertesacker (2020b) is used. The dataset contains information on fuel consumption, household characteristics, dwelling characteristics and investment behavior, fuel prices and the efficiency states of the dwelling and thus all information required for the estimation of the structural model.

The main source behind the dataset is "The German Residential Energy Consumption Survey" (**?**).[6] The survey is based on a random sample of 6,715 German households, that have been interviewed in 2010. The dataset includes information about household and dwelling characteristics as well as the energy consumption between 2006 and 2008.

Households' investment activities are in the centre of our analysis. The survey provides data on the investments that occurred between 2002 and 2008. Households separately report if and when investments occurred into thermal insulation, new windows and new heating systems during this time period, respectively. In our empirical model we define the investment variable to equal 1 in years households have undertaken any of these modernisation measures and 0 otherwise. The investment rate according to this definition amounts to approximately 6.154 % in our sample.

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[6] The subsequent description of the data closely follows Mertesacker (2020b). He also provides additional detailed descriptions of the data cleaning and the generation of efficiency states, including a discussion of potential selection concerns.

We also use fuel consumption data in the estimation of the parameters of the period utility function. The survey provides data on households' fuel consumption between 2006 and 2008. Furthermore, it contains data on the number of household members and children living in the households as well as the income, age, education and employment status, which we use to analyse heterogeneity in households' preferences for thermal comfort.

To obtain price data and information on efficiency states Mertesacker (2020b) combines the main data from the "The German Residential Energy Consumption Survey" with information about average fuel prices households had to pay between 2006 and 2008 and with information on dwellings' efficiency state, $s_{i,t}$. While the price data is obtained from the German ministry of economics (Bundesministerium für Wirtschaft und Energie, 2018), the efficiency states, indicating the amount of fuel (in $^{kWh}/_{m^2}$) required to increase the mean indoor temperature by one degree Celsius have to be generated.

For this purpose, Mertesacker (2020b) uses an engineering calculation procedure developed by Loga et al. (2005). Their program has been developed with the intention to facilitate the creation of energy performance certificates for home owners and to provide guidance on potential savings that can be realized through modernisations. The program requires only few dwelling characteristics, that are easily observable for home owners, as inputs. Mertesacker (2020b) shows that this program can also be used to predict the efficiency states and fuel requirements for every households observed in the main dataset. The average constructed efficiency level amounts to roughly 24.97 $^{kWh}/_{m^2}$ per year. Overall, the efficiency measure varies in building characteristics, it ranges between 13.39 $^{kWh}/_{m^2}$ and 43.93 $^{kWh}/_{m^2}$ at the 5th and 95th percentiles of the efficiency distribution, with less modern buildings exhibiting higher energy requirements.[7]

In our empirical analysis we focus on households using natural gas, oil or long-distance heat for primary heating. Furthermore, tenants as well as dwellings with more than two apartments are excluded from the dataset.[8] This ensures that the investment decisions are made by the

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[7] See Mertesacker (2020b) for a very detailed discussion how the calculation procedure by Loga et al. (2005) can be applied to micro datasets to predict fuel requirements as well as an analysis of the predicted efficiency states.

[8] To ensure reliability of the fuel consumption data and the generated efficiency states outlier corrections have been conducted. Furthermore, households' for which some fuel consumption data is unboserved, some inputs required to generate the efficiency states are missing or whose children have already moved out are excluded.

households studied in the empirical analysis and that the type of investments that are observed are of a broadly similar kind an magnitude.

To allow for households' period utility to vary with demographic characteristics, we construct a couple of discrete variables to include in the empirical analysis. These include three categorial variables indicating the number of adults and children living in the household as well as the age cohort of the survey respondent.[9] Finally, we construct dummy variables indicating whether the survey respondent has a high-school degree (the German "Abitur"), is employed, belongs to a high or low income group and lives in a relatively small or large dwelling, respectively.[10]

4 Estimation and empirical results

Our model can be estimated using data on households' investment decisions, $r_{i,t}$, households' energy consumption $F_{i,t}$, dwelling characteristics, $m_{i,t}$ and $s_{i,t}$, and household characteristics $\boldsymbol{x^{\tau}_{i,t}}$. The estimation of the model involves three steps. In the first step, we estimate the parameters of the period utility function stated in equation (4). The second step estimates the evolution process of the efficiency state, $s_{i,t}$, defined in equation (5). We use this evolution process to model agents' expectations about future realisations of the state variable in dependence of their investment behavior. In the third step, we estimate the parameter of the investment cost distribution using maximum likelihood. The key structural components of the model which we estimate from the data are: (i) the vector of utility function parameters $\boldsymbol{\beta^{\tau}}$, (ii) parameters of the energy efficiency evolution process $(\lambda_0, \lambda_1, \lambda_2, \lambda_3, \lambda_4)$ and the variance the error term σ^2_{ε}, and (iii) the parameter γ of the investment cost distribution.

4.1 Estimation of the period utility function

Following Mertesacker (2020a), we estimate the parameters of the utility function by relating the optimal temperature choice derived from the theoretical model, $\tau^*_{i,t}$, to observed fuel demand,

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See Mertesacker (2020b) for further details.

[9] The number of persons living in the household is top-coded at four adults and two children, respectively

[10] Households are assigned to a low income group, if their income is below 1,500 euro per month and to a high income group if it exceeds 3,500 euro. The reduction of the number of income groups is ensures that a sufficiently large number of observations in each income bin and reduces the number of variables included in the final regression. The main results are robust towards alternative definitions of income bins.

$F_{i,t}$, using the fuel consumption function of equation (2). This yields a regression equation that is nonlinear in the parameters to be estimated:

$$F_{i,t} = s_{i,t} \cdot m_{i,t} \cdot \left(\overline{\tau}_{i,t} - \frac{\beta^{G}}{2\boldsymbol{\beta}^{\boldsymbol{\tau}} \boldsymbol{x}^{\boldsymbol{\tau}}_{\boldsymbol{i,t}}} \cdot p^{F}_{i,t} s_{i,t} m_{i,t} + \varepsilon^{\tau}_{i,t} \right). \tag{8}$$

The error $\varepsilon^{\tau}_{i,t}$ accounts for variations in $F_{i,t}$ that cannot be explained by observed preference shifters in the vector $\boldsymbol{x}^{\boldsymbol{\tau}}_{\boldsymbol{i,t}}$ or by changes in $s_{i,t}$, $m_{i,t}$ or $p^{F}_{i,t}$.

Equation (8) clarifies that preferences for general goods and for thermal comfort cannot separately be identified. A larger fuel consumption can equally be explained by a low marginal utility of income – indicated by a small parameter β^{G} – or by a strong preference for thermal comfort, indicated by a larger value of the product $\boldsymbol{\beta}^{\boldsymbol{\tau}} \boldsymbol{x}^{\boldsymbol{\tau}}_{\boldsymbol{i,t}}$. We therefore normalize the parameter β^{G} to unity. This implies that the parameters in $\boldsymbol{\beta}^{\boldsymbol{\tau}}$ as well as households' period and long-run utility can be interpreted in monetary terms.

Previous work by Mertesacker (2020b) and Mertesacker (2020a) has shown that efficiency states, $s_{i,t}$, generated from an engineering model, are likely to suffer from measurement errors. Concretely, they mostly overestimate the amount of fuel a dwelling requires. The size of the overprediction systematically correlates with dwelling characteristics. To avoid that this introduces biases in our estimates on household characteristics from the vector $\boldsymbol{x}^{\boldsymbol{\tau}}_{\boldsymbol{i,t}}$, we follow Mertesacker (2020a) and model an adjustment term, $\lambda(\boldsymbol{x}^{\boldsymbol{\lambda}}_{\boldsymbol{i,t}}, \boldsymbol{\beta}^{\boldsymbol{\lambda}}, \varepsilon^{\lambda}_{i,t})$, that captures systematic overpredictions in the generated efficiency state, $s^{e}_{i,t}$, over the unobserved true efficiency level, $s^{\circ}_{i,t}$:

$$s^{\circ}_{i,t} = \lambda(\boldsymbol{x}^{\boldsymbol{\lambda}}_{\boldsymbol{i,t}}, \boldsymbol{\beta}^{\boldsymbol{\lambda}}, \varepsilon^{\lambda}_{i,t}) \cdot s^{e}_{i,t}. \tag{9}$$

$$= (\beta^{\lambda}_{0} + \boldsymbol{\beta}^{\boldsymbol{\lambda}} \boldsymbol{x}^{\boldsymbol{\lambda}}_{\boldsymbol{i,t}} + \varepsilon^{\lambda}_{i,t}) \cdot s^{e}_{i,t}. \tag{10}$$

The adjustment term is allowed to vary with observable dwelling characteristics stored in the vector $\boldsymbol{x}^{\boldsymbol{\lambda}}_{\boldsymbol{i,t}}$. The linear specification for the adjustment term of equation (10) can be easily included in regression equation (8):

$$F^{d}_{i,t} = s_{i,t} m_{i,t} \cdot \left(\beta^{\lambda}_{0} + \boldsymbol{\beta}^{\boldsymbol{\lambda}} \boldsymbol{x}^{\boldsymbol{\lambda}}_{\boldsymbol{i,t}} \right) \cdot \left(\overline{\tau}_{i,t} - \frac{\beta^{G}}{2\beta^{\tau}(\boldsymbol{x}^{\boldsymbol{\tau}}_{\boldsymbol{i,t}})} \cdot p^{F}_{i,t} s_{i,t} m_{i,t} \cdot \left(\beta^{\lambda}_{0} + \boldsymbol{\beta}^{\boldsymbol{\lambda}} \boldsymbol{x}^{\boldsymbol{\lambda}}_{\boldsymbol{i,t}} \right) \right) + \varepsilon_{i,t}. \tag{11}$$

The effect of dwelling characteristics on the size of the overprediction is then estimated along with households' preferences for thermal comfort. The error term $\varepsilon_{i,t}$ is a function of $\varepsilon^{\tau}_{i,t}$ and

$\varepsilon_{i,t}^{\lambda}$. Given that we control for many dwelling characteristics in the empirical estimation, we are confident that the remaining unexplained systematic measurement error, $\varepsilon_{i,t}^{\lambda}$, is small and uncorrelated to variables in $\boldsymbol{x_{i,t}^{\tau}}$, such that biases can effectively be avoided.

Table 1 reports results obtained from estimating equation (11). These indicate that there is some heterogeneity in the utility households receive from the consumption of thermal warmth and thus in the choices they make. Older, larger and more educated households are found to have stronger preferences for high mean indoor temperatures. Increases in income have no statistically significant impact on thermal heat consumption of home owners, conditional on the other controls included in the regression equation. However, there is a substanial significant impact of dwelling size on households' temperature consumption, which might capture income and wealth effects that the available income data is not able to pick up.[11]

It is straight forward to derive households' elasticity towards changes in the marginal cost of heating from their optimal temperature consumption stated in equation (3). This elasticity can be predicted for every household given the estimates of the utility function parameters reported in table 1. We obtain a mean elasticity of households in the estimation sample of -0.377.

The results also confirm that there is some overprediction of the efficiency state that varies with characteristics of the dwelling. The intercept, β_0^{λ}, indicates that the efficiency state of a dwelling from the base group is adjusted to 66.1 % of its predicted value.[12] The size of the adjustment is smaller for newer dwellings and those that have received additional thermal insulation. For row houses the adjustment is stronger. We use estimates from the lower panel of table 1 to adjust the efficiency states in our sample and use these for the subsequent analyses. Working directly with the adjusted $s_{i,t}$ greatly reduces the number of state variables that have to be included in the dynamic estimation, which substantially increases calculation time. Before moving to the dynamic estimation, the next section estimates the evolution process using the

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[11] Unfortunately, income data is only available as a categorial variable in the primary dataset, which limits the level of detail in which it can be analysed. In addition, the dataset undersamples low income households. See Mertesacker (2020b) and Mertesacker (2020a) for more details on the role of income on households' temperature choice and problems in the identification of these effects with the given dataset.

[12] The base group is a single family detached dwelling of average size, constructed before 1919, without modernisation investments in the recent years heated with natural gas and inhabited by a household with average income.

Table 1: Estimates of utility function and adjustment term parameters [a]

Dep. Var: $F^d_{i,t}$	Coefficients	Standard Errors
Estimates of households' utility function parameters:		
Constant: β^τ_0	12.790***	(2.333)
Age ≥ 50	4.071**	(1.858)
# adults:		
2	3.045**	(1.404)
3	6.778**	(3.128)
≥ 4	5.119**	(2.445)
# children:		
1	-1.315	(1.603)
≥ 2	2.928	(1.806)
Is employed	-2.304	(2.000)
Has Abitur	3.673**	(1.478)
Income:		
$< 1,500$ €	3.520	(2.243)
$\geq 3,500$ €	0.898	(1.360)
Size of the dwelling:		
Small: $<$ 1st tercile	-1.487	(1.761)
Large: $>$ 2nd tercile	4.373***	(1.520)
Estimates of adjustment term:		
Constant: β^λ_0	0.661***	(0.069)
Row house	-0.207***	(0.029)
Construction year:		
$1919 - 1968$	0.026	(0.061)
$1969 - 1977$	0.125*	(0.067)
$1978 - 1994$	0.240***	(0.065)
≥ 1995	0.159**	(0.062)
Has modernised:		
Windows	0.046	(0.038)
Heating system	-0.024	(0.034)
Thermal shell	0.115***	(0.039)
Income:		
$< 1,500$ €	0.029	(0.058)
$\geq 3,500$ €	0.048	(0.031)
Size of the dwelling:		
Small: $<$ 1st tercile	-0.053	(0.042)
Large: $>$ 2nd tercile	-0.015	(0.031)
Predicted mean elasticity	-0.377***	(0.031)
Observations	1,365	
R-squared	0.893	

[a] The table reports results from an estimation of equation (11) by nonlinear least squares. The ideal temperature increase is set to $\bar{\tau}_{i,t} = 21 - \tau^{out}_{i,t}$ degrees Celsius. Year and fuel type fixed effects are included as adjustment term parameters in the regression. Standard errors are reported in parantheses and clustered on the household level. Statistical significance at a 1 %, 5 % and 10 % level of confidence is indicated by one (*), two (**) and three (***) asterisks, respectively.

adjusted data.

4.2 Estimation of the evolution process

Using the efficiency states that have been adjusted based on the estimation results from section 4.1, we estimate the evolution process of $s_{i,t}$ as a function of the lagged efficiency state and past investment behavior by ordinary least squares. The estimated evolution processes provides an approximation to the full fuel requirement calculation conducted based on the model by Loga et al. (2005). The estimates provide a simple generalised rule to calculate the efficiency states based on the average impact of modernization in our observed sample.

Table 2 reports the estimation results for four different specifications of the evolution process. Since no fuel data is required, the entire time span from 2002 to 2008, for which investments are observed, is used for the estimation. All specifications show that the dwelling experiences some depreciation if households do not invest. If they do, the investment is generally successful, as been illustrated by column (1). On average, the amount of fuel required to increase the effective indoor temperature by one degree is reduced by approximately 10.366 $^{kWh}/_{m^2}$. This is quite a substantial improvement, equivalent to roughly 43 % of the mean efficiency state of 23.96 $^{kWh}/_{m^2}$.

Column (3) differentiates between the different investment alternatives that households have. Investing into thermal insulation has by far the largest impact on the overall efficiency level of the dwelling, reducing it by 16.419 $^{kWh}/_{m^2}$. The impact of new windows and a new heating system is smaller, but still statistically and economically significant. While combined investments into windows and thermal insulations have a reinforcing effect, the joint investment into a new heating system and windows or thermal insulation mediates the total impact. The reason for this is also intuitive. The lower the heat loss due to an improved insulation of the dwelling, the lower the absolute benefit that can be realised by a more efficient heating system.

Finally, it is also important to allow for decreasing marginal impacts of investments in our model. Ceteris paribus, the realisation of (large) efficiency gains should be harder for very efficient dwellings than for inefficient ones. Column (2) confirms that this is indeed the case. The general impact of investing in any type of modernisation measure is the stronger the

Table 2: Estimates of evolution process [a]

Dep. Var.: $s_{i,t+1}$	(1)	(2)	(3)	(4)
$s_{i,t}$	1.071***	1.100***	1.054***	1.056***
	(0.025)	(0.039)	(0.020)	(0.013)
$s^2_{i,t}$	-0.003***	-0.003**	-0.002***	-0.002***
	(0.001)	(0.001)	(0.001)	(0.000)
$s^3_{i,t}$	1.62 e-5*	2.58 e-5*	8.71 e-6	1.32 e-5***
	(9.1 e-6)	(1.36 e-5)	(7.26 e-6)	(3.93 e-6)
$r^{iso}_{i,t}$			-16.419***	2.927***
			(0.300)	(0.351)
$r^{win}_{i,t}$			-3.056***	-1.520***
			(0.134)	(0.375)
$r^{iso}_{i,t} * r^{win}_{i,t}$			-1.587*	0.823
			(0.830)	(0.890)
$r^{heat}_{i,t}$			-5.859***	1.864***
			(0.187)	(0.478)
$r^{iso}_{i,t} * r^{heat}_{i,t}$			3.579***	-0.861
			(1.147)	(1.542)
$r^{win}_{i,t} * r^{heat}_{i,t}$			0.747	3.983
			(0.941)	(2.761)
$r^{iso}_{i,t} * r^{win}_{i,t} * r^{heat}_{i,t}$			0.395	-1.663
			(2.067)	(3.409)
$r^{iso}_{i,t} * s_{i,t}$				-0.638***
				(0.012)
$r^{win}_{i,t} * s_{i,t}$				-0.059***
				(0.015)
$r^{iso}_{i,t} * r^{win}_{i,t} * s_{i,t}$				0.026
				(0.029)
$r^{heat}_{i,t} * s_{i,t}$				-0.317***
				(0.023)
$r^{iso}_{i,t} * r^{heat}_{i,t} * s_{i,t}$				0.174***
				(0.053)
$r^{win}_{i,t} * r^{heat}_{i,t} * s_{i,t}$				-0.077
				(0.113)
$r^{iso}_{i,t} * r^{win}_{i,t} * r^{heat}_{i,t} * s_{i,t}$				0.013
				(0.129)
$r_{i,t}$	-10.366***	4.494***		
	(0.195)	(0.589)		
$r_{i,t} * s_{i,t}$		-0.532***		
		(0.024)		
Constant	0.244	-0.394	0.239	-0.024
	(0.203)	(0.301)	(0.164)	(0.102)
Observations	27,756	27,756	27,756	27,756
R-squared	0.927	0.945	0.953	0.968

[a] The table reports results from estimations of several specifications of the evolution process characterized in equation (5) by ordinary least squares. The binary variables $r^{iso}_{i,t}$, $r^{win}_{i,t}$ and $r^{heat}_{i,t}$ equal one if an investment into the thermal insulation of the dwelling, new windows or a new heating system has occured and zero otherwise. The dummy variable $r_{i,t}$ equals one if any of these investments have occured. Standard errors are reported in parantheses and clustered on the household level. Statistical significance at a 1 %, 5 % and 10 % level of confidence is indicated by one (*), two (**) and three (***) asterisks, respectively.

higher the fuel requirement of a dwelling is before the investment. In column (4) all investment opportunities analysed in column (3) are interacted with the efficiency state, $s_{i,t}$, providing the estimates used in the estimation of the dynamic model.

4.3 Estimation of investment cost

Given that we have successfully estimated the parameters of the period utility function and the evolution process, we are now also able to estimate the fixed investment cost using our dynamic model of household investment. We first obtain the value function, $V(s_{i,t})$, of equation (6) by value function iteration, which we then use to calculate the expected gain from investment, $\Delta EV(s_{i,t}|\boldsymbol{x^{\tau}_{i,t}})$, for every household in the sample. Given the decision rule in equation (7) and our distributional assumption on the investment cost, $C_{i,t}$, we can then determine the investment probability for every household as

$$Pr(r_{i,t}=1|s_{i,t},\boldsymbol{x^{\tau}_{i,t}}) = Pr\left(C_{i,t} \leq \delta \Delta EV(s_{i,t}|\boldsymbol{x^{\tau}_{i,t}})\right). \tag{12}$$

We assume that households' state variables are independent of the cost draws and furthermore that all cost draws, across households and time periods, are i.i.d. from the same distribution Φ^{γ}_{C}, conditional on the observable characteristics. In the main estimation, we allow the distribution of modernisation costs to vary with the size of the dwelling. The goal of the dynamic estimation is to estimate the mean values of the different distributions stored in the vector $\boldsymbol{\gamma}$. The likelihood function for households' investment data is

$$\begin{aligned} L(\boldsymbol{\gamma}|s_{i,t},r_{i,t},\boldsymbol{\beta^{\tau}},\boldsymbol{x^{\tau}_{i,t}}) = \prod_{i}^{N}\prod_{t}^{T_i} \quad & [Pr(r_{i,t}=1)\cdot(r^{d}_{i,t}=1) \\ & + (1-Pr(r_{i,t}=1))\cdot(r^{d}_{i,t}=0)], \end{aligned} \tag{13}$$

where $r^{d}_{i,t}$ is a binary indicator equal to 1 if household i has conducted a retrofitting investment in period t, N denotes the total number of households in the sample and T_i the number of periods household i is observed in the data. In the estimation we assume the discount factor $\delta = 0.95$ and the ideal temperature increase in the dwelling to be $\bar{\tau}_{i,t} = 21 - \tau^{out}_{i,t}$, where $\tau^{out}_{i,t}$ denotes the mean outdoor temperature.

The estimation procedure thus chooses the mean value of the investment cost distribution such that it rationalises the investments observed in the data, given the expected utility gain from investing, which is determined by our model based on the current efficiency state, $s_{i,t}$, and observable household characteristics, $\boldsymbol{x_{i,t}^{\tau}}$. Table (3) reports estimated mean values of the investment cost distribution based on two separate models. In the upper panel, a single mean value has been estimated that applies to all observations in the sample. The mean modernisation cost households encounter is found to equal $66,233$ euros. The columns in the right part of the table report percentiles of the associated exponential distribution. Since the exponential distribution is left-skewed a high probability mass is assigned to modernisation costs below the mean value. This is illustrated by the densities of exponential distributions plotted in figure (1). The large cost estimate mirrors households' reluctance to invest, despite substantial potential increases in the dwellings' energetic performance, that has been observed in the previous literature.[13] It captures all factors that prevent households from conducting retrofit investments.[14] These include the actual monetary costs of the material and installation service, but also for instance inconveniences related to the purchase, the risk of failure in achieving the desired efficiency improvement, problems to aquire the necessary capital or just households' unawareness of the efficiency gains that could be realized. The magnitude of the cost estimate indicates that the impediments to investments are large and likely hard to address even with well designed policies.

The lower panel of table (3) reports results of a separate estimation, that allowed modernisation costs to vary by the size of the dwelling. It indicates that the modernisation costs are larger in the group of households living in larger dwellings. An intuitive explanation for this pattern is that the size of the heating system, the number of windows or the area that has to be covered by better insulating materials get larger and therefore more expensive as the size of the dwelling increases.

Given the estimated investment cost distribution, the investment probability can be calcu-

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[13] The previous literature has often stated households' reluctance to invest in terms of high estimated discount rates. Our estimate of high investment costs is an equivalent way to express the same pattern in the data. To see this more clearly, note that the discount rate and the investment cost draw are two sides of the same coin in equation (7). An alternative estimation could follow our approach, but fix the mean of the investment cost distribution and estimate the discount factor using maximum likelihood.

[14] Because the investment cost are estimated in direct relation to the infinite stream of expected future period utilities, they also have to be interpreted in monetary terms. That is, with respect to the marginal utility of income which has been normalised to unity.

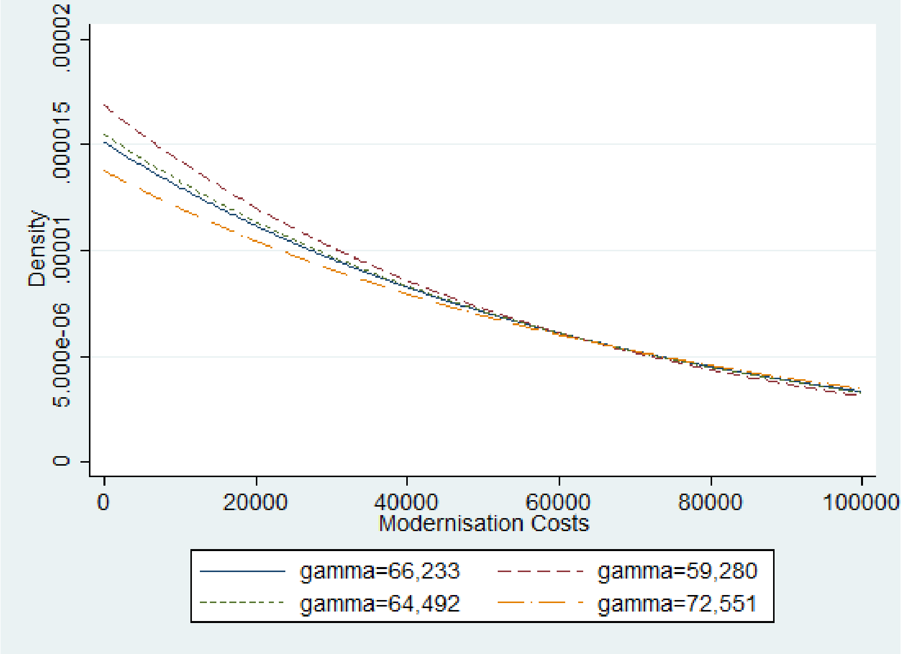
Table 3: Estimates of modernisation costs [a]

	$\hat{\gamma}$	SE	Percentiles				
			5th	25th	50th	75th	95th
Single Cost Estimate							
	66,233	(6,624)	3,397	19,054	45,909	91,818	198,416
Estimated costs by dwelling size [b]							
Small	59,280	(15,708)	3,040	17,053	41,089	82,180	177,587
Medium	64,492	(17,233)	3,308	18,553	44,702	64,492	193,201
Large	72,551	(0,579)	3,721	20,872	50,289	100,577	214,343

[a] The table reports estimates of mean values of the exponential distribution of modernisation costs, $\hat{\gamma}$, based on two separate models. In the upper panel, a single mean value has been estimated that applies to all observations in the sample. In the lower panel three different values have been estimated based on the size of the dwelling. The estimates are obtained by maximizing the likelihood function in equation (13). Standard errors of the estimates are reported in parantheses. The right part of the table reports some percentiles of the exponential distributions associtated to the reported mean values.

[b] Dwellings have been assigned to the group of small, medium and large dwellings based on the terciles of the dwelling size distribution. Dwellings below the first tercile of the distribution are considered small, those between the first and second tercile are medium-sized and those above the second tercile are large.

Figure 1: Density of an exponential distribution with mean γ



lated for every household in the sample. The mean investment probability equals 6.305 % and 6.194 % for the estimates from panel A and B, respectively. Both estimates thus provide a good fit to the data in which the investment rate is 6.154 %.

A distinctive feature of our model is that it allows us to structurally separate the fixed cost that arise at the time of the investment from the (expected) long-run gains that are associated to it. The separation of the two effects requires a dynamic modelling of the investment decision. Static utility models of the investment decision can, in contrast, only estimate the net effect of the two different factors entering the decision process. This makes the use of such models for counterfactual policy scenarios problematic, since it is generally unclear, whether the hypothetical policy change can be incorporated correctly into the decision process of households. Changes in investment cost and expected utility gains are, however, very likely to trigger substantially different economic behavior and outcomes.

The role of the dwelling size nicely illustrates the value of the dynamic estimation framework. The static results reported in table (1) indicate that the benefits from investing increase as dwelling size increases, because households living in larger dwellings are found to value higher mean indoor temperatures more than those living in smaller dwellings. In addition, the absolute level of savings from lower values of $s_{i,t}$, is naturally larger for larger dwellings. The dynamic estimates reveal that these effects are counteracted by higher costs that are associated to investments in larger dwellings. A static regression of investment on dwelling size (e.g., by logit or probit) would only estimate the net effect of both influences on households' decision to retrofit.

The crucial advantage of the developed dynamic framework is that it allows to quantify the temperature consumption, the associated level of period utility and the lifetime benefit of investing for every household in the sample. It also allows to investigate the changes in households' incentives and behavior if certain variables are varied. This enables us to study the two principle forces that govern households' decision process and their interplay in a comprehensive model.

Table 4 reports model predictions of households' optimal temperature increase, $\tau^*_{i,t}$, and fuel consumption, $F_{i,t}$, as well as the associated period utility, $u(\tau^*_{i,t})$, at different values of important model variables. Panel A considers the first, second and third quartile of the efficiency state distribution. It clarifies that households' energy consumption rebounds after an increase in dwellings' efficiency level resulting from a modernisation. A household living in a more efficient dwelling (i.e., having a lower $s_{i,t}$), faces lower marginal cost of consuming thermal warmth and therefore consumes a higher level of $\tau_{i,t}$. As the energy required to increase the mean indoor temperature by one degree Celsius decreases from 27.275 to 19.514 kWh, households' chosen mean indoor temperature rises from 7.620 to 9.464 degree Celsius. The larger mean indoor temperature in the dwelling might be due to a general increase of the ambient temperature level or due to adjustments in the number of rooms being heated or the length of time periods the desired temperature level is reached. The higher temperature consumption implies an increase in period utility, $\tilde{u}(\tau^*_{i,t})$, from -2.712 to -2.128, resulting from reduced thermal discomfort. Despite the increase of temperature consumption, the amount of fuel households consume, $F_{i,t}$, declines, such that their overall expenses for the consumption of thermal warmth decline, which also contributes to the increase in period utility. At the first quartile of the efficiency state distribution, period utility is -1.657 and thus reduced further by the same mechanisms.

The remaining three columns allow to inspect households' incentives to invest at the considered efficiency states. They report the long-run benefit of investing, ΔEV, in thousand euros, as well as the resulting investment probability, $Pr(r_{i,t} = 1)$, and the mean costs households face if they invest, $E[C^{med}_{i,t}|r_{i,t} = 1]$, assuming all households to draw their investment costs from the distribution associated to medium-sized dwellings. The expected gain in lifetime utility associated to an investment gets the smaller, the more efficient the dwelling is. At the first and third quartile of the efficiency state distribution ΔEV equals $6,098$ and $2,792$ euros, respectively. Intuitively, as the level of discomfort from temperature levels below the ideal level declines, also the absolute gain that can be realized through modernisations gets smaller. In addition, the improvements in the energetic performance of the dwelling get the smaller the more efficient the dwelling was before the investment.[15] The smaller long-run benefit of investing, implies

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[15] See the discussion of the estimated evolution process in section 4.2.

Table 4: Model predictions [a]

PANEL A:

$s_{i,t}$	$\tau^*_{i,t}$	$F_{i,t}$	$\tilde{u}(\tau^*_{i,t})$	ΔEV	$Pr(r_{i,t}=1)$	$E[C^{med}_{i,t}\|r_{i,t}=1]$ [b]
14.343	10.718	1399.983	-1.657	2.792	0.042	1.386
	(0.046)	(10.139)	(0.014)	(0.017)	(0.000)	(0.009)
19.514	9.464	1653.395	-2.128	4.946	0.074	2.440
	(0.063)	(12.090)	(0.017)	(0.031)	(0.000)	(0.015)
27.275	7.620	1798.381	-2.712	6.098	0.090	2.999
	(0.083)	(17.520)	(0.020)	(0.041)	(0.001)	(0.020)

PANEL B:

# adults	$\tau^*_{i,t}$	$F_{i,t}$	$\tilde{u}(\tau^*_{i,t})$	ΔEV	$Pr(r_{i,t}=1)$	$E[C^{med}_{i,t}\|r_{i,t}=1]$ [b]
1	7.776	1218.316	-1.996	3.346	0.050	1.654
	(0.121)	(17.135)	(0.025)	(0.065)	(0.001)	(0.032)
2	8.792	1454.114	-2.133	3.829	0.057	1.890
	(0.064)	(10.382)	(0.018)	(0.044)	(0.001)	(0.021)
3	10.414	1859.583	-2.344	4.161	0.062	2.052
	(0.059)	(16.555)	(0.028)	(0.062)	(0.001)	(0.030)
4	9.206	1553.459	-2.188	4.055	0.060	2.000
	(0.104)	(17.682)	(0.032)	(0.080)	(0.001)	(0.039)

PANEL C:

Age	$\tau^*_{i,t}$	$F_{i,t}$	$\tilde{u}(\tau^*_{i,t})$	ΔEV	$Pr(r_{i,t}=1)$	$E[C^{med}_{i,t}\|r_{i,t}=1]$ [b]
< 50	8.436	1372.983	-2.085	3.602	0.054	1.779
	(0.066)	(10.658)	(0.016)	(0.040)	(0.001)	(0.019)
≥ 50	9.735	1686.961	-2.257	4.121	0.061	2.032
	(0.050)	(10.701)	(0.018)	(0.043)	(0.001)	(0.021)

[a] The table reports the mean predictions of several model quantities setting the different model variables for all households to predefined values. Panel A considers different values of the efficiency state, $s_{i,t}$, evaluating households' choices at the first, second and third quartile of the efficiency state distribution. In panel B and panel C mean values are reported for varying size and age of the household. The chosen temperature increase is denoted by $\tau^*_{i,t}$, $\tilde{u}(\tau^*_{i,t})$ provides the period utility from thermal warmth consumption. The fuel consumption is denoted $F_{i,t}$, ΔEV is the long-run benefit from investing, $Pr(r_{i,t}=1)$ the investment probability and $E[C^{med}_{i,t}|r_{i,t}=1]$ the mean cost of those households that the model predicts to invest. The quantities $\tilde{u}(\tau^*_{i,t})$, ΔEV and $E[C^{med}_{i,t}|r_{i,t}=1]$ are stated in thousand euros, $F_{i,t}$ in thousand kilowatt hours. Standard errors are reported in parantheses.

[b] The term $C^{med}_{i,t}$ indicates draws from the cost distribution that applies to medium-sized dwellings.

that households living in more efficient dwellings are less likely to invest. While the investment rate is 9 % at the third quartile of the efficiency distribution, it only equals 4.2 % at the first quartile. At the median efficiency state the investment probability is 7.4 %. The decision rule of equation (7) implies that households only invest if their one-time investment costs are below the lifetime gain in utility. The left-skewed form of the exponential distribution ensures that mean investment costs conditional on investment, reported in the last column of table 4, are substantially smaller than ΔEV. They equal $3,999$ and $1,386$ euros at the third and first quartile of the efficiency distribution respectively.

It is interesting to compare these values to actual monetary costs households encounter when modernising their dwellings. For this purpose appendix A provides summary statistics of the monetary cost of actual modernisation investments conducted by German home owners between 2010 and 2015. The data is obtained from the 34th version of "The German Socioeconomic Panel Study" (SOEP v34), which is a large representative household panel of the German population. The reported investment cost have been deflated to 2007 euros. An advantage of the modernisation cost reported in the SOEP is that they relate to a very similar – relatively broad – measure of investment activity as the information in our main dataset. Households are asked whether they have invested into a new heating system, new thermal insulation or new windows in the last year and what the associated cost have been. The mean cost of households conducting any of the three modernisation investments are 6731.87 euros.[16] This is substantially below the mean unconditional costs reported in table 3. The results of table 4 indicate, that at such monetary cost investments would be profitable for many households at the third quartile of the efficiency state distribution. In contrast, for households living in more efficient dwellings the monetary costs alone might often make investments unattractive.

Panel B and C of table 4 consider the effects of households' preferences for thermal comfort

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[16] Actual monetary cost of retrofitting are hard to measure and vary depending on the extend and type of the modernisation conducted. The conformity of the questions in the "Residential Energy Consumption Survey" and the SOEP is therefore a valuable opportunity to obtain an impression of the monetary cost of the type of retrofit investment considered in this study. Studies providing estimates of investment cost include Palmer et al. (2017), who consider the housing market in the United Kingdom. Their results indicate an average monetary installation cost around 8,000 euros as a plausible benchmark. For the German market Thema et al. (2018) calculate the complete modernisation of an apartment building (including the retrofit of all walls, windows and the heating system) to cost roughly 61,500 euros. However, note that while this helps to rationalise the occasional occurance of extremely high investment cost, households hardly ever conduct investments of that scale at once.

on their temperature and investment choices. As discussed in section 4.1 larger households as well as those older than 50 value higher indoor temperatures more. Panel B and C clarify that this is actually associated to increases in temperature levels and fuel consumption that are statistically and economically significant. Compared to a one person household, a household with two adult members consumes a more than one degree higher mean indoor temperature, resulting in an average increase of yearly fuel consumption by 235.718 kWh. The stronger preferences for thermal comfort results in a lower overall period utility level for the larger household. This implies larger potential benefits that can be realized through investments and accordingly a higher investment rate. The mechanisms and qualitative effects are the same when comparing households form above 50 to younger counterparts.

4.4 Simulation and policy analysis

Using the estimates of our model, we simulate the effects of changes in households' economic environment on temperature consumption and the probability to invest. Table 5 summarises the percentage changes of the investment probability, $Pr(r_{i,t} = 1)$, the long-run utility gain from investing, ΔEV, the period utility, $\tilde{u}(\tau^*_{i,t})$, the optimal temperature choice, $\tau^*_{i,t}$, and fuel expenditure, $p^F_{i,t} \cdot F_{i,t}$, five years after three different policy scenarios compared to the status quo scenario without exogenous changes in the economic environment.

In the first experiment, we consider the impact of a fuel price increase by 10 % (e.g., through the introduction of a new tax). The price increase raises the marginal cost of consuming thermal warmth, leading to a lower period utility of the household due to lower consumption of thermal comfort and higher cost associated with its remaining consumption. The decrease in period utility implies larger potential utility gains to be realised by investing into energy efficient technology. The simulation results in the first row of table 5 indicate, that the incentive to invest, ΔEV, increases by 5.1 % on average going along with an increase of the investment probability by 22.1 %. The efficiency increases due to the additional investments, counteract the fuel tax's impact on average consumption of thermal warmth and period utility. However, simulation results indicate that still the average consumed level of indoor temperature decreases by 4.8 %. Yet, the temperature reduction does not offset the negative monetary affect of the

Table 5: Simulation of counterfactual policy scenarios [a]

Scenario	$Pr(r_{i,t}=1)$	ΔEV	$\tilde{u}(\tau^*_{i,t})$	$\tau^*_{i,t}$	$p^F_{i,t}\cdot F_{i,t}$
Fuel price increase [b]	0.221	0.051	-0.079	-0.048	0.042
	(0.054)	(0.003)	(0.001)	(0.001)	(0.002)
More effective modernisation [c]	0.201	0.009	0.006	0.004	-0.005
	(0.054)	(0.003)	(0.001)	(0.001)	(0.001)
Subsidy on investment costs [d]	0.463	-0.002	0.003	0.004	-0.001
	(0.064)	(0.003)	(0.001)	(0.001)	(0.001)

[a] The table reports the percentage changes of the investment probability, $Pr(r_{i,t}=1)$, the long-run utility gain from investing, ΔEV, the period utility, $\tilde{u}(\tau^*_{i,t})$, the optimal temperature choice, $\tau^*_{i,t}$, and expenditure for for fuel, $p^F_{i,t}\cdot F_{i,t}$, five years after three different policy scenarios compared to the status quo scenario without exogenous changes in the economic environment. The relative changes are calculated as $^{\Lambda^{ps}-\Lambda^{sq}}/_{|\Lambda^{sq}|}$, where Λ and ps denote the considered quantity and policy scenario respectively and sq indicates the status quo. Standard errors are reported in parantheses.

[b] The scenario considers a general fuel price increase by 10 %.

[c] The scenario considers an increase of the impact of the modernisation by 10 %.

[d] The scenario considers a reduction of modernisation costs the household as to pay by 20 % of the average cost.

fuel price increase on total spending. On average households have to spend 4.2 % more on the consumption of fuel. Together with the lower level of thermal comfort, this determines the period utility to decline by 7.9 % on average.

While the impact of a fuel price increase by 10 % thus allows a significant reduction in temperature and thus fuel consumption, the impact of the other two policies we have simulated are less effective. Improving the effectiveness of the retrofitting by 10 % and subsidising investments by 20 % of average construction cost increases investment by 20.1 % and 46.3 %, respectively. However, the policies have no economically significant impact on households' choice of indoor temperature and energy consumption. The effective changes in the efficiency states of the dwellings triggered by the policies are too small to generate significant changes in the average temperature choice and fuel consumption across households. This indicates that policies designed to exclusively increase domestic retrofitting without setting incentives to reduce fuel consumption in households' static decision environment, will therefore have problems to reduce the amount of fuel consumed in the economy by an amount that helps to meet climate targets.

5 Conclusion

In this article we develop and estimate a dynamic structural model of households' investment decision in energy efficient technology. In our model, households are forward looking. When making the decision to invest, they trade-off one-time fixed cost in the current period against long-run gains in utility. By explicitly modelling and estimating the utility households receive in every period from the consumption of thermal warmth and other goods in a first step, we can predict the change in fuel consumption as well as the lifetime utility gains that result from an investment. The investment costs are then estimated in relation to the potential gains in a second step. They are chose such that observed investments can be rationalized by the developed dynamic decision model. All estimated parameters thus have a structural interpretation in terms of the developed economic decision model. This allows us to analyse households' retrofit decision in greater detail than related approaches that rely on static utility models to estimate the relationship between household and dwelling characteristics and the propensity to invest. Using the structural parameter estimates of the model, we can conduct counterfactual experiments on how households would respond in terms of their energy consumption and investment behavior given changes in the economic environment.

We estimate the model using a subsample from "The German Residential Energy Consumption Survey". We find that households' valuation for thermal comfort as well as the marginal costs associated to its consumption matter for their temperature and investment choice. A household living in a less efficient dwelling consumes lower temperature levels and has, ceteris paribus, higher incentives to invest. A household with stronger preferences for high temperature levels, e.g. an older household, chooses a higher mean indoor temperature and has stronger incentives to retrofit the dwelling to further decrease the costs of temperature consumption. The results thus clarify the importance of understanding the sources of heterogeneity in households static temperature choice to achieve a detailed understanding of the mechanisms that determine their investment choices.

In our simulations of counterfactual policies, we find that government subsidy programs that reduce investment costs have a positive impact on the investment decision. In our case, they increase the investment rate by 46.3 %. Yet, the resulting increase in the economy wide level of efficiency is not large enough to reduce households' average energy consumption on a significant scale. Similarly, increasing the effectiveness of modernisation measures, for instance by supporting research and development, increases the rate of investment, but has only a small impact on the fuel consumption in the economy. In contrast, a tax on energy prices induces a higher investment rate, which increases by 22.1 percent, and at the same time is effective in the reduction of temperature and thus fuel consumption. According to our simulation, ten percent higher fuel prices reduce the mean indoor temperature in dwellings by 4.8 %. The results thus emphasize the strength of direct taxes on fuel consumption in incentivising households to reduce their consumption, both, by reducing temperature choices as well as increasing their engagement to retrofit.

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Appendices

A Descriptives of actual monetary cost of retrofitting in Germany

We use data from the 34th version of “The German Socioeconomic Panel Study” (SOEP v34) to gain insights on the monetary cost associated to actual modernisations conducted by German home owners.

The SOEP is the largest and oldest multi-disciplinary household panel in Germany (Goebel et al., 2019). It contains questions regarding households’ modernisation investment since its start in 1984. In the time period from 2010 to 2015 the surveyed households have explicitly been asked for the monetary cost they encountered when modernising their dwellings.[17] This provides an opportunity to study the monetary cost related to modernisation investments directly and separated from additional non-monetary cost that households might encounter.

The modernisations relevant in the context of our research include investments into the thermal shell, windows or heating systems of a dwelling, which are able to increase the overall energy efficiency of the dwelling. The survey questions asking for the respective investments are very similar in the SOEP and the “Residential Energy Consumption Survey”. This makes us confident, that the monetary cost associated to similar types of household decisions as studied in our dynamic model can be captured form the SOEP data.

We deflate the available cost data to 2007 levels, to make them comparable to the time period considered in our empirical analysis.[18] Table 6 provides summary statistics of the monetary cost encountered by households that modernised their dwelling. Panel A of the table focusses on the cost that were reported by households that invested into energy efficiency improvements only. It indicates that the mean cost of investing into heating systems and thermal insulation are at a similar order of magnitude, even though the distribution of cost associated to the latter

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[17] Home owners were asked for general maintenance cost during most years since the start of the survey. Only in the time period between 2010 and 2015 an additional question explicitly asking for the cost of conducted modernisations has been added.

[18] We used inflation rates on consumer prices for the maintanance and repair of dwellings (classification code CC13-043) obtained from the German statistical agency (Statistisches Bundesamt, 2019) to deflate the modernisation cost reported by home owners to 2007 levels.

Table 6: Descriptives of monetary modernisation costs of home owners based on SOEP data between 2010 and 2015 [a]

	Obs.	Mean	Stand. Dev.	Percentiles				
				5th	25th	50th	75th	95th
PANEL A								
Single investment into								
heating system	408	8,306.42	6,737.88	1,638.00	4,101.85	5,984.76	10,098.19	22,207.16
windows	937	4,762.79	5,647.17	532.97	1,522.93	2,866.50	6,391.30	14,608.70
thermal insulation	536	7,970.56	11,852.68	327.60	1,369.57	3,652.17	9,130.43	30,173.68
Combined investment into								
heating system and windows	38	12,287.12	11,255.01	1,724.21	6,391.30	8,924.38	12,931.58	50,040.73
heating system and thermal insulation	28	18,430.77	18,869.38	1,826.09	5,880.30	10,399.95	23,923.23	62,550.92
Total	1,947	6,731.87	8,728.50	499.18	1,724.21	4,095.00	8,340.12	22,207.16
PANEL B								
Any investment into								
energy efficiency	1,947	6,731.87	8,728.50	499.18	1,724.21	4,095.00	8,340.12	22,207.16
other modernisations	3,664	8,589.41	12,118.53	560.37	2,283.50	5,076.45	10,345.26	25,863.16
energy efficiency and other modernisations	1,347	29,251.37	41,710.49	2,001.63	6,847.83	15,846.23	33,360.49	115,477.23
Total	6,958	12,069.58	22,511.01	655.20	2,502.04	5,733.00	12,691.12	41,700.61

[a] The table reports descriptive statistics of the monetary cost associated to actual modernisations conducted by German home owners between 2010 and 2015. The data is obtained from the 34th version of "The German Socioeconomic Panel Study" (SOEP v34). The reported cost have been deflated to 2007 levels using data from the German statistical agency (Statistisches Bundesamt, 2019). Panel A of the table reports statistics of the cost encountered by households that have invested into measures to increase the energetic efficiency of the dwelling only. These can be investments into the heating system, the windows or the thermal shell of the dwelling. Panel B of the table compares the cost of investing into any of the efficiency measures and of investing into some non-efficiency measures only, to the cost that arise if the two types of modernisations are conducted jointly within a year.

is wider. Investments into windows are cheaper than the other two types of energy efficiency modernisations. Combined investments are rare, but occur for investments into heating systems and windows as well as heating systems and thermal insulation.

The primary information of interest in the context of our empirical analysis is the mean investment cost over all types of efficiency modernisations that households can conduct. The last row of Panel A reports their mean to be 6731.87 euros. There is quite some variation in the cost households face, resulting from the variety of investments that can be conducted. Figure **??** plots the distribution of the modernisation cost of interest. It is left-skewed implying a lower probability mass at very large cost. Consistent with this the median of the distribution is $4,095$. The 75th and 95th percentiles are $8,340.122$ and $22,207,16$ euros, respectively.

A limitation of the cost data available from the SOEP is that it does not contain separate reports by modernisation type. In case that households invest in energy efficiency and other types of modernisation, such as a new kitchen or bath, within the same year, the associated cost cannot be distinguished. This is a problem for the assessment of the monetary cost related to energy efficiency retrofits, if particularly large, and therefore expensive, activities are more likely to be conducted jointly with other modernisation measures. The focus on cost reported from households that have only invested in energy efficiency of the dwelling (taken in Panel A of table 6) would then imply that particularly expensive modernisations are undersampled in the data used to calculate mean values and other statistics.

Panel B of table 6 considers this potential problem more closely. It provides summary statistics of modernisation cost separated by investments into energy efficiency measures, other modernisations or both. It is easy to see that the sum of the mean cost of individual investments into energy efficiency and other modernisations respectively, is substantially below the mean cost if both investment types are conducted jointly. The difference of the two values is $13,930.09$ euros, indicating that expensive retrofits are likely substantially undersampled in Panel A.

To gauge the size of the resulting bias, we assume that the relative magnitude of the cost associated to efficiency related investments and other investments is the same, whether the measures are conducted independently or jointly within a year. The cost for efficiency retrofits are a bit smaller, being responsible for 43.94 % of the combined cost of individual investments.

This relationship is very stable over the full range of the distributions, supporting the main assumption of the analysis. If this cost relationship is fixed, the counterfactual modernisation cost associated to efficiency retrofits if other modernisations are conducted in the same year can be approximated to be $12,852.48$ euros. The weighted average of cost of energy efficiency retrofits when other modernisations are conducted in the same year or not can then be calculated to be $9,234.74$ euros. Accordingly, the mean modernisation cost when focussing on households that have only invested into energy efficiency would underestimate the cost over all investments by $2,502.87$ euros or 37.18 %. Obviously, this indicates a substantial bias in the mean cost reported in Panel A implying that the stated mean values should be interpreted with some caution.