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Manuel Frondel, Colin Vance

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Manuel Frondel, Rheinisch-Westfälisches Institut für Wirtschaftsforschung and Ruhr University Bochum

Colin Vance, Rheinisch-Westfälisches Institut für Wirtschaftsforschung and Jacobs University Bremen

Abstract. A longstanding question in the study of energy demand concerns the role of information as a determinant of home-efficiency improvements. Although the provision of information via home energy audits is frequently asserted to be an effective means for governments to encourage the implementation of efficiency-enhancing renovations, empirical support for this assertion is tenuous at best. Two factors have complicated attempts to measure the effect of audits: first, the nature of the information provided by the audit is typically unobserved, and, second, the response to this information may vary over households. Using household-level data from Germany, we address both sources of heterogeneity by estimating a random-parameter model of four retrofitting alternatives. In addition to confirming the importance of costs and savings as determinants of renovation choices, our results suggest that the effects of consultancy vary substantially across households, with some households responding negatively to the provision of information.

JEL classification: C35, D81, Q41.

Key words: Energy audit, mixed logit, random-coefficient models.

Correspondence: Prof. Dr. Manuel Frondel, Rheinisch-Westfälisches Institut für Wirtschaftsforschung (RWI), Hohenzollernstr. 1-3, D-45128 Essen. E-mail: frondel@rwi-essen.de.

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1 Introduction

Increasing efficiency through home renovation is generally asserted to be a highly effective means for households to lower expenditures on energy. From a public policy perspective, increasing efficiency has the additional benefit of reducing reliance on fossil fuels, thereby contributing to both energy security and environmental stewardship. Despite potentially high energy savings, however, it is frequently observed that homeowners refrain from undertaking cost-intensive renovations, such as investing in new windows with a better insulation.

This observation has led to a controversial discussion about what causes the so-called energy efficiency gap (see e.g. STERN, 1986, JAFFE and STAVINS, 1994). Usually, such behavior is attributed to a poor understanding or lack of information about renovation options and the associated costs and benefits (GOLOVE and ETO, 1996, SCOTT, 1997). In response, many countries have introduced free or low-cost energy conservation audits with the aim of assisting consumers in making well-founded decisions regarding the retrofitting of their homes.

The theoretical literature is generally unambiguous about the effect of such audits: more information enables households to assess the renovation options adequately and thus leads to a higher likelihood of efficiency investments (SORRELL, 2006). Nevertheless, empirical support for this view is weak. For example, in an early study, MCDOUGALL et al. (1983) analyze the Canadian residential home audit program 'Ener$ave' and conclude that audits have nearly no effect on residential investment behavior. HIRST and GOELTZ (1985) consider a U. S. residential weatherization program and find likewise no effect of audits, and only a weak influence if the audits are offered together with loans. More recently, SCHLEICH (2004) examines whether energy audits can overcome certain investment barriers in the German commerce and service sector. His results imply that audits help to inform about the own energy consumption structure, but have little effect in reducing a perceived information deficit.

A possible explanation for the disparity between the theoretical and empirical findings is offered by JAFFE and STAVINS (1994), who, among other reasons, attribute it to inertia in consumer adoption behavior. With particular respect to energy audits, this means that an objectively conducted audit may in fact result in a decision against retrofitting. This possibility has also been suggested by METCALF and HASSETT (1999), who speculate that consumers receive coaching from auditors on how to save energy through behavioral changes, which may lead them to conclude that investments are not necessary. If an audit affects an investment decision in both directions, an empirical consequence could be non-significant average effects.

The principal aim of the present paper is to contribute to this line of inquiry by developing a theoretical model focusing on the role of information in influencing decisions about retrofitting. Our model illustrates why this role is ambiguous: When the returns from the retrofitting investment are uncertain, the provision of information may offset the negative expectations of skeptics and thereby increase the likelihood of the investment, but it may also disabuse optimists of their positive expectation and decrease the likelihood. To illustrate this issue, we draw on a unique data set from Germany that combines household, engineering, and GIS-based regional information for analyzing how consumers respond to home energy audits. We apply a mixed logit model, which is highly flexible and can approximate any random-utility model (MC FADDEN and TRAIN, 2000), to allow for the possibility that the effects of an audit on the choice among a variety of renovation options may vary across households and be either positive or negative.

In addition to confirming the importance of costs and savings as determinants of renovation choices, our results suggest that the effects of an audit vary substantially across consumers. Specifically, while the mean effect of an audit is positive, the distribution of its respective coefficient exhibits substantial variability, with the provision of information having a negative effect for some households. We conclude that the mixed logit model reveals important information about behavioral heterogeneity that would otherwise be neglected, particularly with the application of a standard logit model.

The subsequent section presents a theoretical model of the impact of information. Section 3 describes the empirical modeling approach, followed by an explication of the data assembly in Section 4. Section 5 presents an empirical illustration, while the last section summarizes and concludes.

2 Modeling the Impact of Information

Using the example of renovation decisions of homeowners, we present here a stylized two-step model that aims at clarifying the general question as to whether information provision, for instance by audits, may enhance participation in energy conservation programs or may trigger renovation activities. To simplify matters, we focus on a single renovation option such as façade insulation. On the basis of imperfect information about both investment costs as well as energy and cost savings resulting from renovation, homeowner i builds expectations $E(V_i)$ on its individual present value V_i, which is assumed to be random and to depend on i's time preference rate ρ_i, the vector of individual and home characteristics $\mathbf{x_i}$ and uncertain net revenues $R_t(\mathbf{x_i})$ resulting from unknown energy savings in period t and annualized investment cost:

$$V_i = \sum_{t=0}^{T} U_{it}(R_t(\mathbf{x_i})) \cdot (1+\rho_i)^{-t} = E(V_i) + \varepsilon_i, \tag{1}$$

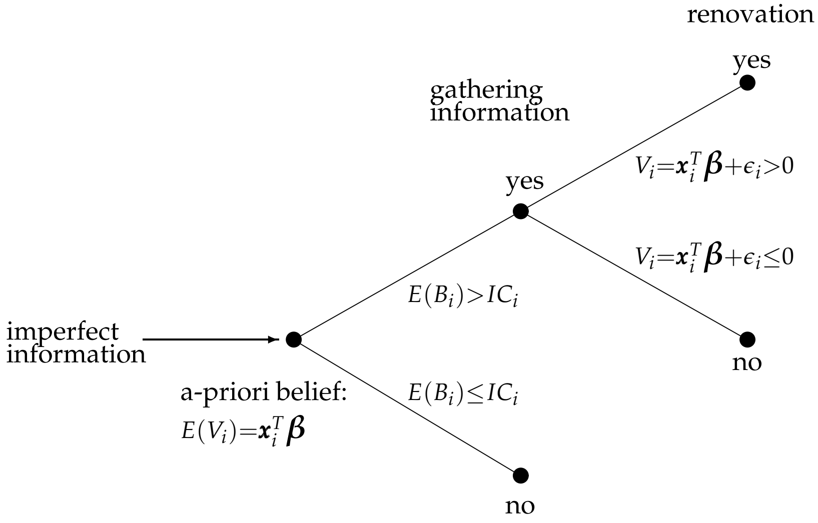
where U_{it} reflects i's ideosyncratic utility. i's uncertainty about net revenues $R_t(\mathbf{x_i})$ and, hence, the net present value V_i of renovating is captured here by a random disturbance ε_i. Most notably, this term reflects unknown future energy prices, being crucial parameters for the profitability of any renovation measure.

Assuming risk neutrality, homeowner i might be inclined to renovate if the expected benefit $E(V_i)$ of renovation appears to be positive:

$$E(V_i) = \int_{-\infty}^{\infty} V_i f(V_i) dV_i > 0, \tag{2}$$

where $f(V_i)$ designates a density function. Given i's imperfect a-priori information, however, there is scope for mistakes. Therefore, any homeowner i may wish to ideally receive perfect information on the energy conservation measure and the incurred cost so that, formally speaking, i is able to observe ε_i and anticipate whether the net present value V_i will be positive indeed.

Figure 1: A Two-Step Information Acquisition and Renovation Decision Model



Homeowners may gather the desired information either on their own or by engaging in energy conservation audits, where the information cost are frequently reduced through subsidization. Either way, we assume that gathering information is costly and, just for didactic purposes, that uncertainty may at least be reduced insofar as i is then informed whether V_i is positive: $V_i > 0$. Only in this case will homeowner i actually renovate.

In the first step of our model, homeowner i decides upon information acquisition, e. g. through an audit. At the second stage, i decides on whether to renovate. Without any loss of generality, it is assumed that acquiring information on the renovation option, and hence incurring information cost, is an indispensable prerequisite for any renovation activity. This simplification of the model implies that the decision tree is asymmetric (Figure 1).

A rational homeowner i will incur the generally well-determined information cost IC_i only if the expected benefit $E(B_i)$ of acquiring information exceeds the cost:

$$E(B_i) > IC_i > 0. \tag{3}$$

The expected benefit $E(B_i)$ of information results from either the positive renovation outcome that *a priori* has been expected ($E(V_i) > 0$) or from avoiding mistakes. A first type of mistake – from an ex-post perspective – results from the fact that although i expected a non-positive renovation outcome, $E(V_i) \leq 0$, i should have renovated if $V_i > 0$. If i is able to avoid this kind of mistake through information acquisition, the conditional expected benefit is positive: $E(B_i|V_i > 0) = \int\limits_0^\infty V_i f(V_i) dV_i > 0$. In this case, in which i had negative expectations $E(V_i) < 0$, the unconditional expected benefit $E(B_i)$ from information acquisition is given by

$$\begin{aligned} E(B_i) &= P(V_i > 0) \cdot E(B_i|V_i > 0) \ + P(V_i \leq 0) \cdot E(B_i|V_i \leq 0) \\ &= P(V_i > 0) \cdot E(B_i|V_i > 0) \ + P(V_i \leq 0) \cdot 0 = P(V_i > 0) \cdot \int\limits_0^\infty V_i f(V_i) dV_i, \end{aligned} \tag{4}$$

with a vanishing conditional expected benefit $E(B_i|V_i \leq 0) = 0$ in case that the non-positive expectation $E(V_i) \leq 0$ is confirmed.

A second type of mistake is that, although i expected a positive outcome $E(V_i) > 0$, i should have not renovated if, ultimately, it turned out that $V_i < 0$. If i is able to avoid this kind of mistake, the conditional expected benefit of information is positive: $E(B_i|V_i \leq 0) = -\int\limits_{-\infty}^0 V_i f(V_i) dV_i > 0$. Overall, the unconditional expected benefit $E(B_i)$ from information acquisition in the case of positive expectations $E(V_i) > 0$ reads as follows:

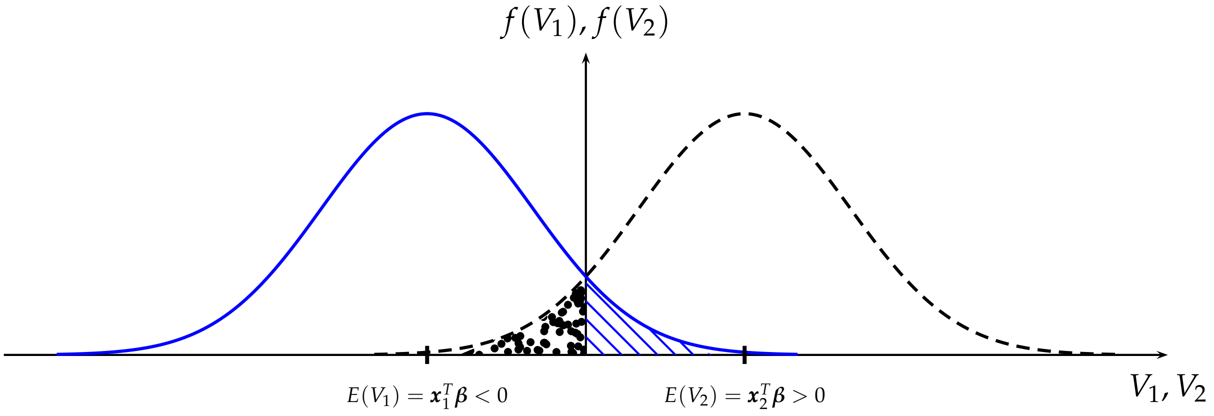
$$E(B_i) = P(V_i \leq 0) \cdot [-\int\limits_{-\infty}^0 V_i f(V_i) dV_i] + P(V_i > 0) \cdot \int\limits_0^\infty V_i f(V_i)\, dV_i. \tag{5}$$

Note that the second part of this expression is non-vanishing because of our assumption that acquiring information is indispensable for renovation activities.

While formulae (4) and (5), and condition $E(B_i) > IC_i$ rationalize the decision on acquiring information, Figure 2 illustrates that information measures do not necessarily foster conservation activities. This holds true for those who expect a positive net present value, $E(V_2) > 0$, but then must realize that an investment is actually not advantageous, i. e. $V_2 \leq 0$, and thus refrain from any renovation activities. This situation is illustrated in Figure 2 by the dotted part of the right-hand distribution centered around the positive expectation $E(V_2)$.

Such negative impacts of information measures on renovation activities might be

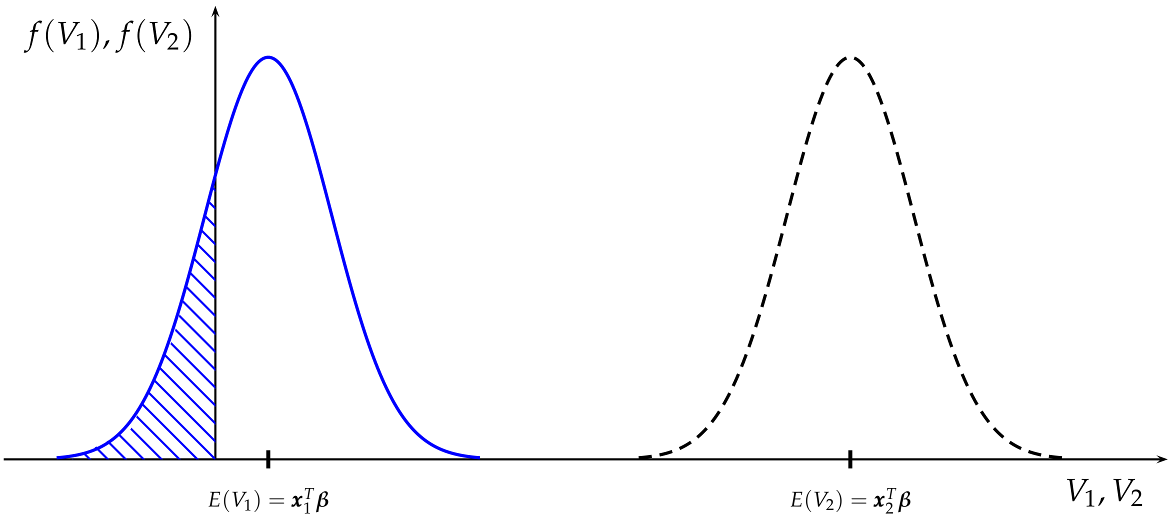
Figure 2: Expectations $E(V_i)$ and Actual Renovation Outcomes V_i



outweighed through the unexpected activities of skeptics, who *a priori* expect a negative net present value, yet have mild hopes that conservation measures might turn out to be positive and thus are open-minded to information measures such as audits. This case is illustrated in Figure 2 by the highlighted part of the left-hand distribution centered around the negative expected value $E(V_1) < 0$. In this case, information measures would positively affect renovation investments, yet not by providing additional incentives, but by convincing skeptics that conservation would be a success. Overall, though, it clearly remains a matter of the particular conservation measure and the concrete conditions and incentives, in other words an empirical issue, in which direction information measures, such as audits, affect an investment decision.

The basic role of information provision by audits is that it may lower individual information cost IC_i and, in the end, may favor conservation by increasing the number of potential investors. Much more important than information measures, however, should be incentives that substantially increase the attractiveness of conservation investments, as is illustrated in Figure 3 by the right-hand side distribution with a large positive expected net present value $E(V_2)$. In the extreme case that the uncertainty reflected by ε_2 is negligible compared to $E(V_2)$, information measures should not have any impact on renovation decisions at all. In sum, while information measures, such as audits, do not necessarily spur renovation activities or participation in conservation

Figure 3: Investments with Low and High Conservation Benefits



programs, they are to be embraced from an individual welfare perspective. After all, information measures may help to avoid mistakes, as the two-step decision model presented in this section has demonstrated. From this perspective, the question arises as to whether information measures, such as audits, should be publicly subsidized, rather than being afforded privately (see Frondel, Grösche, Schmidt, 2008).

3 Data Description

Our data is drawn from a sample of 2,530 single-family home owners, surveyed in 2005 as part of the German Residential Energy Consumption Survey (GRECS). From this survey, it is known whether household i participated in an audit – captured by a binary variable *audit* – and what retrofit measure was implemented within the last 10 years, if any. Four different retrofit measures have been surveyed: roof insulation ($j = 1$), façade insulation ($j = 2$), windows replacement ($j = 3$), and replacement of heating equipment ($j = 4$). The information on the retrofit measures is captured each with a separate binary response variable r_{ij}, yielding four entries for each household i on its retrofit choices j. In total, 64% of the households undertook at least one of these four retrofit measures between 1995 and 2005.

Table 1: Descriptive Statistics

Variable Name	Variable Definition	Mean	Std. Dev.
audit	Dummy: 1 if household received an audit	0.12	–
cost	Cost of renovation option in 1,000 €	7.72	4.86
savings	Annual energy savings in 1,000 kWh	5.01	4.59
consumption	Annual energy consumption in 1,000 kWh	31.48	14.65
age	Age of the single-family house in years	43.01	42.49
income	Net monthly household income in 1,000 €	2.23	1.04
east	Dummy: 1 if house is located in Eastern Germany	0.16	–
degree	Dummy: 1 if household head has a university degree	0.24	–

Most of the remaining variables were elicited directly via the questionnaire, the descriptive statistics for which are presented in Table 1. These variables include the age of the house, household income and energy consumption for the year 2003, a dummy indicating whether the household head has a university degree, and a dummy indicating location in Eastern Germany. 402 of the 2,530 sample households, that is around 16%, originate from Eastern Germany and 293 households received an audit, representing a share of 11,6%. In addition to socio-economic and dwelling characteristics, the data includes a location identifier measured at the municipal level for each household.

The data is completed by information on the investment cost for each retrofit option, the resulting household-specific energy savings, and a suite of variables describing the home itself and the socioeconomic characteristics of its occupants. Estimates of energy savings following a retrofit are based on engineering calculations. Investment cost estimates draw on cost values of actual retrofit projects published by the German Architectural Association. We have refined these figures by controlling for regional wage differences for craftsmen. Details on the data assembly for energy savings and investment cost are given by GRÖSCHE and VANCE (2009).

4 Methodology

While investment cost of retrofitting options and the resulting energy savings are certainly two key determinants of renovation decisions, the net benefit of any renovation option is difficult to anticipate for households because of numerous uncertainties, including unknown future energy prices that may undermine the profitability of a renovation. Furthermore, households may face information deficits about the variety of retrofitting alternatives. Not least, even if all alternatives are known, the calculation of energy savings is likely to go beyond the capabilities of the majority of households.

By informing about the variety of retrofitting options, the associated costs, and the energy savings to be expected, energy audits may provide for valuable information that is highly relevant for the decision of households. As demonstrated by the theoretical model presented in the previous section, it is an open question, however, as to whether the information provided by audits increases the likelihood of undertaking a renovation. Moreover, there might exist unobservable factors that affect the households' decision, such as aspects often referred to as "hidden costs". For example, a household may eschew the noise and dirt that accompany some retrofit measures. Such factors, which are typically unobservable may vary the effect of observable factors such as *audit*.

To account for both the potentially varying effect of an audit on household i's retrofit decisions and the inherent dependency among the $J = 4$ renovation decisions of household i, we employ a logit model with mixed effects, frequently called mixed logit, random-parameters, or random-coefficients logit (REVELT and TRAIN, 1998:647). For brevity, we use here the term mixed logit, even though our model specification is motivated through a random-coefficients concept. This model generalization overcomes the three limitations of standard logit models by allowing for (1) unrestricted substitution patterns, (2) correlation in unobserved factors over repeated choices, and (3) correlation of unobserved and observed factors commonly described by the notion of random-taste variation (TRAIN, 2003:46). Of course, decision-makers' tastes or preferences also vary for reasons that are not linked to observed individual characteristics and attributes of the alternatives. That is, two household heads with the same income, education, etc. will make different choices, reflecting their individual preferences (TRAIN, 2003:47).

Closely following the illuminating introduction given by TRAIN (2003), mixed logit models can be defined on the basis of the functional form for the probabilities P_{ij} of household i's choices among the alternatives $j = 1, ..., J$:

$$P_{ij} = \int (\frac{\exp(\boldsymbol{\beta}^T \mathbf{x}_{ij})}{\sum_k \exp(\boldsymbol{\beta}^T \mathbf{x}_{ik})}) f(\boldsymbol{\beta}) d\boldsymbol{\beta}, \tag{6}$$

where

$$L_{ij}(\boldsymbol{\beta}) := \frac{\exp(\boldsymbol{\beta}^T \mathbf{x}_{ij})}{\sum_k \exp(\boldsymbol{\beta}^T \mathbf{x}_{ik})} \tag{7}$$

is the well-known formula for the conditional logit probability evaluated at $\boldsymbol{\beta}$, with $\mathbf{x}_{ij}$ designating the observable factors and $f(\boldsymbol{\beta})$ being a density function. In other words, the mixed logit probability given by (6) is a weighted average of the conditional logit formula evaluated at different values of $\boldsymbol{\beta}$, with the weights being given by density $f(\boldsymbol{\beta})$.[1] The mixed logit model degenerates to the conditional logit model for the special case in which $f(\boldsymbol{\beta}) = 1$ for $\boldsymbol{\beta} = \mathbf{b}$ and zero otherwise. In this special case, choice probability (6) coincides with the logit formula given by (7), when $\boldsymbol{\beta}$ is replaced by $\mathbf{b}$.

In line with random-utility theory, the mixed logit probability (6) can be derived from utility-maximizing behavior, with the utility U_{ij} of household i from alternative j being specified as follows:

$$U_{ij} = \boldsymbol{\beta}_i^T \mathbf{x}_{ij} + \epsilon_{ij}. \tag{8}$$

Vector $\mathbf{x}_{ij}$ captures both alternative-specific attributes, such as investment cost, and household-specific characteristics, such as income, while ϵ_{ij} represents the portion of utility that is unobservable to the researcher and often referred to as "unobserved heterogeneity".[2] $\boldsymbol{\beta}_i$ is an unobservable vector of coefficients that represents household i's preferences and, hence, generally varies over households.

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[1] In the statistics literature, the weighted average of distinct functions is called a mixed function, which explains the name of the mixed logit model, while the density that provides for the weights is called the mixing distribution.

[2] For both the standard and the mixed logit, the error terms are assumed to be independently and identically distributed, obeying a Gumbel or Type I extreme value distribution with $F(\epsilon) = e^{-e^{-\epsilon}}$ being

Therefore, the researcher cannot condition on $\boldsymbol{\beta}_i$ and cannot calculate the probability *conditional* on $\boldsymbol{\beta}_i$ that would be given by the conditional logit formula (7). Rather, the researcher is forced to assume that $\boldsymbol{\beta}_i$ is a random variable with density $f(\boldsymbol{\beta})$, so that solely the unconditional choice probability resulting from the integral given by (6) can be computed, generally through simulation. Note that the researcher has to specify the distribution of $\boldsymbol{\beta}_i$ and, hence, density $f(\boldsymbol{\beta})$, with the normal or the lognormal distribution being selected in most applications, such as REVELT and TRAIN (1998:647): $\boldsymbol{\beta} \sim N(\mathbf{b}, \mathbf{W})$ or $\log \boldsymbol{\beta} \sim N(\mathbf{b}, \mathbf{W})$, where the moments $\mathbf{b}$ and $\mathbf{W}$ of the distribution of the household-specific coefficients $\boldsymbol{\beta}_i$ are to be estimated.

As a formally equivalent alternative to the random-coefficients interpretation, a mixed logit model can be derived from a utility representation that allows for an error component interpretation:

$$U_{ij} = \boldsymbol{\beta}^T \mathbf{x}_{ij} + \boldsymbol{\Delta}_i^T \mathbf{z}_{ij} + \epsilon_{ij}, \tag{9}$$

where the unobserved utility portion $\eta_{ij} := \boldsymbol{\Delta}_i^T \mathbf{z}_{ij} + \epsilon_{ij}$ consists of two error components, with the first component creating correlations among alternatives:

$$Cov(\eta_{ij}, \eta_{ik}) = E(\boldsymbol{\Delta}_i^T \mathbf{z}_{ij} + \epsilon_{ij})(\boldsymbol{\Delta}_i^T \mathbf{z}_{ik} + \epsilon_{ik}) = \mathbf{z}_{ij}^T \mathbf{W} \mathbf{z}_{ik},$$

where $\mathbf{W} = E(\boldsymbol{\Delta}_i \boldsymbol{\Delta}_i^T)$ is the covariance matrix of $\boldsymbol{\Delta}_i$ that generally differs from $\mathbf{0}$. It bears noting that utility is correlated over alternatives even when error components are assumed to be independent, such that $\mathbf{W}$ is diagonal.

It is instructive to demonstrate that the random-coefficients and the error components specification (8) and (9) of utility are formally equivalent. First, when decomposing the coefficients $\boldsymbol{\beta}_i$ into their mean $\boldsymbol{\beta}$ and respective deviations $\boldsymbol{\Delta}_i := \boldsymbol{\beta}_i - \boldsymbol{\beta}$, the error components specification (9) follows from the random-coefficients specification (8) by replacing $\boldsymbol{\beta}_i$ through $\boldsymbol{\beta} + \boldsymbol{\Delta}_i$: $U_{ij} = \boldsymbol{\beta}^T \mathbf{x}_{ij} + \boldsymbol{\Delta}_i^T \mathbf{x}_{ij} + \epsilon_{ij}$, with the $\mathbf{z}_{ij}$ from the random-coefficients representation (9) being equal to $\mathbf{x}_{ij}$. Conversely, under an error components motivation, utility is given by $U_{ij} = \boldsymbol{\beta}^T \mathbf{x}_{ij} + \boldsymbol{\Delta}_i^T \mathbf{z}_{ij} + \epsilon_{ij}$ (see expression (9)),

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the cumulative distribution function. Differences $\epsilon^*_{ijk} := \epsilon_{ij} - \epsilon_{ik}$ of two error terms then follow the logistic distribution: $F(\epsilon^*_{ijk}) = \frac{\exp(\epsilon^*_{ijk})}{1+\exp(\epsilon^*_{ijk})}$.

which is equivalent to a random-coefficients model with fixed coefficients for variables $\mathbf{x}_{ij}$ and random coefficients with zero means for variables $\mathbf{z}_{ij}$.[3]

Along the lines of this methodological discussion, we specify the probability for the binary choice that household i chooses retrofit response r_{ij} as follows:

$$\begin{aligned} P(r_{ij} = 1) &= \alpha + \zeta_i + \mathbf{x}_{ij}^T\boldsymbol{\beta} + (\delta + \psi_i) \cdot audit_i + \varepsilon_{ij} \\ &= \alpha + \mathbf{x}_{ij}^T\boldsymbol{\beta} + \delta \cdot audit_i + \underbrace{\zeta_i + \psi_i \cdot audit_i + \varepsilon_{ij}}_{\eta_{ij}}, \end{aligned} \tag{10}$$

where household- and option-specific characteristics are captured by vector $\mathbf{x}_{ij}$. ζ_i and ψ_i denote random deviations from the intercept and the mean effect of home audits on retrofit decisions, respectively, and are assumed to be normally distributed with zero mean and covariance matrix

$$\boldsymbol{\Sigma} = \begin{bmatrix} Var(\zeta_i) & Cov(\zeta_i, \psi_i) \\ Cov(\zeta_i, \psi_i) & Var(\psi_i) \end{bmatrix}. \tag{11}$$

Various covariance structures can be specified, the most flexible of which allows unique variances and covariances. Restrictions can also be introduced, such as by imposing a single variance and constraining the covariances to zero.

The residuals ε_i are assumed to be uncorrelated with ζ_i and ψ_i and, as with the standard logit model, are independently and identically distributed type I extreme value with variance $\pi^2/6$. The composed error term $\eta_{ij} = \zeta_i + \psi_i \cdot audit_i + \varepsilon_{ij}$ allows for correlation among any two response probabilities $P(r_{ij} = 1)$ and $P(r_{ik} = 1)$ for the same individual i, thereby controlling for the inherent dependency among the individuals' four response options.

5 Empirical Illustration

The primary goal of our empirical illustration is to explore the extent of heterogeneity in household responsiveness to home audits. To this end, we conceive of the decision

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[3] If $\mathbf{x}_{ij}$ and $\mathbf{z}_{ij}$ overlap, that is, some of the variables enter both vectors, $\mathbf{x}$ and $\mathbf{z}$, the coefficients of these variables can be considered to vary randomly with mean $\boldsymbol{\beta}$ and the same distribution as around their mean.

tree depicted in Figure 1 as involving two sequential and independent steps, whereby the household first decides to gather information, e. g. via an audit, and subsequently chooses which, if any, renovation options to undertake. We thereby assume that the *audit* dummy is exogenous. It is, of course, likely that the decision to undertake an audit is endogenous, an issue to which we return in the discussion of the results.

Table 2 compares estimates from both a standard logit model in which the coefficients are fixed without exception, and a mixed logit model in which the coefficient on *audit* is treated as a random parameter obeying a normal distribution. Turning first to the dummy variable *audit*, the coefficient estimate is seen to be positive and statistically significant at the 1% level in the standard logit model. Interpretation is facilitated by exponentiating the coefficient to yield the odds ratio. As seen in column two, the odds of undertaking a renovation are 1.67 times higher for households that have received an audit relative to those without any such information measure.

Table 2: Estimation Results for the Decision on Renovation.

	Standard Logit				Mixed Logit	
	Coeff.s	Std. Errors	Odds Ratios	Std. Errors	Coeff.s	Std. Errors
audit	** 0.513	(0.092)	** 1.669	(0.154)	** 0.730	(0.130)
cost	**-0.108	(0.017)	** 0.898	(0.016)	**-0.084	(0.015)
savings	** 0.185	(0.013)	** 1.204	(0.016)	** 0.152	(0.012)
consumption	0.002	(0.002)	0.998	(0.002)	0.0001	(0.003)
age	**0.010	(0.001)	** 1.010	(0.001)	** 0.016	(0.001)
east	**0.326	(0.089)	** 1.386	(0.123)	** 0.464	(0.115)
income	0.042	(0.030)	0.960	(0.029)	-0.060	(0.040)
window	**0.841	(0.084)	** 2.319	(0.196)	** 0.979	(0.103)
facade	**-1.066	(0.071)	** 0.344	(0.025)	**-1.296	(0.088)
heating	** 0.580	(0.129)	** 1.785	(0.230)	** 0.924	(0.141)
constant	**-1.414	(0.166)	–	–	**-2.120	(0.194)

Note: * denotes significance at the 5 %-level and ** at the 1 %-level, respectively.
Observations used for estimation: 10,120. Number of households: 2,530.

All of the remaining coefficients have signs consistent with intuition and, with the exception of *income* and *energy consumption*, are statistically significant at the 1% level.

The cost of the renovation decreases the likelihood that it is undertaken, while the expected energy savings and the age of the home both increase it. Likewise, residence in East Germany, where the housing stock is generally more dilapidated, increases the likelihood of a renovation. As reflected by the coefficients on the option-specific constants, retrofitting of the roof and facade tend to be more onerous undertakings in terms of the cost and grime incurred than window and heating retrofits, so that these renovation options both have higher likelihoods.

Column 3 presents the results from a mixed logit model in which the coefficient on *audit* is allowed to vary over households. Several variants of the mixed logit model were explored using different covariance structures. When estimated with the most flexible structure having unique variances and covariances, the model failed to converge. As an alternative, we specified a structure that imposes a common variance and allows for a non-zero correlation. Based on a likelihood ratio test, this structure proved a better fit than one that imposes a common variance and zero covariance. Moreover, the chi-square statistic obtained from a likelihood ratio test with which the mixed logit is compared to the standard logit is $\chi(2) = 521$, suggesting that the mixed logit provides a significantly better fit to the data. The estimated mean effect of the distribution of the coefficient on *audit*, at 0.73, is somewhat higher than in the standard logit model. Moreover, the highly precise estimate of 1.39 of $\sqrt{Var(\zeta_i)} = \sqrt{Var(\psi_i)}$ suggests the existence of significant heterogeneity in the responsiveness of households to information.

Further insight into this result can be gleaned from the distribution of the individual slope coefficients on *audit*. These estimates range from -0.65 to 2.23, suggesting that for a small share of the households – about 4% – the effect of the audit is negative. This finding is consistent with our theoretical conjecture presented in Section 2 that information provision can, in some cases, lead the household to decide against undertaking a renovation. As METCALF and HASSETT (1999:517) note, this outcome is conceivable if, for example, the household receives coaching from the auditor about cheaper alternatives than retrofitting for saving energy.

An important qualification in interpreting these findings is the possibility that the coefficient estimate on *audit* is biased because of endogeneity. It may be that those households who are seriously considering a renovation are also more likely to seek an audit, which would impart a positive bias via the positive correlation between the error term of the model and *audit*. In the absence of instruments to correct for this simultaneity, we cannot rule out the possibility that the expected value on the coefficient on *audit* is less than our estimate. This would in turn imply that the estimated 4% of households for whom the impact is negative can be regarded as a lower bound estimate.

6 Summary and Conclusion

This paper has addressed the question of how the provision of information bears upon renovation decisions in the German residential sector, which is seen seen as a cornerstone in the country's efforts to combat climate change via improvements in energy efficiency. Using an expected utility framework, we began with a theoretical model of the decision to renovate that assumes that homeowners are equipped with imperfect information about the associated benefits and costs. Under these circumstances, home audits can serve to avoid two types of mistakes: They may encourage skeptics who have negative expectations about the net benefits to renovate when the realized net benefit is positive. Conversely, they may discourage optimists who have positive expectations about the net benefits to refrain from renovating when the realized net benefit is negative. The overall effect of the audit on the likelihood of a renovation is thus ambiguous.

This ambiguity was reflected in the results from an empirical illustration that explored the impact of home audits on the probability of undertaking a renovation among a sample of 2,530 single-family homeowners in Germany. To capture response heterogeneity, we applied the mixed logit model, which generalizes standard logit models for analyzing multinomial choices by allowing the parameter associated with observed variables, e. g. its coefficient, to vary randomly across observation units such as households (REVELT and TRAIN, 1998:647). Our estimates suggested substantial heterogeneity in how homeowners respond to audits, with roughly 4% of households exhibiting a negative response.

While we have abstracted from the question of whether publicly financed audits are justified for capturing positive externalities from the provision of information, our results nevertheless suggest that the beneficial impacts for residential efficiency may be muted. In this regard, it bears noting that the social benefits of the program emerge only from those retrofits that would not have been undertaken in the absence of the home audit. This effectively excludes those homeowners who receive an audit from which they are correctly persuaded not to undertake a renovation (but who clearly enjoy a private benefit). It also excludes those homeowners who would have undertaken the renovation irrespective of the audit.

According to work by FRONDEL, GRÖSCHE, and SCHMIDT (2008), the share of such homeowners may be substantial: for a range of renovation types, these authors find that far less than half of those households who participated in an audit reported it to be a decisive factor in their decision to renovate, with shares varying from 11% for the insulation of the basement ceiling to 34% for the insulation of heating and water pipes. Looking ahead, we would therefore advocate that the state leave the acquisition of information to private households and energy-price signals, rather than tapping scarce public funds to correct an externality whose magnitude is highly questionable.

References

FRONDEL, M. , GRÖSCHE, P. , SCHMIDT, C. M. (2008) Energiesparen: Warum wird Beratung gefördert? *Zeitschrift für Energiewirtschaft* 32 (2): 97-101.

GOLOVE, W. H. , ETO, J. H. (1996), *Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency*, Research Report LBL-38059 UC-1322, Lawrence Berkeley National Laboratory, University of California.

HIRST, E. , GOELTZ, R. (1985), Estimating Energy Savings Due to Conservation Programmes: The BPA Residential Weatherization Pilot Programme. *Energy Economics* 7, 20-28.

JAFFE, A. B. , STAVINS, R. N. (1994), The Energy-Efficiency Gap: What Does It Mean? *Energy Policy* 22, 804-810.

GRÖSCHE, P. , VANCE, C. (2009), Willingness-to-Pay for Energy Conservation and Free-Ridership on Susidization - Evidence from Germany. *The Energy Journal* 30 (2): 135-154.

MCDOUGALL, G. H. , CLAXTON, J. D. , J. R. RITCHIE (1983), Residential Home Audits: An Empirical Analysis of the Ener$ave Program. *Journal of Environmental Systems* 12, 265-278.

MCFADDEN, D., TRAIN, K. (2000), Mixed MNL Models of Discrete Response. *Journal of Applied Econometrics* 15, 447-470.

METCALF, G. E. , HASSET, K. A. (1999), Measuring the Energy Savings from Home Improvement Investments: Evidence from Monthly Billing Data. *The Review of Economics and Statistics* 81, 516-528.

REVELT, D. , TRAIN, K. (1998), Mixed logit with repeated choices: Households' Choices of Appliance Efficiency Level, *The Review of Economics and Statistics* 80, 647-657.

SCHLEICH, J. (2004), Do energy Audits Help Reduce Barriers to Energy Efficiency? An Empirical Analysis for Germany. *International Journal of Energy Technology and Policy* 2, 226-239.

SCOTT, S. (1997), Household Energy Efficiency in Ireland: A Replication Study of Ownership of Energy Saving Items. *Energy Economics* 19, 187-208.

SORRELL, S. (1997), Understanding Barriers to Energy Efficiency, in S. Sorrell, E. O'Malley, J. Schleich, and S. Scott (eds.): *The Economics of Energy Efficiency: Barriers to Cost-Effective Investment*, Edward Elgar, Cheltenham, UK.

STERN, P.C. (1986), Blind Spots in Policy Analysis: What Economics Doesn't Say About Energy Use. *Journal of Policy Analysis and Management* 5, 200-227.

TRAIN, K. E. (2003), *Discrete Choice Methods with Simulation*. Cambridge University Press, Cambridge.