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Abstract

This paper separates technological from human capabilities with regard to the operating of advanced heating systems. Our study shows that attitudes towards using such systems are equally influenced by a system's ease of use and its related thermal comfort as perceived by the user. However, the user does not perceive either of these influences directly; they are both mediated through the latent construct “perceived usefulness”. Our results reveal that in order to maximize the technology acceptance of advanced heating systems, the focus of interventions needs to be a twofold one. It is not only perceived thermal comfort – in its technological capacity of a delivered energy service – which is relevant; an easy-to-use system is equally important. The underlying psychological theory of this paper is that of the Theory of Planned Behavior (TPB). Using an adapted version of the technology acceptance model (TAM) – the energy TAM (eTAM) – we draw on questionnaire data from a field experiment conducted in Germany. The statistical inference is based on a partial least squares patch modeling (PLS-PM) approach.

Keywords: heat energy consumption, technology acceptance, rebound effect, perceived utility
JEL Classification Nos.: D12, D81, Q47, O33, R22

1. Introduction

Technologies can influence user behavior and, likewise, user behavior can influence efficiency of technology usage. Comprehensive thermal retrofits of residential buildings often lead to a discrepancy between the actual heat energy consumption and the previous theoretically calculated consumption. One of the reasons for this phenomenon (which is kind of an “efficiency gap”) is that the user may have difficulties handling modern appliances (e.g. the heating system). This paper analyzes technology acceptance as an explanation for difficulties encountered by users of energy-efficient appliances in retrofitted dwellings. In order to render the specific influences visible, we distinguish between the influence of the

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human variable "perceived ease of use" and the technological variable "perceived thermal comfort" (as a delivered energy service).

Following comprehensive thermal retrofits, energy consumption often deviates from the *ex-ante* calculated values. Often, users are blamed for causing the rebound effect by influencing initial efficiency potentials through their choices. Our research on energy consumption behavior following energy efficiency retrofits identifies the influences that result in individual energy consumption. Our aim is to differentiate between the perceived technical and user barriers that influence technology acceptance. We identify a gap in the literature, because research that investigates the behavioral influences underlying the operation of modern heating systems is still scarce.

This article focuses specifically on advanced heating systems as end-user systems, a phenomenon emerging in multifamily homes in Germany in increasing diversity and complexity. The field experiment, which provides insights as well as data for our research, is located in the south-west of that country and comprises two multifamily buildings with 2 x 30 = 60 apartments overall. The evaluated data stem from a monitoring campaign, a questionnaire survey, and quantitative interviews.[1] As one can observe from Figure 1, the monitored deviations from calculated to measured heat energy consumption exhibit rebound effects, at least for the years 2012 and 2013. Since this article does not focus on heat energy consumption, but is more specifically targeted at the perceptions regarding heating systems and their operation, the observed dynamics in heat energy consumption will only briefly be touched upon in the conclusion. Perceptions of heating systems are analyzed using the energy technology acceptance model (eTAM). The technology acceptance model (TAM) proposed by Davis et al. (1989) has been adapted to address our research question. The modifications are based on a literature review as well as on the results obtained from our quantitative interviews. The model distinguishes attitudes towards using a heating system as (i) perceived ease of use and (ii) perceived quality of the delivered energy service (in our study) the thermal comfort. By doing so, the model enables us to differentiate between user capabilities and system capabilities. The proposed model is estimated using a partial least squares path modeling (PLS-PM) approach (Wold 1985). The estimation suggests that the proposed model describes a considerable proportion of the attitudes towards using the heating system. Furthermore, it shows that the influence of perceived ease of use is as strong as the influence of perceived thermal comfort. Last but not least, the estimation reveals that attitudes towards using the system are mostly determined by a mediator variable.

[1] The research presented here also builds on two other projects closely associated with our project. These projects have been conducted by the Institute for Energy Efficient Buildings and Indoor Climate (EBC) at RWTH Aachen University. A first project was concerned with the design and implementation of the new thermal concept (BMWi research contract no. 0327400H) enabling us to study these multifamily buildings and their occupants. A second project ensures the monitoring campaign and evaluates the energy consumption from an engineering standpoint (BMWi research contract no. 03ET1105A).

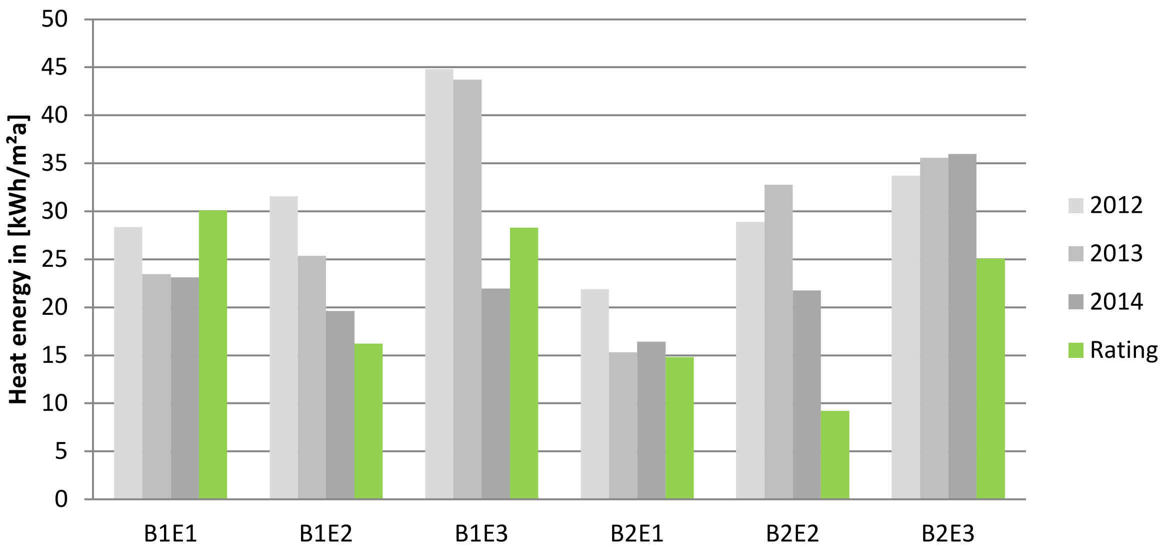

Figure 1: Comparison of previously rated and observed heat energy consumption from 2012-2014 for two multifamily houses (B1 and B2) with three Entrances each (E1-E3).

The remainder of this paper is structured as follows. Section 2 provides a literature review, which is followed by a description of the methodology in section 3. In section 4, the estimation results are presented. Section 5 concludes on the most important findings and the contribution of our study, and also delivers an outlook on future research.

2. Literature review

The scope of the literature review is twofold. On the one hand, the field experiment evaluated needs to be placed within a framework in order to connect the research subject to its research field. On the other hand, a review of the relevant literature on technology acceptance is necessary in order to better understand the methodology applied.

2.1 The rebound effect

In the field experiment, energy consumption behavior following energy-efficient retrofits is evaluated. A vast body of literature exists on this matter, primarily in five academic disciplines - engineering, economics, psychology, sociology, and anthropology - with each discipline bringing its own techniques and frameworks into the research. The engineering as well as the economic sciences focus on quantitative research, whereas psychology, sociology, and anthropology tend to focus on quantitative aspects. As this paper is focussing on behavior, one source of literature originates in the psychological/social sciences, which will be reviewed within the realm of technology acceptance. The energy economics literature contributes to the physical–technical–economic model that originates in the engineering and economic sciences. This body of literature provides a microeconomic framework for the upcoming behavioral analyses and conclusions.

In energy economics, Khazzoom (1980) was the first to acknowledge that energy efficiency potentials are not fully realized because of users' reactions to a price change following efficiency improvements. His main observation was that a change in the price elasticity of demand as the central reaction to an increase in the appliance efficiency does not relate to the congruent energy demand reduction. Khazzoom's idea has been further developed by numerous scholars, theoretically as well as empirically (Greening et al. 2000; Berkhout et al. 2000; Binswanger 2000; Madlener and Alcott 2008; Sorrell 2009; Madlener and Hauertmann 2011; Thomas and Azevedo 2013).

The empirical literature, which calculates magnitudes of price elasticity demand for heat energy, is vast; Sorell et al. (2009) collected and sorted empirical studies with regard to rebound effects and their mode of measurement/estimation. The field experiment presented in our paper is most closely associated with the category of quasi-experimental studies presented in Table A9 in Sorrell et al. (2009). The results presented in that table not only report a shortfall in energy savings as a result of a behavioral reaction stemming from changes in the price elasticities, but also relate to a temperature take back.[2] Twelve studies are compared reporting a range of between 10% and 68% for the energy shortfall of potential savings, a rebound effect, or a rise in temperature, at a temperature take back of between 0.2 °C and 2.8 °C. The temperature take back is important for an understanding of that article because,

> "In all cases it is resource use and consumer amenity satisfaction that is being optimized, not simply energy use per unit of output". (Schipper, 1979, p. 362.)

Keeping Schipper in mind, our own article takes a closer look at the drivers of consumer amenity satisfaction, in order to better understand the drivers of energy consumption. To measure the shortfall in energy savings does not deliver interventions designed to seize the problem. Our article contributes to the existing literature by identifying the individual drivers of the associated influences. With this knowledge, individual drivers can be addressed selectively through appropriate interventions, although this is beyond the scope of the present paper.

2.2 The technology acceptance model (TAM)

The behavioral model presented in this article is based on the technology acceptance model (TAM) proposed by Davis et al. (1989). Their model is based on the Theory of Reasoned Action, developed in the 1970s by Ajzen und Fishbein (1980). This theory is a predecessor of the anticipated progress of the Theory of Planned Behavior. Although there exists a large number of models that try to capture different aspects of residential energy consumption,

[2] Temperature take back is a percentage of an increase in the average indoor temperature following the adoption of an energy efficiency measure.

we choose Davis et al.'s model, which was designed to evaluate technology acceptance of new information technology, because it exhibits a transferable initial situation.[3]

Madlener and Harmsen-van Hout (2011) provide a good overview of consumer behavior capturing residential energy consumption. The model presented in the present paper can best be classed as a behavioral model such as that of van Raaij & Verhallen (1983), as described in Keirstead (2006). In our analysis, the focus is on the single agent, because we are examining the drivers of individual behavior. We are interested in technology acceptance, which distinguishes our analysis from more complex models, such as that proposed by van Raaij & Verhallen (1983).[4] To capture energy-consuming intentions and behavior in the field experiment, a thorough understanding of the installed equipment is required as well as its perception by the user. Davis et al. theorize that an individual's attitude towards using a system is determined by two beliefs: *perceived usefulness*, defined as the extent to which a user believes that using the system will enhance his or her user performance, and *perceived ease of use*, defined as the extent to which a user believes that using the system will be "free of effort". In the energy economics/psychological literature, the TAM, to our knowledge, has never been applied to investigate user behavior for built-in end-use appliances. Nevertheless, for example, Huijts et al. (2012) or Broman-Toft et al. (2014) apply the TAM in order to investigate social phenomena such as the acceptance of renewable energy or smart grids.

Apart from the numerous empirical applications of the TAM, mostly in the information systems literature, the model was further enhanced theoretically through a series of publications by Venkatesh and research associates (Venkatesh and Davis 2000; Venkatesh and Bala 2008; Venkatesh et al. 2003). These activities show that the TAM is a well-established model in information systems research. It serves as a platform for further advancements in other academic disciplines as well. Furthermore, our starting point from a technical perspective is comparable to Davis et al.'s research in the 1980s. Heating systems have developed considerably in the last two decades, also incorporating technological changes from the digital world. All considered, this is why, from a theoretical point of view, the original TAM developed by Davis et al. is the basis for our research and for the application of the eTAM.

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[3] Davis et al. (1989) use the case of electronic mail to study technology acceptance, in our case the introduction of new heating systems. Especially the interaction capabilities are comparable to those of these early studies in the field of information systems research.

[4] The complexity arises from the fact that van Raaij and Verhallen (1983) incorporate multiple agents into their analysis.

3. Methodology

This methodological derivation is twofold. First, the theoretical as well as empirical considerations underlying the eTAM will be presented. Second, the PLS-PM algorithm is introduced and explained.

3.1 The qualitative interviews

The qualitative interviews are a good starting point for the methodology, as they give first empirical insights into the field experiment. They direct the focus towards technology acceptance as a main influence on heat energy consumption. In June 2013, twelve households in Germany were interviewed. These interviews were semi-structured, and participants were pre-selected according to their energy consumption in the previous heating period. The pre-selection was based on a segmentation of all households into low-, average-, and high-energy consumers based on the slope of the ordered heat energy consumption curve (Figure 2).

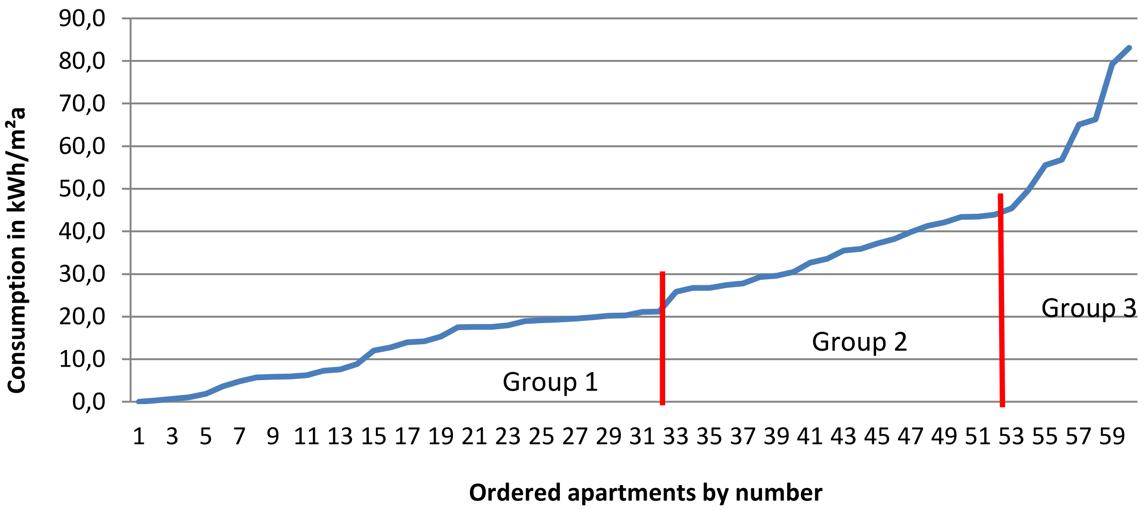

Figure 2: Segmentation of the researched apartments based on their heat energy consumption.

From each group, an equal number of interviews were performed. After transcribing the recorded interviews, they were coded and analyzed accordingly. Three main problems were identified with regard to the installed heating system. Malfunctioning equipment is one of the three main issues reported. Further, the missing synchronization of the system capabilities according to the desired human needs are of importance for most of the interviewees. Last but not least, the operation of the system is reported to be too complex.

One or more of these three problems are included in all responses. In a first step, the insights were used to eliminate the malfunctioning of equipment.[5] Second, problems nos. 2 and 3 were selected for further investigation in our research. To assess the household needs and perceptions of the installed system, a behavioral model is needed to describe the

[5] This task was outsourced to the owner of the multifamily buildings.

underlying processes shaping the behaviors and perceptions. This is because influencing factors that drive behavior and perception remain latent. Without a measurement model, one could only hypothesize about the influencing variables as well as the magnitude of their influence.

3.2 The energy technology acceptance model (eTAM)

We adapt the TAM because it best suits the observed problem theoretically. Furthermore, the findings from the qualitative interviews hint at the use of the eTAM empirically. This is because it offers a construct which aims at explaining very similar objectives to those identified through the qualitative interviews. Davis et al.'s model translates well to the observed problem in the field experiment, because the latent variables "*perceived ease of use"* (EOU) as well as "*perceived usefulness"* (US) directly relate to problems nos. 2 and 3 as identified in the qualitative interviews.

The latent variable EOU relates to the problem of the complex operation of the heating system, whereas US expresses the inter-correlation between users' needs and the system's capabilities.[6] EOU can be measured by manifest indicators directly, thus operationalizing the ability and perception of the user regarding the ease-of-use experience. However, US as a latent variable is more complex. That is because a heating system itself cannot be perceived as a service, so that a further order is necessary to distinguish between users' needs and the system's capabilities.

To account for the actual service that is delivered by the heating system, a new latent variable is added to the original TAM. We call this variable *perceived thermal comfort* (TC). Thermal comfort is the main service that a heating system provides to the user. This deviation from the existing model seems to be necessary in order to distinguish between the actual service delivered as a systemic influence and the EOU as the users' influence. This distinction enables us to distinguish between system and user capabilities, which influence the attitudes towards using the system.

The latent variables in this eTAM are measured by manifest variables. Manifest variables are directly observable variables, which, in our case, are the questions. The measurement mode of all latent variables is reflective. "Reflective" refers to how the latent variables are gained, which can be specified further as to whether the latent variable is formed or measured by the manifest variables. The difference between a formed and a measured variable is a conceptual one. "Forming" a variable implies that all information on manifest variables is grouped together, thus comprising the latent variable. "Measuring" a variable implies that the manifest variables must be selected according to a certain algorithm so that the true value of the latent variable can be estimated. The presented eTAM is a third-order model, as the variable ATT is caused by US, EOU, and TC. The second-

[6] Human needs are, for example, certain levels of thermal comfort (e.g. room temperature, air quality etc.).

order model is TC and EOU, resulting in US. The first-order model is TC and EOU, as indicated by their manifest variables. EOU and TC are thus exogenous variables, whereas US and ATT are endogenous. The rationale behind this ordered model is that EOU, TC, and US are constructs that explain the behavior affecting the heating system, whereas ATT is the consequence of the relations between the other latent variables.

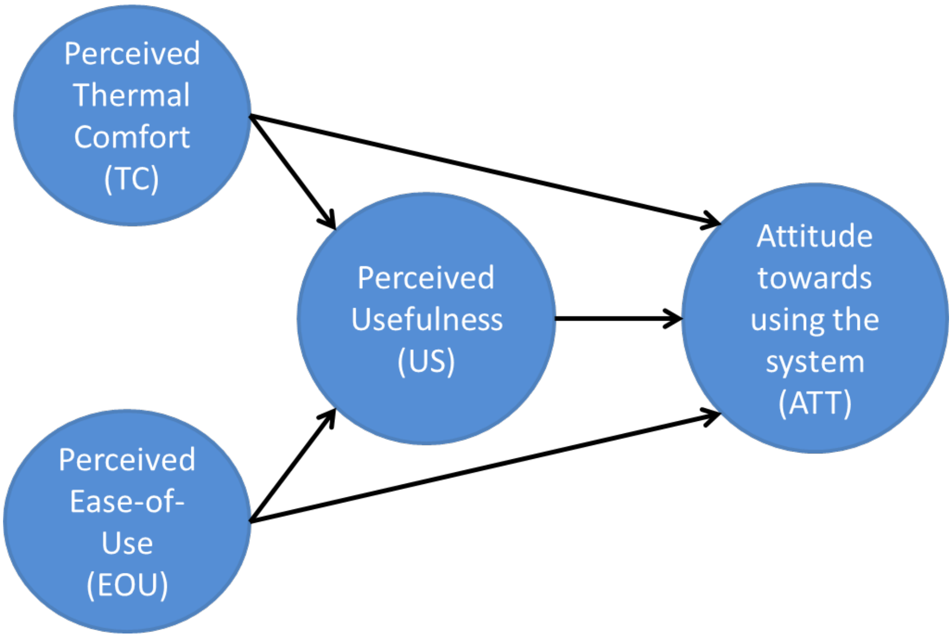

Figure 3: The energy technology acceptance model (eTAM).

As indicated by the Theory of Planned Behavior, consumer/user attitudes influence behavior (Ajzen 1991). Although this dimension is not added to the final model, it still can be anticipated that such a relation exists. The following hypotheses are implicitly tested:

H_1: TC has a positive influence on ATT

H_2: EOU has a positive influence on ATT

H_3: The influence of US on ATT is positive and greater than the individual influences of TC and EOU respectively.

H_3 tests that the relationship between TC/EOU and ATT is mediated by US. This implies that the user acts (in the sense of an ATT) upon a combination of the two influences rather than on the basis of an individual influence. Note that the relation of H_1 and H_2 with H_3 tests the conceptual framework.

3.3 The questionnaire

All manifest variables are extracted from a quantitative questionnaire implemented in November 2014. The design of the questionnaire is based on the methodology proposed in de Leeuw et al. (2008). The item wording is adapted from Davis et al. (1989). Before conducting the final questionnaire, a pretest among seven engineering management students evaluated the wording as well as the importance of each question according to its latent variable. Thus, the number of items was reduced from initially 14 to finally eight per latent variable. The further reduction in dimensions is due to the discriminative data screening, which will be presented later on in the results section. The complete questionnaire was also revised by five research experts prior to its final execution. In this final check, some minor wording as well as the position of individual items was changed. The questionnaire was implemented jointly with university colleagues from the mechanical engineering sciences, thus also comprising questions other than on technology acceptance. To minimize distraction, questions directed towards technology acceptance were positioned in the first part of the questionnaire. All items measuring technology acceptance use a seven-point Likert scale. The scale ranges from 1 = "very negative" to 7 = "very positive"; the wording corresponds to the questions accordingly. The item wording can be found in Table 1 in association to each latent variable.[7]

Table 1: Item wording according to the latent variables (translated from the German).

Perceived thermal comfort	**Variable**
Since we started using the new heating system, we achieve desired temperatures faster.	v_649
All in all, the new heating system produces a pleasant indoor climate.	v_667
Since we started using the new heating system, the indoor temperature on a winter's day is about … °C.	v_733
Perceived ease of use	
I often find the new heating system confusing to use.	v_652
I regularly make mistakes when operating the new heating system.	v_653
I often have to consult the user manual when operating the new heating system.	v_655
You really need to concentrate hard when you operate the new heating system.	v_656
Perceived usefulness	
I find that interacting with the new heating system is a very demotivating activity.	v_654
The new heating system often reacts differently from how I expected it to.	v_661
The new heating system is good for the environment.	v_646
Since using the new heating system, my relationship with it has become a more comfortable one.	v_647
Attitude towards using the system	
In my opinion, I find that the new heating system is inconvenient to use.	v_662
In general, I find that the new heating system is easy to use.	v_666
Overall, on a scale from -3 to 3 what is your general impression of your apartment?	v_730

Demographics, which are of further importance for all associated research, are assessed at the end of the questionnaire. Brounen et al. (2012) and Kronenberg (2009) show that demographic influences considerably impact the energy consumption of households.

[7] The study was conducted in Germany, which is why the questionnaire was formulated in German. The wording presented in Table 1 reflects the German wording of the questions as accurately as possible.

Overall, 130 questions were posed in the questionnaire, and 52 out of 90 apartments took part (i.e. a response rate of 57.7%). Out of these 52 participants, 47 questionnaires were completely answered, determining the sample size *n*. Of the participants, 67% were female and 54% were younger than 65 years of age.

3.4 The structural equation modeling approach

Apart from the model, a structural equation modeling (SEM) approach is required to determine the causal structures and their gradual influences. The partial least squares approach to SEM (PLS-PM), originally developed by Wold (1980, 1982, 1985) and Lohmöller (1989), offers an alternative to the covariance-based (CB-SEM) approach developed by Jöreskog (1970). There have been significant improvements to the usability of PLS-PM in recent years, giving rise to a series of theoretical as well as empirical contributions to the literature, as described, for example in Urbach and Ahlemann (2010) and Henseler et al. (2009).

PLS-PM is primarily chosen because this analysis aims to find critical success drivers of the acceptance/use of the new heating systems installed in the field experiment. Upfront, a vague knowledge about associated success drivers exists, but no other research to our knowledge has touched on this particular topic before. Thus our analysis can be categorized as "explorative". It directly links up to the second reason – the parameter estimation – acknowledging that the underlying causal relationships connecting the latent variables still do not explain their magnitude of influence. Even though PLS-PM is an estimation technique, and thus *per se* subject to errors, it does provide data-driven insights into the causal relations as well as magnitudes. Finally, a sample size of *n*=47 is low and if estimated by covariance-based SEM, would not be sufficient to deliver valid results. Nevertheless, since PLS-PM is chosen, the observations are sufficient, as indicated by their psychometric properties.[8]

After explaining the model as well as the rationale behind its selection and adaptation, the PLS-PM algorithm estimating the model is shortly presented in the following. The PLS-PM algorithm proposed by Lohmöller (1989) is a two-stage process. The algorithm is introduced as applied in the results.[9] First, an estimation of the latent variables scores proceeds via the iteration of four steps which are explained below. The final estimation of the outer weights/loadings follows in a second stage.

[8] Chin (1998) suggests that a researcher may use 10 cases per predictor as a rule of thumb, whereby the overall sample size is 10 times the largest of two possibilities: (1) the block with the largest number of indicators (i.e., the largest so-called measurement equation) or (2) the dependent variable with the largest number of independent variables impacting it (i.e. the largest so-called structural equation).

[9] At certain steps of the algorithm, certain methodologies can be chosen. For systematic mathematical insights into each step and the alternatives available, we refer to Tenenhaus et al. (2005).

The first step of stage one is to compute the outer proxies of the latent variable scores as the sums of the assigned indicators. In the initial iteration, we chose equal weights to initialize the latent variable scores. Later iterations use the weights from the previous iteration. In step 2, so-called inner weights are provided to quantify the strength of the latent variables' outer proxies. In this analysis, the "path weighting scheme" as it is considered to be favorable over the centroid and factor-weighting scheme, is adopted (Fornell and Cha 1994). In step three, the computation of the latent variables' inner proxies follows as a linear combination of their respective adjacent outer proxies, using the weights determined in step two. Finally, the outer weights are calculated according to their mode. This process is dependent on the causal direction between the indicators and the latent variables.

All four steps are repeated until the change between the sums of the outer weights in two consecutive iterations is sufficiently low. In stage 2, the final outer weights are used to calculate the final latent variable scores via an OLS regression. Thus, the causal relationships in the model are determined in the second stage. Because the eTAM is measured in a reflective mode, it imposes several testable conditions that follow the nature of its specification as a series of simple regressions. After estimating all the weights, a thorough assessment of the quality criteria becomes necessary.[10] A complete model evaluation of the final estimates is given in the following section.

4. Results

Having proposed the model, which is consistent with all currently available theoretical knowledge, and collecting the data to test the theory, we present the estimation results from applying the eTAM. Data screening comes first, thereafter the psychometric properties are examined and, last, the parameter estimates and their statistical properties are presented. In assessing the reflective model of heating system usage using PLS-PM, we follow the guidelines suggested by Marcoulides and Saunders (2006). The parameters in the model are estimated using SmartPLS 3 (Ringle et al. 2015). At a maximum number of 300 iterations and a stop criterion at 10^{-7}, the estimation delivers the results presented in Figure 5. Moreover, nonparametric bootstrapping, as implemented in SmartPLS 3 with 2000 replications, is used to obtain the standard errors and test the significance of the estimated path coefficients as well as mediation.

[10] For a theoretical derivation on the quality criteria, we refer to Tenenhaus et al. (2005) and Chin (1998), among others.

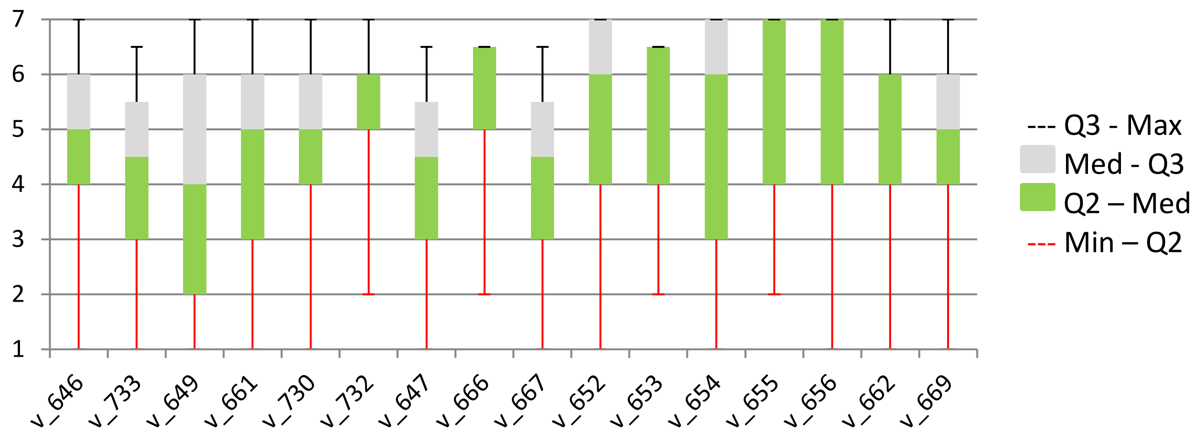

Figure 4: Box plots of the items.

4.1 Data screening

It is important to mention that in the preparation for the estimation, the variables posed in a negative direction are inverted so that their results point in the same direction as the positive ones. There are no outliers or missing data in the final dataset. As one can observe from Figure 4, the manifest variables are skewed towards more positive answers ranging from 4-7, thus a predominant second quartile can be identified in almost all box plots. The skewness is on average ≈-0.7, affirming these findings. The kurtosis of the single items varies from ≈+1 to ≈-1.4 and, on average, is slightly negative (≈-0.3). The Shapiro-Wilk test rejects the hypothesis of univariate normality for every item on a 1% level. Thus the data are not normally distributed, but as Reinartz et al. (2009) mention, PLS-PM does not build on any distributional assumptions which restrict further estimations. As for most of the items (12 out of 16), the participants took advantage of the full range of the offered scale, indicating that the slightly more negative range of 1-3 reasonably belongs to the choice possibilities.

4.2 Examination of the psychometric properties of all variables in the eTAM

To assess the reliability of the measures, the composite reliability (CR) and average variance extracted (AVE) are calculated.[11] As shown in Table 2, all CRs exceed 0.80, and the AVE of all measures exceeds the cut-off value of 0.50, as proposed by Fornell and Larcker (1981). Moreover, as shown in Table 3, the Fornell-Larcker criterion exceeds the inter-correlations of the construct with the other constructs in the model, which is in support of discriminant validity. Additional support for discriminant validity comes through inspection of the cross-loadings, which are small in magnitude compared to the loadings (Table 4). This shows that the manifest variables are best connected with their current latent variable and cannot be associated more adequately with any other latent variable. The latent variables are thus the most adequate conjunction of the grouped manifest variables.

[11] Cf. Chin (1998); Fornell and Larcker (1981); Werts et al. (1974).

Table 2: Composite reliability, average variance extracted and Cronbach's Alpha of the estimated model.

	CR	AVE	Cronbach's Alpha
Attitude towards using the system (ATT)	0.847	0.649	0.727
Perceived Ease of Use (E0U)	0.910	0.717	0.868
Perceived Thermal Comfort (TC)	0.846	0.649	0.732
Perceived Usefulness (US)	0.855	0.598	0.775

Table 3: Fornell-Larcker criterion for validity testing.

Fornell-Larcker Criterion	ATT	E0U	TC	US
ATT	0.806			
E0U	0.490	0.847		
TC	0.525	0.038	0.806	
US	0.716	0.429	0.510	0.773

Table 4: Cross loadings for validity testing.

Cross Loadings	ATT	E0U	TC	US		ATT	E0U	TC	US
v_662	0.870	0.326	0.594	0.639	**v_649**	0.335	-0.158	0.700	0.259
v_666	0.723	0.644	0.209	0.517	**v_667**	0.548	0.114	0.881	0.440
v_730	0.817	0.213	0.441	0.565	**v_733**	0.357	0.067	0.826	0.500
v_652	0.411	0.842	0.087	0.401	**v_646**	0.504	0.247	0.347	0.738
v_653	0.393	0.798	0.046	0.311	**v_647**	0.531	0.305	0.404	0.751
v_655	0.392	0.861	-0.039	0.348	**v_654**	0.689	0.549	0.419	0.879
v_656	0.460	0.884	0.029	0.386	**v_661**	0.452	0.132	0.417	0.714

4.3 Examination of the magnitude of the relationships and effects between the variables being considered in the eTAM

As displayed in Figure 5, the parameters of the outer model, e.g. of the manifest variables on the associated latent variable, all exceed 0.7. Based on the loadings, a discriminative data screening ensured that those MVs remaining are above that threshold, thus yielding the final number of MVs.[12] The inner model corroborates the hypotheses *H1-H3*. Based on the weights estimated, all three hypotheses are supported. As the bootstrapping results implicate, all effects are significant on a 5% level, as one can observe from the p-values in Table 5. *H3* is further examined through the mediation test.

Table 5: Results of the bootstrapping with 2000 replications.

Bootstrapping	Sample mean (μ)	Standard error (SE)	t-statistics (|ß/SE|)	p-values	Confidence interval
(E0U) → (ATT)	0.281	0.139	2.078	0.038	[-0.009, 0.545,]
(E0U) → (US)	0.424	0.118	3.469	0.001	[0.204, 0.659,]
(TC) → (ATT)	0.272	0.140	2.042	0.041	[-0.011, 0.520,]
(TC) → (US)	0.508	0.104	4.764	0.000	[0.284, 0.691,]
(US) → (ATT)	0.455	0.156	2.867	0.004	[0.142, 0.756,]

[12] This procedure follows Wold (1980) to ensure accuracy of the PLS estimation.

The variance explained as measured by the R^2 of the endogenous latent variables ATT (0.611) and US (0.428) indicates that large parts of the data fit to the model. The predictive relevance Q^2 deviates from 0 significantly. Furthermore, the calculated f^2s indicate that the effects can be classified at least as medium (in one case TC → US large).

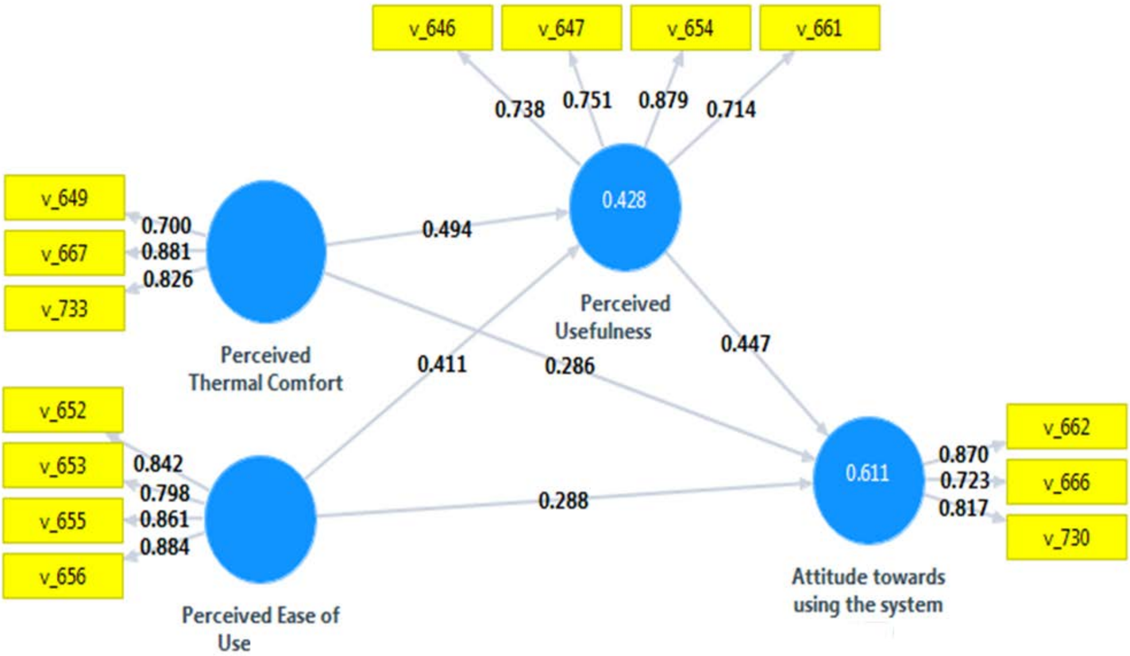

Figure 5: Results from the estimated eTAM.

In a next step, the mediating role of US needs to be verified. First, an estimation of the model without the mediator yields higher path coefficients (0.486 > 0.288 EOU → ATT; 0.512 > 0.286 TC →ATT) as compared to the model with mediator. This is a first indicator of the mediating role of US following Baron and Kenny (1986). As US is the only mediator in this model, mediation can further be tested using the indirect effects as reported for the bootstrapping results. Table 6 reports these results. One can see that the indirect effect is still significant at a 5% level but smaller in size when compared to the direct effects. These results provide support for a partially mediating role of US between TC/EOU and ATT. Following Shrout and Bolger (2002), the confidence intervals in Table 6 emphasize this role.

Table 6: Indirect effects as reported by the bootstrapping results, testing mediation.

Indirect effect bootstrapping	Original sample (O)	Sample mean (μ)	Standard error (SE)	t-statistics (|O/SE|)	p-values	Confidence interval
(E0U) → (ATT)	0.183	0.192	0.087	2.116	0.034	[0.049, 0.384]
(TC) → (ATT)	0.221	0.231	0.093	2.383	0.017	[0.063, 0.428]

In conclusion, we find that the PLS-PM algorithm delivers meaningful results for the eTAM. On the basis of the estimation results, Hypotheses H_1- H_3 cannot be rejected, which corroborates the results from the qualitative survey. Concerning the magnitude of the parameter estimates, it becomes obvious that the two exogenous latent variables, differentiating between human and technological influences, are of equal importance for ATT. This implies that a balanced mix between the delivered technological amenities and adaption to user capabilities must be in the focus of heating system designers. Furthermore, we find evidence that the user is only partially incentivized by these exogenous latent variables. The mediator variable US shows that users mingle their impressions and thus do not base their ATT on individual influences. Put differently, users base their actions on a perceived general impression, rather than on one specific influence. Addressing the overall perception and trying to incentivize behavior thus promises the greatest impact.

5. Conclusion

Our study shows that attitudes towards using a heating system are determined equally by perceived ease of use and perceived thermal comfort. Users do not perceive these influences directly; these are mediated through the latent construct “perceived usefulness”. With this estimation we are able to gain concrete knowledge of how users form their attitudes towards using a heating system.

Our results reveal that in order to maximize the technology acceptance of advanced heating systems, the focus of interventions needs to be a twofold one. It is not only perceived thermal comfort – in its technological capacity of a delivered energy service – which is relevant; an easy-to-use system is equally important. These insights can be used in a next step to assess the deviations from calculated to measured heat energy consumption.

First, ease-of-use problems were identified in the field experiment through qualitative interviews. In spring 2014, new manuals were handed out to the occupants of the case study buildings, which delivered more meaningful guidance for system usage. As a result, we have found that energy consumption dropped significantly over the investigated time period. The results from the PLS-PM estimation corroborate these initial, qualitative findings. High levels of perceived ease-of-use levels correlate positively with high levels of perceived thermal comfort.

These findings suggest that the rebound effect, or more precisely the energy performance gap, needs further research to account for dynamic behavioral reactions. We do not find any evidence that the income or substitution effect has the wrong predictive power, presumably because there are multiple other influences at play when heat energy consumption is investigated. From the evaluations it becomes obvious that ratings provide a very static view of a dynamic problem; unfortunately, these ratings are commonly used to benchmark energy efficiency. Disentangling price elasticity effects from the overall problem thus might lead to incorrect insights and might possibly overestimate the rebound effect.

Finally, some caution is needed when interpreting the results. There are multiple factors possibly influencing and biasing them. First of all, the limited number of observations might reduce statistical relevancy. This argument can only be devitalized through the quality criteria, which turn out to be satisfying. Furthermore, the nature the field experiment setup might not be comparable to other field experiments. We do not find self-selecting biases among the participants, as they are not volunteering for participation. But we do find raised awareness levels towards our research problems, as participants had been in contact with our research team for over two years prior to the questionnaire. They received information that a "regular" occupant would not receive as easily and as frequently. Nevertheless, our analysis delivers new insights into a field of research that is believed to deliver major energy consumption reductions to the energy transition. It explains technology acceptance and prerequisites to this technology acceptance, and thus the optimal usage of new heating systems. Future research needs to address the problem of dynamic utility maximizers, incorporating meaningful variables into utility maximization and the design of appropriate interventions in order to make use of the results of this study.

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