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Consumer behavior in energy-efficient homes: the limited merits of energy performance ratings as benchmarks

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Abstract

In Germany, policy-induced energy efficiency improvements typically aim at reducing primary energy consumption. Private households, on the contrary, pursue the maximization of wellbeing, or in microeconomics jargon, the maximization of utility of the occupants. There is a marked difference between upfront-calculated energy performance ratings (EPRs) and realized heating energy consumption (HEC). From an energy and environmental policy point of view, a deviation of energy consumption from ex ante calculated EPRs is problematic, as it offers poor guidance for (prospective) homeowners, policy-makers and researchers relying on the EPRs as benchmarks. The EPR-HEC gaps reported are, apart from heterogeneity, i.e. deviations from the mean aggregate values, often attributed to (unanticipated) behavioral effects. From an energy economist's point of view, energy rebound induced by a decreasing unit price per unit of energy service output is one explanation. The existing literature in this field almost entirely treats building-specific EPRs as universal standards, trying to explain the empirically observed discrepancies. In this paper, we investigate whether and to what extent the current EPR scheme in place in Germany today can address behavioral issues. To this end, we empirically investigate the deviations between EPRs used in regulation and observed HEC levels based on two different data sets for Germany. The results show that it is not necessarily the behavioral dimension, but rather the static and mostly technically guided calculations of the EPRs itself that account for the major part of this deviation. The results obtained and insights gained from our analysis highlight the need for further improvements in the field of EPR regulation and methodology.

Keywords: Energy performance rating, Energy performance gap, Heating energy, Consumer behavior

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1. INTRODUCTION

Although physical principles determine the closed energy system that a home represents, large proportions of the heterogeneous consumption patterns observed within one energy performance rating (EPR) are commonly attributed to behavioral differences. EPRs are building-specific calculations of energy consumption required for delivering certain energy services levels, based on regulations. Thus, an EPR reports on average household heating energy consumption (HEC) based on the building specifics.[1] Ideally, an EPR captures average household energy consumption. If this is the case, EPRs can be employed as energy efficiency proxies, and thus benchmarks, to HEC deviations. Using EPRs as benchmarks to evaluate HEC behavior is standard practice also in the scientific literature (Aydin et al., 2014; Galvin and Sunnika-Blank, 2012; Hens et al., 2010). Figure 1 shows, based on a representative population of 125,000 homes in Germany, that EPRs usually do neither capture *average* consumption well nor the heterogeneity of occupant-building (dwelling) combinations. This phenomenon is most problematic for energy-efficient buildings, as the EPR of buildings below 100 kWh/(m²a) tends to underestimate average HEC. From prospect theory (Tversky and Khanemann, 1991) it is well known that people are more sensitive towards losses than gains. So, relying on an ambitious EPR and not reaching it might be perceived as worse than having an unambitious one, and eventually outperforming expectations in terms of energy consumption.

Figure 1 also shows that, on average, energy consumption for heating purposes does not just deviate from the EPR, but interestingly also the skewness of the cumulative frequency distribution of empirical HEC changes from high to low EPRs. In contrast to the early, and thus

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[1] EPRs report on more than just the HEC, but as this paper focuses on HEC we neglect other types of heat energy consumption like e.g. energy consumption for hot water preparation.

comparatively low energy efficiency EPRs, where consumption distribution shows an almost normal distribution, the later and thus higher efficiency EPRs deviate significantly in the first quantile.

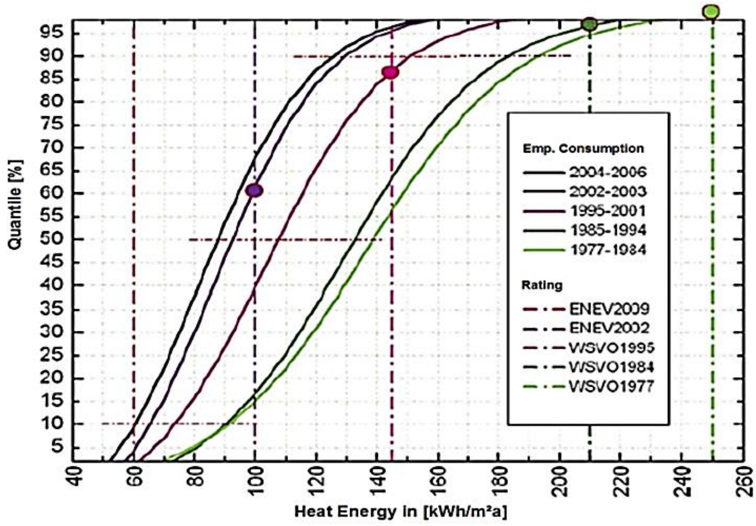

Figure 1: HEC distribution and EPRs, by energy efficiency ordinance in Germany (Greller et al., 2010).

The higher the energy efficiency level of the EPR value is, the steeper the increase is up to the 25% quantile. This in turn leads to the observation that in the respective EPRs more homes over-consume with respect to their according EPR. This observation shows that either a change in the occupant’s technical environment or a changed behavioral response to more energy-efficient living environments occurred. It could for example be that characteristics like an increase in the effective area or a systematic increase of the room temperature due to better insulation biases the empirically observed HECs. Likewise, it could be that systematic influences like a decreasing price per unit of utility/service exacerbates the deviations.

The research question addressed in this paper is why EPRs of modern energy-efficient homes or energy-efficient retrofits do not capture the actual HEC well and whether the static calculation of EPRs suit the needs of a behavioral analysis after all. Our analysis takes a closer look at the influence of occupant behaviors such as e.g. window opening and indoor thermal comfort and their impact on the system's HEC. The empirical results are based on a panel data analysis of monitoring data. Results are referred back to the prior calculated EPRs. In combination with the overall HEC dynamics, the impact of energy-efficient retrofits on HEC behavior offers new insights on the deviations and problems identified with EPRs in the representative sample population of homes surveyed.

The paper proceeds as follows. In section 2, a short literature review identifies the state-of-the-art of the academic discussion of EPRs and HEC behavior. In section 3, the data and other information sources used are described. The results of our analysis are presented in section 4. Section 5 concludes and discusses the results obtained with a view on the presented literature as well as future research needs.

2. RELATED LITERATURE

The standard evaluation of the success of energy efficiency measures is based on the thermodynamic potentials in contrast to the resulting energy consumption levels (Hens et al., 2010; Aydin et al., 2014). However, the reference of the thermodynamic potentials neglects human preference dynamics. Although heterogeneity in heating energy consumption as well as the energy-consumption-causing preferences for e.g. thermal comfort has been intensively researched, the current building-related energy norms in place rely on the assumption of an "ideal" behavior. This idealized behavior is meaningful if it reflects the average actual behavior and energy consumption. In the German case, fixed room temperatures as well as fixed ventilation rates are based on the corresponding norms (see Section 4). Figure 1 shows that even though different influences lead to an almost normal distribution of energy consumption per EPR, the corresponding EPR, which is based on calculation algorithms defined in the norms, does not reflect a shifting average energy consumption.

Improvements in energy efficiency lower the marginal price of energy services - which is equal to the marginal energy price divided by the efficiency rate - and will lead to a higher demand for energy services theoretically. Hence the expected private households' reactions to improved energy efficiency are analogously to a reduction in the price of energy. This behavioral response to efficiency gains was first discussed by Brookes (1978) and Khazzoom (1980) in the realm of mandated energy efficiency standards. Since then, the energy rebound literature gained momentum due to the contributions by Lovins (1988), Saunders (1992) and Jaffe and Stavins (1994), culminated in the late 1990s in a special issue on the topic published in *Energy Policy* (Greening et al., 2000). In more recent years, Sorrell and Dimitropoulos (2008) contributed an extensive theoretically reasoning, delivering widely accepted definitions. Turner (2012), Thomas and Azevedo (2013), Chan and Gillingham (2015) and Borenstein (2013) shed new theoretical light on the rebound matter. Apart from those theoretical contributions, the rebound literature delivers a rich source of empirical research, partly also focusing on HEC. Haas and Biermayr (2000) or Nesbakken (2001) were amongst the first to focus on HEC as a result of energy efficiency improvements in homes. Madlener and Hauertmann (2011), Chitnis et al. (2013) and Galvin (2015) are some of the latest examples exploring still existing research gaps in the field of HEC, rebound effects and associated behavior.

Nevertheless, the rebound literature treats EPRs as universal benchmarks (see Section 1), questioning occupant behavior as the only source of the deviations. Thus, the categorical divergence of HEC from EPR subsumes effects such as technical, economic and psychological ones under the variable “occupant behavior”. This can lead to poor guidance of policy-makers, which in turn can lead to inefficient or even counterproductive policy intervention. One reason why EPRs are not commonly identified as the source of the problem might be that they are calculated on the thermodynamic properties of the building and thus are not wrong in a physical sense, but taking the human dimension wrongly into account, if at all.

Literature targeting the EPR as the problem is still scarce. For instance, Pérez-Lombard et al. (2009), Menezes et al. (2012) and de Wilde (2011) agree on the necessity for future research in that field. Menezes et al. (2012) mention that “with building regulations relying heavily on predictive indicators of performance, it is vital that we understand the limitations of the current compliance modeling and aim at predicting realistic energy consumption levels by using detailed dynamic simulation models that account for realistic occupancy and management behaviors” (p. 355). deWilde (2011) goes one step further and concludes that it “is important to remember that energy efficiency is only one performance aspect of buildings. Once predicted and measured energy use[s] are adequately matched, further work will be needed to address performance gaps in areas like thermal comfort, indoor air quality and others” (p. 40). This demonstrates that the focus of the current discussion needs to change away from technology to human-centered EPRs, and in this realm, more human-centered research, policy and public awareness, as for instance Galassi and Madlener (2016) do. Laure Itard and associated researchers come closest to the work presented in this paper. Guerra-Santin and Itard (2012) show that correlations between EPRs and HEC is generally low. Majcen et al. (2013a) add that in the existing building stocks HEC is typically much lower than the according EPR. In Majcen et al. (2013b) the authors reflect on the behavioral drivers of the observed deviations. Further down, we pick up on their results and investigate the impact of those behavioral HEC drivers further.

Based on this literature review, the current praxis in energy efficiency research is questionable. To assess the required system capacity a static calculation and thus the use of fixed behavioral patterns seems to be sufficient. The evaluation of success of energy efficiency measures as well as the evaluation of behavior might require more adaptive algorithms. One could e.g. use historical data to determine average behavior *ex post*. Thus, *ex ante* calculations can be interpreted as potentials only, whereas the realized behaviors unveil their own benchmarks and distributions. Using measured data and its evolution instead of thermodynamic potentials might lead to more accurate forecasts in the end.

3. DATA

As introduced in Figure 1, the representative German HEC data set stems from the research department of a large HEC billing company. As we focus on energy-efficient homes, the more important EPRs depicted in Figure 1 are the norms contained in WSVO 1995 and ENEV 2002, respectively. The corresponding HEC measures cannot be approximated by the standard normal distribution. This is worrisome, because the empirical HEC of the WSVO 1984 and WSVO 1977 can be approximated by the standard normal distribution, while the mean distribution only shifted. The data presented in Figure 1 reflects the situation in 2008. Table 1 gives a short overview on the data sources used throughout this paper.

Table 1: Description of the data sources used.

Name	**Short description**	**Population *N***
Representative German HEC data	German heat meter readings in conjunction with technical building parameters evaluated in 2008 and 2013	125,000
Field experiment monitoring	Comprehensive high resolution monitoring in all rooms of the field experiment in Germany from 2011 to 2014	60
Field experiment questionnaire	Internet-based questionnaire about living and technical conditions in the apartments of the field experiment in Germany in 2013	31

Analyzing the same HEC patterns in the same data set five years later, as presented in Table 2, results in a clearly visible reduction for the EPRs in, WSVO 1995 and ENEV 2002, respectively. In Table 2, the other EPRs are not included since their numbers do not change. The difference between the Median HEC in 2008 and 2013 is largest for the smallest apartments of the latest EPR, contained in ENEV 2002, (i.e. < 200 m²). Table 2 shows that, overall, the HEC reduces during the first 10 years after construction or renovation and that this effect is stronger for the latest new builds. This indicates that analyses featuring the initial phase after retrofitting, or construction only, are biased towards higher HECs. Consequently, the research question arises as from where the energy consumption reductions achieved actually result from. This research question can only be answered with more sophisticated, human-centered research into the actual conditions in homes.

A clear separation of technical from economic and behavioral influences on HEC is necessary. To accomplish this, the results of a field experiment are analyzed. When assessing general trends in HEC, descriptive statistics of a large nationwide sample are usually sufficient. Yet, analyzing distinctive behavior needs detailed information on multiple interdependent variables, which is usually not reported in large data sets. The field experiment considered, which is located in South-West Germany, offers the possibility to evaluate occupant behavior in 60 apartments more closely.

Table 2: HEC with 5-year differences in measurement. Source: Own illustration, based on (Greller et al., 2010).

WSVO 1995	**Median HEC [in kWh/(m²a)] in 2008**	**Median HEC [in kWh/(m²a)] in 2013**	**Difference [in %]**
< 200 m²	107	109	0.02
200 - 400 m²	100	95	-0.05
400 - 700 m²	92	85	-0.08
700 - 1500 m²	91	83	-0.09
> 1500 m²	86	80	-0.07
ENEV 2002			
< 200 m²	82	69	-0.16
200 - 400 m²	78	67	-0.14
400 - 700 m²	73	65	-0.11
700 - 1500 m²	67	62	-0.07
> 1500 m²	69	62	-0.10

We are grateful to our partner, the Institute for Energy Efficient Buildings and Indoor Climate (EBC) at RWTH Aachen University, in setting up and accompanying the retrofits as well as the monitoring campaign. According to ENEV 2009, EPRs are calculated for each entrance of the two multi-family buildings, thus comprising six different EPRs overall (Cali et al., 2016). The analysis that follows focuses on the description of the observed behavior in relation to the EPRs calculated.

4. RESULTS FROM THE FIELD EXPERIMENT

Starting from the big picture, the descriptive statistics of the monitoring data from the field experiment are reported in Table 3. The mean outside temperature and radiation is slightly above the German average as defined by the German norm DIN V 18599-10. This can be attributed to the geographical location of the field experiment in South-West Germany, in contrast to the German reference climate which is based on the city of Potsdam in the East of Germany. The variable ‘Window opening’ consists of two binary measures of the window opening in each apartment. Thus, a maximum of two openings is reported. ‘Mean window opening’ reports on the average of the total time that both sensors are triggered. The mean value of 0.46 is high, considering a given ventilation of 0.7 air change rate per hour, as defined in DIN V 4108-6. At an assumed airflow of 100 m^3 per hour, the measured occurrence of window opening of 0.46% of the time results in a 30% deviation from the norm. The mean room temperature deviates clearly from the 19 °C defined in DIN V 18599-10. The reported mean of 24.45 °C needs to be corrected downwards by about 2.5 K, but this would still be 15% above the energy service level identified in the norm. Carbon dioxide, room humidity and volatile organic compounds are not of much concern, the corresponding statistics show that the values are within a normal range.

From the descriptive statistics one gets the impression that increased room temperature and excess window opening may be important explanatory variables for HEC. Furthermore, one could suspect that the HEC overshoots the EPRs. The comparison between EPR and HEC is displayed in Figure 2. One can observe that the average HEC per apartment overshoots the EPR in five out of the six entrances of the multi-family building in 2012 and 2013. However, the HEC drops significantly in the first five entrances in 2014.

Table 3: Descriptive statistics of the monitored variables in the field experiment. All variables are hourly averages and run from October to March, 2011-2014.

	Outside temp. [in °C]	**Radiation [in W/m²]**	**Window opening [in %]**	**Carbon dioxide [in ppm]**	**Room humidity [in %]**	**Room temp. [in °C]**	**Volatile organic compounds [in ppb]**
Mean	5.81	57.79	0.46	906.52	38.91	24.45	1164.42
Median	5.40	3.61	0.40	779.03	38.84	24.52	977.79
Standard deviation	5.68	115.29	0.41	467.70	8.78	1.72	674.78
Maximum	25.72	725.95	2.00	6288.74	68.48	31.40	14512.55
Minimum	-15.05	0.00	0.00	207.68	9.92	14.42	341.62

This development is accompanied by an increased window opening in 2014 of about 23% compared to 2013, yet the average room temperature stayed the same. Figure 2 shows that there must have been significant changes from 2013 to 2014, resulting in the observed HEC development. To identify whether behavioral differences can be credited as a source for this development we investigate the HEC pattern further to check for specific patterns on the household level.

In Figure 3, the HEC distribution of the individual apartments is displayed in a radar graph. Although the EPR can only be calculated on an entrance level per ENEV standards, we can investigate the HEC on the apartment level since the monitoring campaign covers the required resolution. Note that in Figure 3 the HEC per apartment is displayed in kWh/m²a, increasing from the inner to the outer circles. Most prominent are the spikes in HEC in single apartments, like e.g. apartment no. 10 or no. 22, which both feature an over-proportionally decreased consumption level.

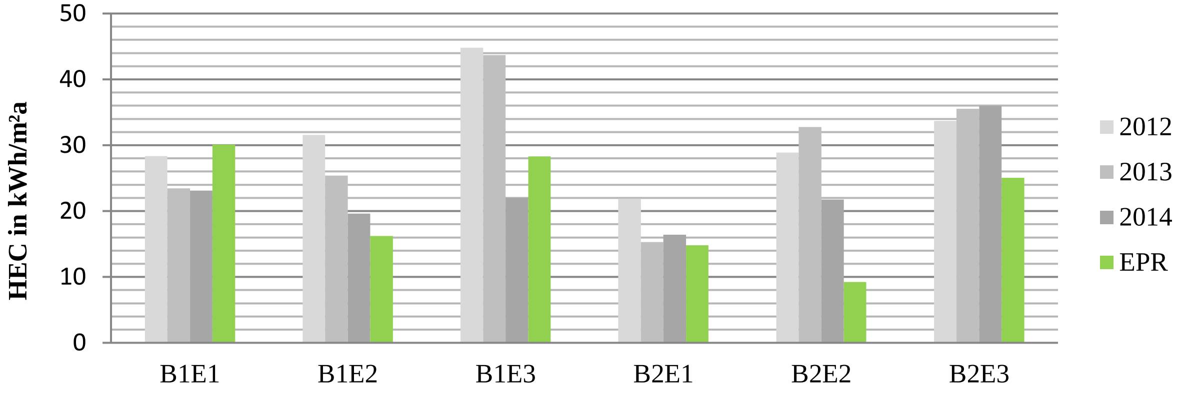

Figure 2: HEC vs. EPR in the field experiment from 2012-2014, weather-adjusted.[2]

This pattern does not hold true for the apartments in B3E3. However, Figure 2 congruently shows that the apartments in that entrance do not decrease the average HEC at all. This indicates that the overshooting of the average HEC, as displayed in Figure 2, in the years 2012 and 2013 is due to a few "over-consumers" (and in B3E3 this might still be the case in 2014). This development in the apartments concerned cannot be attributed to a radical change in behavior, as for example the average room temperature in apartment no. 10 only decreases 4% over the investigated period and the respective window opening increases (congruent to all other apartments and most probably because of the increased mean outdoor temperature).

From the descriptive results, it becomes apparent that the technical operation of the apartments' heating system must have changed to result in such clear HEC reductions. This could in part be a result of a system checkup during November 2013, which led to the removal of existing teething troubles, like e.g. the fine-tuning of existing ventilation systems. Nevertheless, the relation of heating energy consumption to its constituting causes is in the focus.

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[2] B#E# refers to the EPR-relevant reference building unit. The EPR is calculated based on the buildings shell properties, which is uniform for all B#s. However, building-technology differs across all B#s as well as all E#s, resulting in different EPRs.

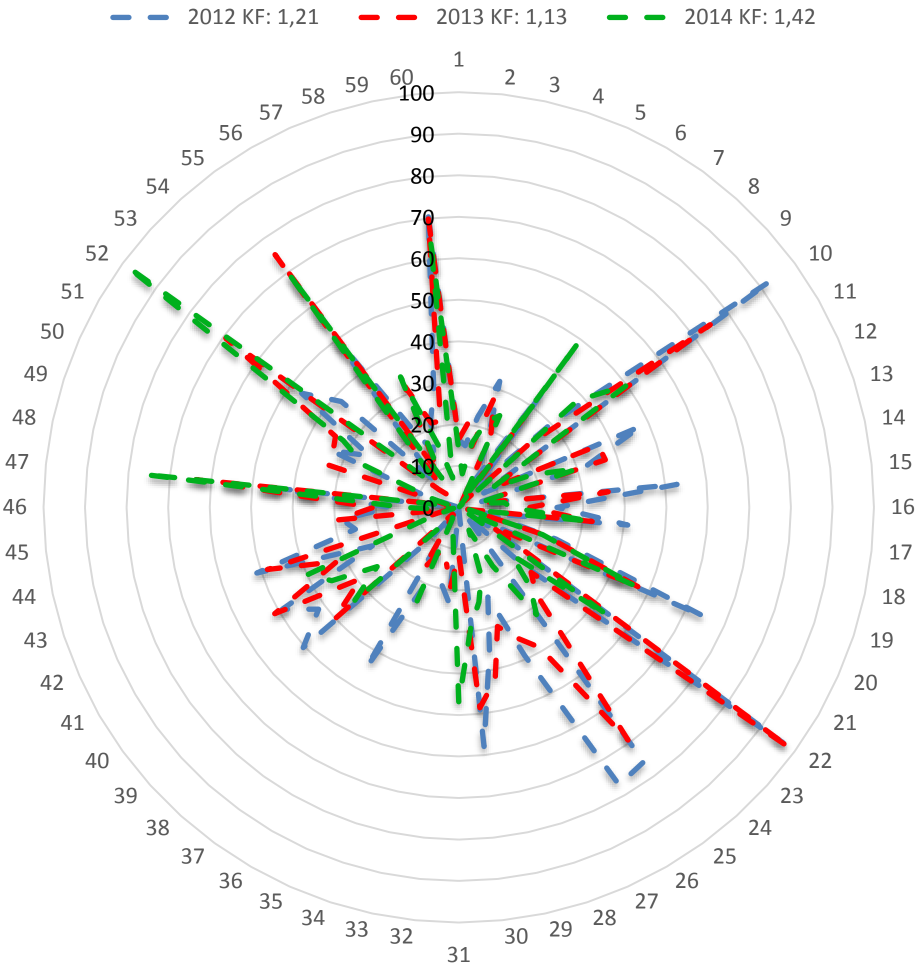

Figure 3: HEC in the 60 apartments of the field experiment in kWh/m²a from 2012 to 2014.

To make use of the long-range time series data available, eq. (1) presents a heating energy consumption model. Despite of the identified technical problems and interventions a general trend or dependencies of the variables influencing HEC should become visible. In eq. (1) HEC, represented by q_{it}, is the endogenous variable. The time series of the exogenous variables X_{it}, which were all introduced in Table 3, are used to explain HEC. We choose a log-log configuration of HEC to the explanatory variables to directly analyze the elasticities from the dependent on the explanatory variables. The constant term α_i incorporates unobserved time constant effects of each household, as e.g. the time constant socio-demographics. The error term ε_{it} captures the remaining variance in the data set.

$$\ln(q_{it}) = \alpha_i + \beta_x * \ln(X_{it}) + \varepsilon_{it} \quad \text{i = 1, … n, t = 1, … T} \qquad (1)$$

The HEC model is estimated using R, an open source programming environment. R offers the plm-package, devoted to panel data manipulation and estimation (Croissant & Millo 2008). Prior to a final model estimation, the data needs to be specified to select the right model type and check for possible barriers or inadequacies. First an F-test shows whether a simple OLS regression is better suited to estimate the model over a panel estimation. The F-test rejects the null hypotheses, proving that individual effects (as of households) are present and that the panel estimation is more efficient.

The Hausman test specifies whether the data incorporates significant fixed effects (Hausman 1978). In general, the random effects model is more efficient. If the Hausman test were rejected, the random model is biased and a fixed effects model delivers more reliable results. Table 4 summarizes all specification tests and reports that the χ^2 test rejects the null hypotheses; hence a fixed effects model is chosen as the preferable alternative.

Cross-section dependency is tested via the Pesaran-CD test (Pesaran et al. 2008). If cross section dependency is found in the data set, the estimation results can be biased. Accordingly, the null hypothesis tests whether the residuals between the panels are correlated. Autocorrelation in the data is checked via the Breusch-Godfrey/Wooldridge test. If present, autocorrelation biases the standard errors of the estimation and thus the results are less significant (Drukker 2003).

Table 4: Specification tests.

F-test on individual effects
F = 64.163, df1 = 24, df2 = 2691, p-value < 2.2e-16
Hausman test
χ^2 = 15.654, df = 6, p-value = 0.01574
Pesaran CD test for cross-sectional dependence in panels
z = 3.1936, p-value = 0.001405
Breusch-Godfrey/Wooldridge test for serial correlation in panel models
χ^2 = 1442.6, df = 94, p-value < 2.2e-16
Lagrange Multiplier test - time effects (Breusch-Pagan)
χ^2 = 1.1374, df = 1, p-value = 0.2862

The estimated standard errors are smaller than the true standard errors, so that the estimates seem to be more precise than they are. The null hypothesis of this test is rejected, indicating positive serial correlation in the panel. This result does not come as a surprise since the time series of the monitored variables are correlated in the short run (e.g. room temperature). To still gain valid results we need to account for cross-sectional dependence and autocorrelation when estimating the model. Consistent covariance matrix estimation is achieved using the vcovSCC estimator of Discroll and Kray (1998).

Time fixed effects are found in the data. The Lagrange Multiplier testing according to the method of Breusch Pagan fails to reject the null hypotheses, as shown in Table 5. This indicates that different times of the day, week or month impact the data evolution. We account for this phenomenon by aggregating the data set at the respective resolutions, as displayed in the three columns.

Table 5: Estimation results of the log-log model of HEC.

	Dependent variable: log(HEC)		
Aggregation level:	**Daily**	**Weekly**	**Monthly**
log(Outside Temp)	-0.2847***	-0.3343***	-0.5014***
	(0.0052)	(0.0129)	(0.0382)
log(Radiation)	-0.0217***	-0.0275***	-0.0167***
	(0.0012)	(0.0029)	(0.0050)
log(Window Opening)	0.0867***	0.1161***	0.2664***
	(0.0088)	(0.0206)	(0.0505)
log(Room Humidity)	-0.2956***	-0.2894***	-0.2184***
	(0.0091)	(0.0206)	(0.0428)
log(Room Temp)	0.9868***	0.9809***	1.1207***
	(0.0296)	(0.0690)	(0.1486)
Observations	18,531	2,726	609
R^2	0.3238	0.4249	0.4596
Adjusted R^2	0.3232	0.4196	0.4339
F statistic	1,771.6180*** (df = 5; 18497)	397.8326*** (df = 5; 2692)	97.7988*** (df = 5; 575)
Note:	*p<0.1; **p<0.05; ***p<0.01		

The results presented in Table 5 show that all variables are significant on the 1% level. The largest influence on HEC is found in the variable room temperature. A 1% increase in room temperature leads to a corresponding effect of a 1% increase in HEC. This indicates a strong relation between the two variables. The outdoor temperature's impact ranges from 30% to 50% indicating a still significant impact on the HEC. The impact of room humidity as well as window opening on HEC are both in a range between 10% to 30%. As identified by the adj. R² of the monthly aggregated data, the explained variance amounts to 43%, which, with respect to the large number of observations and heterogeneity of the data, can be characterized as good. The estimation results show that all variables have a significant impact and that already a slight deviation of one of the variables to its assumed value from the EPR might bias the HEC considerably. The matter gets worse as the different variables are not just linearly dependent on the HEC, but share interdependencies which in turn influence the individual impact on the HEC. All this might be captured in the remaining 50% variance, which is the unexplained part.

5. CONCLUSION

The results from the field experiment show that there is a very heterogeneous consumption pattern within one EPR. Furthermore, a clear evolution towards decreasing energy consumption levels since the commissioning of the retrofits can be identified. Especially households consuming high amounts of heating energy reduced their consumption over-proportionally during the investigated period. At the end of the monitoring campaign the upfront calculated EPRs fit the observed HEC. This observation needs to be put in perspective as we can still identify a very heterogonous HEC. A good proportion of the observed heterogeneity can be estimated through the panel estimation. The estimation results show the importance of the most prominent influences to HEC. Since the HEC model and, accordingly, the panel estimation is in a log-log format the elasticity of the variables to the HEC could be directly computed. Based on the magnitude of the influences, the variation of each of the variables was found to influence HEC considerably.

The insights gained from the analysis indicate that the observed problem of EPRs as benchmarks for HEC is twofold. On the one hand, we observe a temporal evolution in household energy consumption. The reduction of the overall HEC in the first years after a renovation, or the construction of a new building, seems to be due to structural characteristics or the reduction of teething troubles of the homes. Therefore, evaluations of the first years after an energy efficiency retrofit, or after construction of a new building, might always be biased towards higher energy consumption levels. The second problem concerns the deviations from the assumed conditions set as the calculation basis in the relevant norms. The range of each variable has a significant and powerful impact on HEC, leading to the observed heterogeneous HEC patterns.

This leads us to the conclusion that the current static EPRs are not suited to explain HEC behavior well. According to our results, they can serve as a best guess only when all variables are comparable. Considering these findings, it is questionable why for the outdoor temperature only one reference climate (the one of Potsdam, a city in the North-East of Germany) is applied, when climate data is readily available for almost every place in Germany. Furthermore, to make the EPR scheme more trustworthy for the customers, a range of the energy performance of the building, per range of the influence parameters would highlight the importance of behavior in the built environment. Promoted as by today, the EPR is like a performance catalogue, which later is expected to be achieved during the occupancy. It seems as if the regulation needs to put the normative agents in action to change the current EPR scheme to make it more transparent, reliable and thus trustworthy.

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