LoPa Working Paper

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May 2017

www.lokale-passung.de
Gefördert von
Funded by

Bundesministerium für Bildung und Forschung

FONA Forschung für Nachhaltige Entwicklung BMBF

Acknowledgements

The financial support for the study is acknowledged from the German Federal Ministry of Education and Research under the socio-economic research funding programme "FONA Research for Sustainable Development" under the Contract number 01UN1208A.

Explaining flat-specific heating energy consumption by building physics and behaviour. An interdisciplinary approach.

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Abstract

Households' heating energy consumption shows a large variance. Simply comparing consumption measures between households misses out on differences in heating demand according to building physics. On the other hand, solely comparing demand measures between houses misses out on differences between apartments in the same house and the behaviour of their occupants. This paper presents findings from an interdisciplinary work combining the approaches of engineers and social sciences. By implementing a flat-specific calculator for the heating demand, gathering heating energy consumptions according to bills and performing semi-standardized interviews with households, it can be shown that the heating energy consumption is composed of the flats' heating energy demand according to building physics and the variance in the behaviour of individual households. By relating households' individual consumption to the heating energy demand of the flat, we achieve a highly accurate prediction of households' heating energy consumption. With respect to retrofitting policies, better predictions on energy saving potentials can be made, when households' heating energy consumption is captured in the described way, instead of only relying on demand calculations according to building physics, as it is common practice in Germany and other countries.

Keywords: heating energy consumption, building physics, occupants behaviour, building and occupant interaction effects, retrofitting policies

1 Introduction

Engineers usually focus solely on the building and its thermal properties when predicting the heating energy demand of buildings. More specifically, factors such as energy conversion losses from the heating system, transmission and ventilation losses, solar and interior heat gains are taken into account only from a heating technology and building physics perspectives. Technical refurbishment potential studies however often overestimate the potential energy savings because the impact of consumer behaviour is neglected (Haas et al., 1998). The calculations are mostly based on the assumption, that households' behaviour is standardised. In contrast, studies from the fields of economics and social sciences exhibit that socio-demographic factors, behavioural routines and (rational) decision making of occupants are influential factors on the heating energy consumption (Boardman, 1991; Gram-Hanssen, 2010; Henger et al., 2012; Morley and Hazas, 2011; Schuler et al., 2000). The importance of households' behaviour is demonstrated by the fact that the variance in households' heating energy consumptions even in identical or similar buildings is substantial. Individual households' consumption has shown to be up to fourfold as high as the consumption of other households in similar buildings (Fell and King, 2012; Galvin, 2013; Gram-Hanssen, 2011; Loga et al., 2011). Building on this phenomenon, our interdisciplinary study aims to combine the approaches of engineers and social sciences systematically in order to further explain the variance of heating energy consumption between different households.

The basic consideration is, that there exists an interaction between buildings and occupants. A few studies already tackled this variance by analysing the impact of building characteristics, household characteristics and behavioural characteristics on the heating energy consumption (Branco et al., 2004; Fell and King, 2012; Gram-Hanssen, 2011; Guerra-Santin et al., 2009; Haas et al., 1998; Schuler et al., 2000). These studies agree that, apart from the building characteristics, especially the behaviour is an important factor in this respect. However, with most available data sets, building physics' characteristics and corresponding behavioural variance are hard to integrate, resulting in a need for further analysis of the specific interaction.

We suggest that the heating consumption of a household is the result of the heating demand according to building physics, socio-demographics and *varying* behavioural aspects of households. This connection shall be systematically derived in this paper. For this purpose, data on heating energy consumption according to bills (N = 336) was collected and extended with information from semi-standardized interviews with 80 households living in apartment buildings in two retrofitting areas in Germany. Furthermore, a calculator estimating the flat-specific heating demand according to the building physics has been designed and applied in the study's context. The flat-specific calculator is of particular importance, as the heating demand of single flats in one building varies largely and cannot be directly derived by averaging the overall buildings' heating demand. Without such a device, it is hard to determine whether below- or above-average consumption is based on behavioural or physical variance.

This paper is structured as follows: In section 2, the current state of research on the heating demand of buildings according to an engineering perspective is presented and the considerations for a calculator to predict the heating energy demand of flats are deduced. Subsequently, the influence of socio-demographical and behavioural aspects on the heating energy consumption according to social sciences is outlined. Section 3 then presents the data used and the methods applied for the analysis of household's heating consumption. Results from descriptive statistics and regression analysis are presented in section 4. Section 5 discusses the results including their policy implications.

2 Analysing and predicting household's heating consumption

2.1 Heating demand of buildings and flats

The heating demand of a building is usually calculated on the basis of losses and gains. First, there are conversion losses within the heating system itself – energy which is lost through the chimney. Secondly, a building loses heat energy by transmission through the insulation and by the exchange of warm and cold air through ventilation. Through solar radiation and interior heat gains from cooking, electrical appliances and the presence of humans, a building also gains heat energy (Casties, 1997).

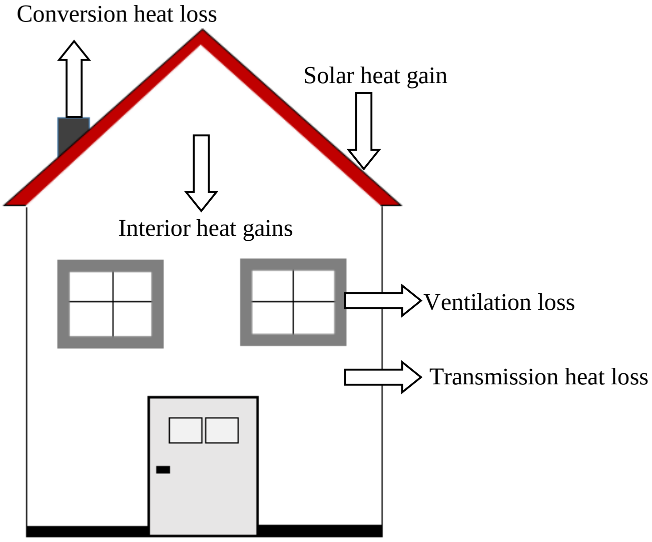

Figure 1: Influencing factors on the heating demand of a building.

The transmission heat loss of a building depends on the thermal transmittance, often referred to as U-value. It is defined as the rate of heat transfer in watts through one square metre of an insulation material divided by the temperature difference across the material. A low U-value (W/m^2K) stands for a good resistance of a material to resist heat flows, thus a low U-value represents a good insulation of the building's thermal envelope, the roof, floors, windows and doors (Hall and Allinson, 2010).
With this information, along with information on the heating system installed and standard assumptions about ventilation, solar radiation and interior heat gains, the heat energy consumption of a building can

be predicted. In this paper we adapted a well-introduced and publicly available software[1] from the German Institute for Housing and the Environment (IWU; Loga et al., 2005), which calculates the heat energy consumption of houses on the basis of an internet questionnaire. This tool offers a simplified method for energy performance certificates which are required in Germany, i.e. when selling or renting real estate. The questionnaire includes topics such as the building age, the number of floors and apartments in the building, as well as the heated living space. Data concerning the height of the rooms, whether the building is detached or (partly) attached to other buildings, whether an existing cellar is heated and whether the attic is heated, is likewise collected. Assumptions about typical building standards corresponding to the building age, information on the windows and the thickness of (additionally) installed insulation allows the calculator to determine which U-values need to be used in order to calculate the heat loss, but also the heat gains of a building (Loga et al., 2005).
But within one building, the heating energy demand differs for individual flats, resulting from the position of the specific flat within the building and hence the larger or smaller share of the building's outer surface area as envelope of that flat. This is the reason why we advanced the already established calculator for buildings to make it useable for the heating energy demand of individual flats.

2.2 Calculator for the flat-specific heating demand

The heating demand of single flats depends on several factors. In addition to the influencing parameters which play a role when determining the energy demand for buildings (see section 2.1), the position of the apartment in the building is a key factor. This is attributable to the fact that the outer surface area of the flat is dependent on the position in the building. For instance, flats in the top floor have a larger surface-to-volume ratio (SA:V) because of the roof area in comparison to flats in the middle floors of a large residential building. Similar relations apply for flats situated at the corner of buildings. According to these principles, the heating demand of an apartment building can be outlined as in Figure 2.

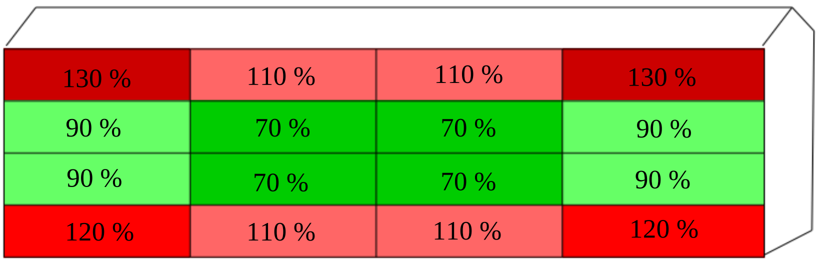

Figure 2: Heating demand for flats according to position in a building.

Figure 2 illustrates that the heat energy demand is higher in the top floors, bottom floors and the corners of the building. Flats situated in the middle of the building (coloured in dark green) consume on average 40 % less heat energy compared to flats situated in the top or bottom floors (coloured in red). These

[1] More information and software download: http://www.iwu.de/forschung/energie/laufend/kurzverfahren-energieprofil/, last accessed 28.10.2016. The resulting online tool can be found e.g. here: http://www.bnu.de/verbrauchrechner/bde/

differences are more accentuated for buildings with weaker insulation, and smaller for buildings with more energy efficient envelopes. To account for these differences when comparing the heating energy consumption for households, a calculator has been designed by an engineer of our working group according to the principles described above (2.1). In order to make this calculator accessible also for a broader group of users, the questions about the building and the flat need to be answerable without too much background knowledge. The building standard was raised following the German building typology classifications, either via direct input of the building age or by choosing between three root categories (until 1969, 1970-1994 and as of 1995) (Loga et al., 2015). Furthermore the input mask asks if the building was retrofitted since the year 1995. Basic information such as the floor space, room height, position in the building (basement, ground floor, middle floor, top floor), the number of rooms and the number of exterior walls has been likewise included into the input mask. Like in the calculator for the heating demand of buildings, this data is necessary to determine which U-values need to be used in order to calculate the heat losses and gains of the flat and thus determining the heat energy demand of the flat. The input mask is shown in Figure 3.

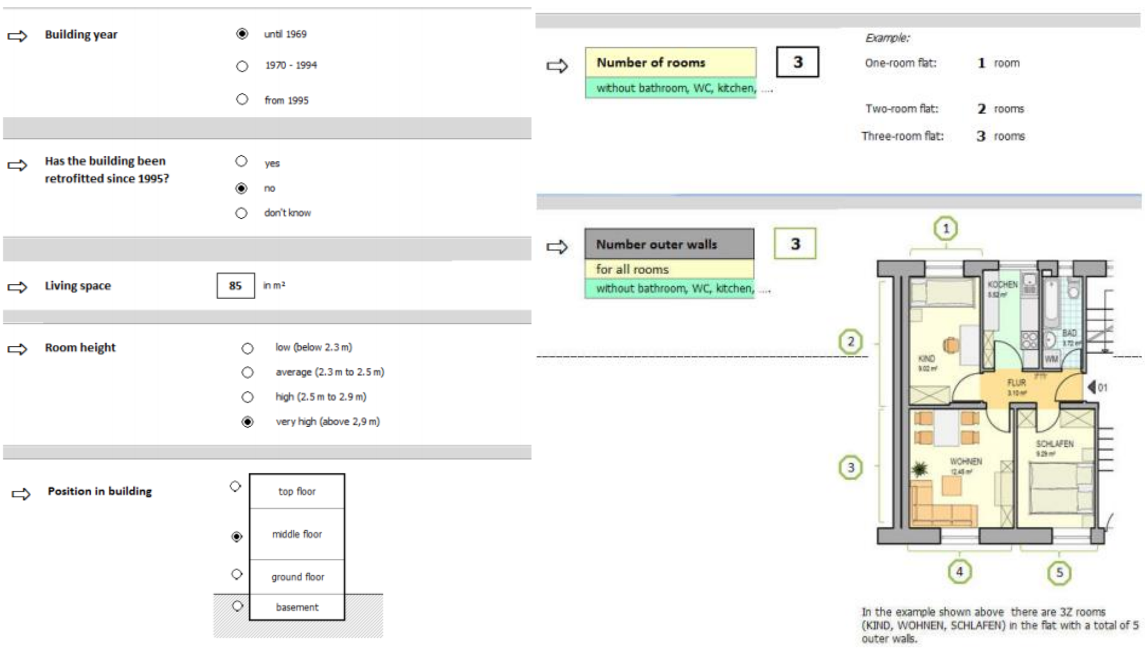

Figure 3: Input mask of the flat-specific heating demand calculator.

Before the calculator for the flat-specific heating demand was used for the investigation of interaction between building and occupants, it was evaluated with a dataset of actual existing buildings to check its reliability. The process of evaluation will be laid out in the following.

2.3 Evaluation of the flat-specific heating demand calculator

From two retrofitted quarters in Germany we gathered data about the building itself and the floor plans of the individual flats in the buildings; thus all the information needed for the input mask of the flat-specific heating demand calculator is available to us. In a first step, the calculator for the flat-specific heating demand is evaluated by calculating the heating demand for the nine whole buildings after the retrofit in our data set with the calculator for heating demand of whole buildings as already established by IWU (see above, 2.1). The sum of the individually calculated heating demand for the single flats in these buildings was then compared with the demand for the whole building. Results are illustrated in Table 1.

Table 1: Comparison of building-specific heating demand and cumulated flat-specific heating demand

Building	Building-specific heating demand per m²/a	∑ Flat-specific heating demand per m²/a	Deviation
30200-1	159	142	−11 %
30200-2	163	149	−9 %
30200-3	168	154	−8 %
31100-1	143	140	−2 %
31100-2	143	140	−2 %
31100-3	143	140	−2 %
31104-1	159	168	+6 %
31141-1	153	148	−3 %
31141-2	153	151	−1 %

The sum of the heating demand calculated for single flats in the building matches the forecasted heating demand for the whole building with a mean deviation of −3.56 %. Given the comparatively small amount of information which is included into the calculation of the heating demand for flats (cf. section 2.2) we suppose that this is a rather good fit.

In a second step, the calculated heating energy demand for flats is contrasted with a large data set for heating energy consumptions with respect to the position of the flat in the building for similar buildings. This data set, which we received from a commercial heating costs billing firm, consists of 1987 non-retrofitted buildings and 51419 flats, consumption data covers the year 2009 and 2010.

Table 2: Comparison of relative heating energy consumptions to relative flat specific heating demand with respect to flats' position in the building

	BRUNATA-METRONA data (N = 51419)	Flat-specific heating demand (N = 168)
Ground floor	111 %	112 %
Middle floor	92 %	63 %
Top floor	119 %	154 %

In contrast to the average heating energy consumptions for the different levels in a building received from the billing firm, the calculated heat energy demand for 168 non-retrofitted flats in our sample of the retrofitting areas shows a larger range. Especially the heating demand for top floors is considerably higher compared to the mean of all flats and the heating demand for flats situated in the middle of the buildings is much lower than the arithmetic mean of the consumption data from heat billing firm. We trace these differences between calculated heating demand and measured heating consumption first to the known prebound/rebound effect (Sunikka-Blank and Galvin, 2012) and secondly to the fact that the low number of flats leads to rather building-specific patterns with higher standard deviations compared to the consumption data covering a large number of buildings where building-specific patterns are balanced out against each other.

2.4 Incorporating socio-demographical and behavioural aspects

Research shows that heating energy consumptions of households differs even when looking at identical flats (Fell and King, 2012; Galvin, 2013; Gram-Hanssen, 2011; Loga et al., 2011). Looking at particular buildings, actual heating energy consumption is often far away from the predicted heat energy demand, as it is shown in an exemplary way in Figure 4.

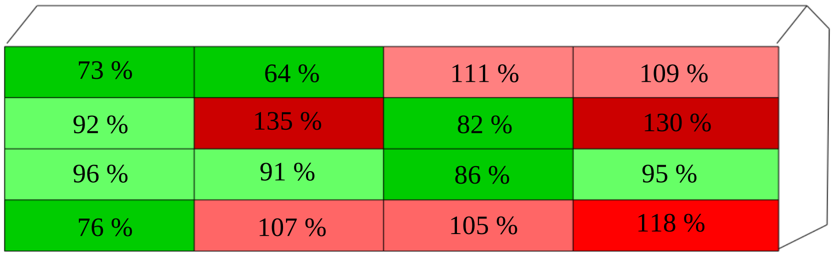

Figure 4: Heating consumption for flats according to position in a building.

Seen in contrast to Figure 2, the variance in buildings' heating energy consumption leads to the following preliminary conclusions: first, energy performance certificates, usually issued for buildings, are insufficient for predicting the heating energy consumption of households living in flats. Second, the high variance in household's behaviour and preferences leads to the fact, that even a flat-specific heating demand is imprecise for the prediction of households' heating energy consumption. Additional to the isolating of the heating demand of single flats, the behavioural aspects of the households in these flats therefore need to be taken into account.

From the existing literature stock on heating consumption, a number of factors leading to a heating consumption above or below the calculated heating demand have been identified. First of all, the calculation of the heating demand proceeds on the assumption that each flat is heated up to a static and homogeneous indoor temperature of 20 °C (Fanger, 1970).[2] However, thermal comfort preferences in homes vary between individuals and between activities. For instance, some people prefer to keep the body warm by wearing warm clothes rather than heating the flat to higher temperatures. Households' indoor temperatures therefore show a rather wide range (Schröder et al., n.d.). Of course a preference for indoor temperatures of 23 °C increases the heat energy consumption compared to the assumption of 20 °C, while lower temperatures result in lower heat energy consumptions. Preferences for room temperatures also depend on the life cycle and associated daily schedules of household members. Households with children or elderly and residents with high levels of attendance usually heat more rooms to higher temperatures over longer periods (Fritzsche, 1981; Van Raaij and Verhallen, 1983).

[2] The World Health Organization recommends indoor room temperatures of 21 °C for living rooms and 18 °C for other occupied rooms (World Health Organisation, 2007).

Ventilating method and ventilating frequency of flats further influences the heat energy consumption of households (Branco et al., 2004; Galvin, 2013). The windows in Germany allow occupants to ventilate in two different manners, first the recommended shock-ventilation where windows are widely and simultaneously opened for a few minutes, second the so-called trickle ventilation, where windows are in a tilt position for a longer time period. According to Galvin (2013a), typical shock-ventilation consumes around 1 kWh per apartment of heat energy each time (depending on activity and occupancy, one to five times ventilation per day is recommended), whereas trickle ventilation throughout the day consumes more than 30 kWh of heat energy in a day. Also, many households don't turn off the thermostats while ventilating. Especially in the case of trickle ventilation this leads to large heat energy losses. The improved thermal insulation of newer buildings results in higher ventilation impacts, as the proportion of transmission heat loss in comparison to the ventilation loss declines (Casties, 1997; Haas et al., 1998). Furthermore, it was shown that the better insulation often leads to the situation where people feel overheated and are therefore more prone to leave their windows open (Schröder et al., n.d.). The heat energy losses through ventilation thus play a major role for the overall heat energy consumption. In newer buildings they can account for over 50 % of the total heat loss (Casties, 1997). Guerra-Santin (2009) likewise notes that the role of the occupant becomes more important when the thermal properties of the building improve.

Studies examining the composition of households heating energy consumptions so far could not explain the high variance in consumptions sufficiently. For instance Guerra-Santin et al. (2009) aimed at gaining greater insight into the effect of occupant behaviour on varying energy consumption for space heating. Their study controlled for building characteristics by including factors such as the type, size and insulation. Although occupant characteristics (age, household size, income) and behaviour, i.e. occupants' preferences for temperatures in various rooms and information on the attendance at home, found to have a significant influence on the heating energy consumption, these variables could only explain 4.2 % of the variance. Building characteristics on the other hand determined the variation with an explanatory power of 42 %. Added up, still more than half of the variation of occupants' energy consumption remains unexplained. In this case the authors themselves trace the low explanatory power of occupants' characteristics and behaviour to the categorical rather than continuous data on the occupants' behaviour. In a further study from Schuler et al. (2000), the utilisation intensity for heating and warm water is explained by building characteristics with an explanatory power of 14.4 %. Household characteristics such as household size, age, employment and income however could only explain 0.8 % of the variance and only household size and age were found to be statistically significant in their model.

Overall, empirical evidence explaining the heating energy consumption of households is scarce and the results above further demonstrate that predictions on the impact of occupant's behaviour are inconsistent. This can be attributed to the fact that the integration of building physics and behavioural variation in these studies is incomprehensive, mostly due to a lack of accurate data. With the data on the heating demand of flats and the information from the semi-standardized interviews of households living in these flats, we seek to add to this state of research. Data used and methods applied are laid out in the following.

3 Data and methods

With the goal of systematically deriving the interaction between building and occupants we gathered data for households from two retrofitting areas in Germany, as there not yet any comprehensive dataset on households' consumption and the heating demand according to building physics for Germany. Our collected data include information from the building floor plans, i.e. the size of the apartments as well as their position in the building, their surface share area etc. On that base we calculated the heating demand for each flat occupied by the households (N = 336). From the tenants we received data about the actual energy consumption of the households according to bills. Household's total heating energy consumption was converted into heat energy consumption per square metre. A climate adjustment to take the annual changing temperatures into account was carried out. Furthermore, consumption data was only considered if the household lived in the flat for a total of at least 12 months.

With regard to seeking further explanations why households consume above or below the calculated heat energy demand, we conducted semi-standardized interviews, comprising 81 households. The standardized questionnaire consisted of 33 questions including various subjects. First, households were asked to answer questions concerning the process of retrofitting, the condition of the apartment prior to retrofitting and the changes in the apartment after retrofitting. Furthermore, the questionnaire asked households about their heating behaviour in the winter time, i.e. how and how often they regulate their indoor room temperature. Also they were asked how often they ventilate and how they ventilate. Information on socio-demographics, including household size, number of children, household income, highest educational achievement and employment relationship was likewise gathered.

The collected data before and after the retrofit were pooled for the regression analysis to give a more representative picture in respect to the overall existing building stock in Germany. Because we have fewer observations in our data set before the retrofit compared to the observations after the retrofit, we weight the cases before the retrofit with the factor 2.19 to minimize the bias due to the imbalanced data. In the following results section, descriptive statistics illustrate the ratio between heating consumption and demand before and after the retrofit in the data set. Ordinary least squares regressions are then performed in order to test the relationship between heating demand according to building physics, actual consumption of the households and other explanatory variables obtained through the interviews. We used the multivariate OLS-regression model, which is defined as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_k x_k + u,$$

where y is the dependent variable, heat energy consumption in kWh/m²/a, β_0 is the intercept and β_1 is the parameter associated with x_1 etc, thus the explanatory variables such as the heating demand according to building physics and the variables for behavioural aspects (Wooldridge, 2013).

4 Results

With our data we can compare the consumption data with the predicted heating energy demand for a large number of households before and after the retrofit. Table 3 gives an overview of the heating consumption in kWh/m^2/a before and after retrofit in our dataset.

Table 3: Heating energy consumption in kWh/m^2/a before and after the retrofit

	Mean	Min	Max	Std. Dev.
Prior retrofit	142	26	308	42
After retrofit	44	8	121	23

The large range in consumption measures already indicate to the large variance in heating energy consumption. Next, scatter plots are shown to illustrate the high variance in household's heating energy consumption while controlling for the heating energy demand according to building physics.

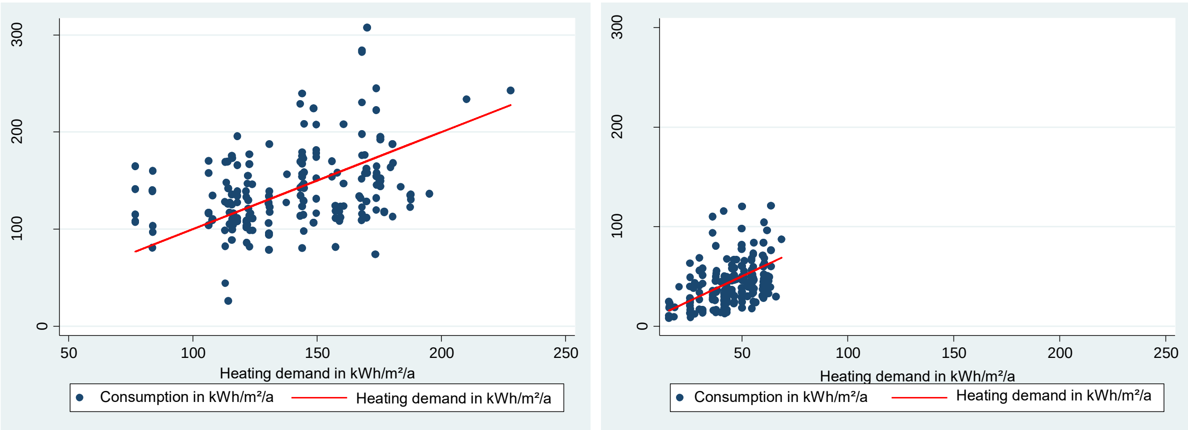

Figure 5 & 6: Scatterplots of measured energy consumption in kWh/m^2/a against calculated heating energy demand in kWh/m^2/a before retrofit (left) and after retrofit (right).

Figures 5 & 6[3] show the ratio between the calculated flat-specific heating demand for each flat and the corresponding heat energy consumption of the households before (left) and after (right) retrofit.[4] The high variance in households' consumption is apparent in both figures. The angle bisector (red line) indicates where the heating consumption equals the calculated heating demand. Thus, all households above the red line consume above the calculated heating demand, households below the line consume below the calculated heating demand. The ratio between the calculated flat-specific heating demand and the heat energy consumption ranges from 0.23 for the household with the lowest to 2.14 for the household with the highest consumption within the sample prior to retrofit. After the retrofit the ratio of heating demand versus consumption in our data set even ranges from 0.3 to 3. This high variance in our consumption data is in line with findings in other studies (cf. also Fell and King, 2012; Galvin, 2013; Gram-Hanssen, 2011; Loga et al., 2011). The scatter plots show that the variance in the heating consumption of households, especially while controlling for the flat-specific heating demand, is obvious.

[3] For a better comparability Figures 5 & 6 are plotted on an identical axis range.
[4] For one of the retrofitted areas we had to manually adjust the heating demand with the factor 0.5 for the time-span after the retrofit. This is due to the fact that these buildings were retrofitted to an above-average standard and moreover the windows in the buildings are – for heritage conservation reasons – much smaller than usual.

Furthermore, Figures 5 and 6 give an overview of heating consumptions before and after the retrofit. Note that the standard deviation in relation to the mean consumption is in relative terms much higher after the retrofit compared to the statistical measures before the retrofit (cf. also Table 3). This result indicates that the role of the occupants' behaviour becomes more important as the thermal properties of the building improve (Branco et al., 2004; Guerra-Santin et al., 2009).

In the following two regression tables we further explore the variance in heat energy consumptions of households with ordinary least squares regression analysis for the pooled data set.

Table 4: POLS regression on the heating energy consumption in kWh/m²/a

Dep. Var.: Heating energy consumption in kWh/m²/a	(1)	(2)
Building-specific heating demand	1.011^{***}	
	(23.88)	
Flat-specific heating demand		0.946^{***}
		(26.56)
Constant	-19.01^{***}	3.866
	(-3.67)	(0.99)
Observations	336	336
Adjusted R^2	0.630	0.678

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4 represents two bivariate regressions with the heating energy consumption in kWh/m²/a as dependent variable. In the first model the heating demand for whole buildings is included as the independent variable. As the first regression model shows, the building-specific heating demand explains around 63 % of the variance in households' heating energy consumptions. The coefficient of 1.011 indicates, that the heating consumption in kWh/m²/a rises on average by 1.011 kWh/m²/a, if the heating demand in kWh/m²/a rises by one unit. In the second model the flat-specific heating demand, predicted with our calculator on the basis of outer surface area of the flats etc., explains nearly 68 % of the variance of households' heating energy consumption. The model shows that as the flat-specific heating demand in kWh/m²/a rises by one unit, the consumption in kWh/m²/a rises on average by 0.946. Model 2 thus emphasises, that the flat-specific heating demand more precisely predicts the variance in heating energy consumption of households. The following figures illustrate once more the importance of the flat-specific heating demand.

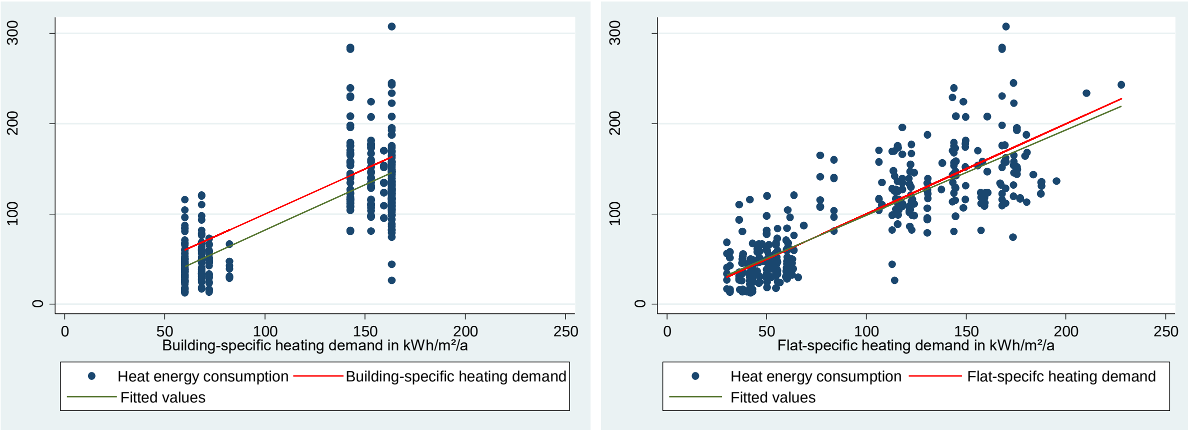

Figure 7 & 8: Scatterplots of heat energy consumption in kWh/m²/a against calculated building-specific heating demand (left) and flat-specific heating demand (right).

By ignoring the position of households' flats in the building the building-specific heating demand only ranges between 60 and 170 kWh/m²/a. Acknowledging the fact that single flats differ from the building in their heating demand leads to a much larger range of heating demands, i.e. between 30 and 227 kWh/m²/a. Households with very low (< 20 kWh/m²/a) or very high (> 200 kWh/m²/a) consumptions unjustly appear to be "low user" or "heavy users" in Figure 7. Hence, for the following regression model, the flat-specific heating energy demand is used. Furthermore, behavioural variables are included into the regression models shown in Table 5.

Table 5: POLS regression on the heating energy consumption in kWh/m²/a

Dep. Var.: Heating energy consumption in kWh/m²/a	(1)	(2)	(3)	(4)	(5)
Flat-specific heating demand in kWh/m²/a	0.987***	0.992***	0.962***	0.923***	1.177***
	(22.28)	(24.73)	(24.30)	(7.18)	(7.90)
Thermal comfort in °C	15.05***	13.74***	13.92***	12.63*	
	(6.57)	(6.55)	(6.96)	(2.50)	
Efficiency of ventilation		-7.306***	-6.839***		-4.480
		(-4.14)	(-4.05)		(-1.18)
Attendance at home			5.872**		
			(2.90)		
Flat-specific heating demand in kWh/m²/a*Thermal comfort				0.0257	
				(0.54)	
Flat-specific heating demand in kWh/m²/a*Efficiency of ventilation					-0.0628
					(-1.46)
Constant	-35.01***	-9.329	-31.50**	-28.77*	18.68
	(-4.62)	(-1.01)	(-2.70)	(-2.07)	(1.44)
Observations	76	76	76	76	76
Adjusted R^2	0.873	0.896	0.906	0.872	0.839

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The employed variables thermal comfort, efficiency of ventilation and attendance at home range on a 9-step scale from 1 to 5 and have been created on the basis of the conducted interviews. Holding the flat-specific heating demand constant, the average heat energy consumption of a household increases by 15.05 kWh/m²/a with each step on the thermal comfort scale in Model 1. As was to be expected, the warmer the households want their apartment to be, the higher their consumption. In Model 2, the efficiency of ventilation has lower impacts on the consumption, however the coefficient of −7.3 implicates, that a household with the highest ventilating efficiency (shock-ventilation while turning off thermostats) consumes on average 36.53 kWh/m²/a (5*-7.306) less compared to a household with the lowest ventilating efficiency (trickle-ventilation for long time periods while leaving the windows open). In Model 3, the attendance at home furthermore influences the heating consumption of households insofar, as one step on the attendance scale increases the heat energy consumption on average by 5.9 kWh/m²/a, while the other variables remain constant. Concurrently the third model reaches an explanatory power of 90 %. From a theoretical point of view (cf. section 2.4) we further expect interaction effects between the heating demand according to building physics and the ventilation behaviour of households. To test these, we include interaction terms in model 4 & 5. As the regression table however shows, both interaction terms are statistically not significant and the coefficients are negligible. Classical socio-demographical variables such as the net equivalence income, household size, employment relationship and school leaving qualification have been likewise tested, but showed no significant effect.

5 Summary, discussion and policy implications

The aim of this paper was to integrate the perspectives of engineers and social sciences into an interdisciplinary concept to analyse and explain heating energy consumption as a result of the interaction of the physical characteristics of buildings and occupants' behaviour. First of all, since the object of observation is the private household as a self-governing unit in regard to heating and ventilation behaviour, the necessity for calculating a flat-specific heating demand was deduced. On this basis, we isolated the specific influence of behavioural variance. The flat-specific heating demand explains 68 % of the variation in households' heating energy consumptions. Behavioural variables, in particular preferences for indoor room temperatures, efficiency of ventilation and attendance at home explain 14 % of the variation in households' heating energy consumptions. Taken together in one regression model, building physics and behavioural variables explain almost 91 % of the variation in households' heating energy consumptions. Compared to the results in the existing literature (Guerra-Santin et al., 2009; Schuler et al., 2000), we gain a more comprehensive picture of households' heating energy consumption. To put this result into a broader perspective, it should be emphasized that the dependent variable was heating consumption per square metre (as measured in kWh/m²/a), which is used as general indicator in retrofitting studies, whereas in socio-demographic surveys usually the overall heat consumption of the household (in kWh/a) or the respective expenditures are analysed. In these surveys (Lutzenhiser, 1993;

Schubert et al., 2012) first of all living space, household size, and to a rather weak extend income together explain around 30–40 % percent of the variance of the annual heating consumption of households, whereas information on buildings physics, while rather incomplete and including only building size and building age in rough categories, add only a few percent to the overall 35–45 % of explained variation. Following model 3 (cf. Table 5) but using the overall heating consumption (instead of consumption per square metre) as dependent variable and including living space on the other side of the equation as additional independent variable, we reach 92 % of explained variance. This result again shows the advantage of a truly integrated interdisciplinary approach which includes building physics, household characteristics and behavioural aspects.

Whereas our results in general exceed our expectations, the hypothesis concerning a direct interaction between heating demand and efficiency of ventilation was not supported. More precisely, in line with theoretical assumptions (Casties, 1997) we would expect, that the impact of the efficiency of ventilation is the higher, the lower the heating demand of a flat according to building physics. But in our sample, results in this respect had been statistically not significant and negligible in impact. Thus, there is a need for further research concerning this issue. It is apparent at this point and in general, that a larger and more representative dataset containing more households from different buildings and corresponding behavioural data from more various social milieus is needed for further investigations.

However, our results show that energy saving policies should not focus on building physics alone but also on behavioural aspects. With decreasing heating demand of the buildings due to refurbishment, the understanding of households' behaviour becomes ever more relevant. But in apartment buildings its impact can be isolated and analysed only on the basis of a flat-specific heating demand calculation. In particular the ventilation behaviour of the households has been identified as an important component: the efficiency of ventilation has high impacts on the households' heating energy consumption, and in comparison it is easier for households to adopt efficient ventilation behaviour than to restrict thermal comfort.

Generally, taking current individual consumption together with behavioural aspects into account, better predictions on energy saving potentials in regard to retrofitting can be made. This can lead to better focused refurbishment measures, as the prediction of the economic efficiency will become more accurate. Further, it can be useful for tenants seeking to relocate due to either above-average heating costs or high cold rents. Households with a frugal heating consumption could be better off when living in un-refurbished houses with lower cold rents than in better isolated buildings with higher rents (the German law allows landlords to raise a modernization allocation up to 11 % of the amount invested into energy saving refurbishment). In comparison, households which identify themselves as "heavy users" would be better off in refurbished apartments and/or middle floors of buildings as the heating demand in these flats is comparatively low. Acknowledging the impact of building physics and behaviour additionally may be beneficial to better target heating subsidies or offer relocation support for households experiencing fuel poverty.

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