Statistical study on the link between real energy use, official energy performance and inhabitants of low energy houses

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SUMMARY:
Energy performance regulations are becoming increasingly strict and governments supply simplified calculation tools to assess whether new buildings fulfil the requirements. However, one can wonder what the accuracy of those tools is for assessing the next generation of houses, that will have to fulfil the upcoming energy requirements. In order to investigate the discrepancy between predicted and real energy use in low energy houses, 537 dwellings were analysed. Data on building characteristics and theoretical energy use from the Flemish EPBD-database was complemented with data from the energy utilities and a survey of the inhabiting households, providing information about the households, their user behaviour and real energy use. While an undeniable correlation was found between theoretical and real energy use, the EPBD-method overestimated the heating energy use for most of the cases. Two building related parameters and two user related parameters proved to have a significant impact on that gap: the use of default values for the air tightness of the envelop and for the efficiency of the gas boiler, the heating profiles of the master bedrooms and the amount of baths and showers taken by the inhabitants. However, two comments must be made. First, the dataset consists of early adopters who could afford such energy performance years before it would be imposed and are therefore not representative of the average household. In addition, the analysis showed significant correlations between household characteristics on the one hand and building characteristics and performance on the other. These last two points question the possibility to extrapolate findings from samples of existing forerunners towards prognoses on future, entire building stock level.

1. Introduction

It is often questioned whether theoretical improvements in the energy performance of buildings, imposed by European and national regulations, will be fully obtained in practice. This question is important not only to estimate the real reductions in CO2-emissions, but also to calculate the financial returns on investments and cost-optimal performance targets, as asked by the European Union to each member state. However, when defining the future energy standards that will be imposed, the question on prediction accuracy becomes even more difficult to answer as there are few houses already fulfilling those performance targets, resulting in less relevant data being available. Building simulation software allow researchers to calculate the energy performance of building more in detail and to compare those results with results from the simplified assessment tools. However, this approach might overlook unpredicted user behaviour as well as the varying thoroughness of the energy assessors when performing the calculations. One solution is to use large datasets, analysing together both the officially reported building characteristics and performance on the one hand and real energy use and data on user behaviour on the other hand, as was done by Guerra Santin (2010). For this study, the approach was similar, though it focused solely on recent houses with good energy performances and therefore it is based on a much smaller dataset.

2. Material & methods

2.1 Data collection

Every new house in Flanders, built from 2006 onwards, must meet the energy performance requirements from the Energy Performance of Buildings Directive (EPBD). Technical building data and administrative data (e.g. address) of all these houses is kept in one centralized database by the Flemish Energy Agency (VEA). For this study, VEA selected 1850 projects, based on the four following criteria. (1) The energy performance had to meet at least the current energy standards. (2) The housing units had to have their own, individual heating system. (3) They had to be inhabited for at least two years. (4) Their EPBD-file had to be free of any major error or shortcoming with regards to data (e.g. missing data) or with respect to the energy performance requirements.

Three complementary data-sources provided the needed information for this study. (1) The EPBD-database itself provided technical data on the buildings and on their theoretical energy performance. The database does not contain the full inputs for the EPBD-calculation (e.g. data on each individual wall). However, it does contain some of the most important variables (e.g. the size and type of the building, the type of services, the average insulation levels etc.) as well as the intermediate and final results of the energy calculation. Those are expressed in monthly primary-energy use for sanitary hot water, heating, cooling and auxiliary energy for services, calculated with a primary energy conversion factor for electricity of 2,5. The database also contains the estimated monthly electricity production of the photovoltaic-panels (PV-panels). (2) Surveys of the households supplied additional data on the buildings as well as on the households, their behaviour and their real energy use. (3) Meter readings from the energy utilities further completed this dataset. The surveys obtained a response rate of 29%, resulting in a total dataset of 537 housing units. However, the response rate was not homogeneous over all energy performance levels: significantly higher response rates were obtained for the better performing houses, as will be further discussed in paragraph 3.2.

2.2 Data filtering & subsampling

A thorough analysis of the dataset revealed hidden shortcomings as well as contradictions, e.g. between the survey and the EPBD-database. As it was often impossible to elucidate the contradictions, several cases had to be removed from the dataset for further analysis. In order to keep the dataset as large as possible, those cases were only excluded from subsets for analyses depending on their specific erroneous or dubious data points. Thus, for example, faulty data on the PV-panels were not taken into account for the analysis on heating energy use based on gas combustion.

Three subsamples were identified within the full dataset, in order to analyse the total energy (subsample S1), the heating energy use for space heating and sanitary hot water (subsample S2) and the domestic electricity use (subsample S3) separately. Due to the relevant shortcomings in the dataset, these subsamples were reduced respectively from their original size of 350, 135 and 260 to 100, 75 and 150 cases. However, the analyses that didn't require real energy use, could be performed on much larger subsamples, with small variations depending on the specific analysis.

2.3 Normalization method

The statistical study of the data and further analysis were performed in SPSS, using multivariate regression analysis. However, prior to comparative, statistical analysis of the predicted, calculated energy use and the real energy use, both have to be normalized to comparable boundary conditions such as similar climatic data. The most common way to do this, is to normalize the real energy use of all houses to one single, average climatic year, coinciding with the one used in the theoretical calculation method. However, this was impossible for this dataset due to several reasons. Normalization of the energy use requires to perform some regression, based on the real energy figures. However, data on real energy was provided for only one time period per dwelling and different types of energy demands were often aggregated into one single figure (e.g. sanitary hot water and heating on one single, yearly gas consumption bill). Therefore, individual normalisation regression could not be performed for the separate energy use types of the individual houses. Applying one common (e.g. degree-day based) formula on all the houses would neglect both the technical differences between the houses (e.g. thermal time constants) as well as the behavioural differences between households (e.g. heating profiles). Applying, on the real energy use data, a normalisation based on the theoretical EPBD-calculation of each separate house, would also ignore the impact of user behaviour of the individual household and it would assume an approximately correct, relative weight of the different energy demands of the house. However, these are two of the investigation topics of the study.

To tackle these issues, the procedure of normalisation was turned around: the theoretical calculation of each individual energy demand, according to the EPBD-method, was '(a)normalised' to coincide with the period of the real energy figures available. Redoing the full EPBD-calculation for the real climatic conditions was impossible, due to missing calculation input data in the EPBD-database. However, based on the formulas of the EPBD-method and on the main characteristics of the buildings and their services, accurate normalisation of the energy use was possible, using the monthly calculated values available for space heating, sanitary hot water, cooling, auxiliary energy and electricity-production for the PV-panels for each house separately. The limited variations in climatic conditions and time periods between the separate cases, were taken into account in the statistical, multivariate analysis, in order to ensure that these variations would not bias further analysis. However, their impact proved to be negligible, due to the relative homogeneity of the duration and average climatic conditions of the real periods.

3. Buildings & inhabitants

3.1 The buildings

The sample mainly consists of detached houses, with only a very low percentage of terraced houses, as shown in TABLE 1. Due to the very low number of apartments within the dataset, these were left out of the further analysis. With an average gross floor area of 257m² (median: 248m²), these relatively large houses are also not representative of the average size of new built houses in Flanders, though these numbers lie close to those of all detached houses within the EPBD-database (Defruyt et al. 2013).

TABLE 1. Distribution of housing typologies, showing the overrepresentation of detached houses

		Detached	Semi-detached	Terraced	Apartments
EPB-database:	total	26%	20%	8%	45%
EPB-database:	Single family houses	48%	37%	15%	-
Data sample		68%	28%	4%	-

In Flanders, each new building gets an 'E-level' as a label to indicate the primary-energy performance of the house with regard to space heating, sanitary hot water, cooling and auxiliary energy use for services, after deducting the electricity production of PV-panels if present. This level indicates the relative primary-energy use of a building, in comparison to a reference building of the same type dating from 2006. Reaching the same level as the reference building would deliver a level 'E100' (100%), but in the meantime, the requirements have been tightened towards E70. All of the selected houses fulfil this current requirement, even though their building permits date from between 2006 and 2010. In addition to the total primary-energy use requirements, the insulation level of the houses is also subject to legal requirements. While all selected houses fulfilled the insulation requirements valid at the time of their building permit, only approximately 60% of the houses would fulfil the current, updated insulation requirement. This discrepancy within the sample is explained by the high performance of the building services and the very high presence of PV-panels, compensating the lower insulation levels within the calculation of the primary-energy demand. 83% of the houses have a mechanical, balanced ventilation system with heat recovery, 33% use heat pumps and 46% have PV-panels. While these numbers are not representative at all of current standard built houses, let alone standard practice three years ago, these numbers are representative for houses with similar E-levels, as illustrated by De Baets and Jonckheere 2013.

3.2 The inhabitants and their houses

Almost all of the households (co)owned their respective houses (99%) and were the original builders (99%). They are mainly young households (FIG.1), from the upper middle class (with high level of education, a good job and a good income). While this is to be expected for the average builder of a new house, this is not representative of the total population. These households having built their own houses, we can also assume they had their saying during the building process and were thus at the basis of the choice for an energy-performant house (considering the requirements and standard practice of that time). This assumption of looking at a sample of deliberate low-energy builders is strengthened by the response-rates to the survey: the response rate proved to be significantly larger for the higher performing houses within the sample, as shown in TABLE 2. The income of the households also proved to be significantly, positively correlated with the primary-energy performance of their houses. This could be directly linked to the correlation that was found between the income of the households on the one hand and, on the other hand, the possession of PV-panels or, even stronger, the area of PV-panels installed on the roofs. Looking further at the link between the households and their houses, one could expect to find a correlation between the size of the house and the size of the household. However, this was not found and the lack of correlation can be explained by the young age of the households, building for the future and, possibly, considering future family extension.

These tight links between household characteristics and building characteristics oblige us to be cautious with the further analysis as well as with possible extrapolation of further findings. These cross-correlations complicate the task of disentangling the relationships between the building characteristics, household characteristics and resulting energy use, let alone the goal to assess causality. Furthermore, due to the specificity of this sample, the applicability of findings on this dataset, onto the larger Flemish, Belgian or other population has to be questioned.

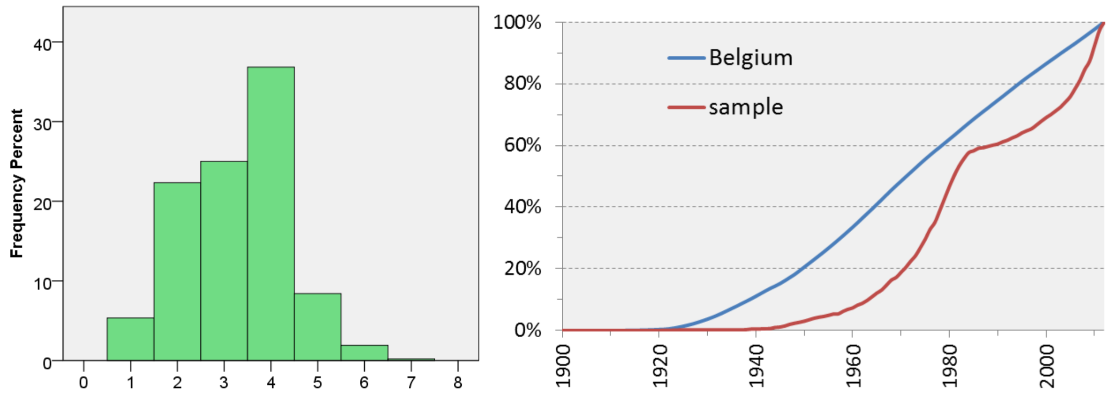

FIG 1. (a) Amount of inhabitants and (b) age distribution (date of birth): mainly young families

TABLE 2. Response rate to the survey, suggesting a sample of motivated low-energy builders

	≤ E40	E40-E50	E50-E60	E60-E70	TOTAL
Contacted	167	241	611	833	1850
Participated	70	86	183	199	537
Response-rate	42%	36%	30%	24%	29%

4. Real energy performance

4.1 Total energy use

Within the EPBD-calculation method, not all of the types of domestic energy demands are included. Foremost missing, are the energy demands for cooking, for lighting and for domestic electrical appliances (from refrigerators onto televisions). Further analysis in this paper will focus on the heating demand for space heating and for domestic hot water. As a reference, FIG. 2(a) compares the total primary energy demand of the households with the heating demand and the electricity demands (not for heating) according to data from the surveys and energy suppliers. The auxiliary electricity demand for building services, included in the EPBD-method, can be considered low in comparison to the other electricity demands. Furthermore, houses with active cooling were removed from the sample. Therefore, the total energy demand from subsample S1 in FIG. 2(a), can be (approximately) considered as the sum of the heating demand from subsample S2 and the electricity demand from subsample S3. Comparing real energy use with predicted energy use, FIG. 2(b) shows that the underestimation of the total, primary energy use is caused mainly by the higher domestic electricity use, as the heating-energy use is overestimated in most of the cases.

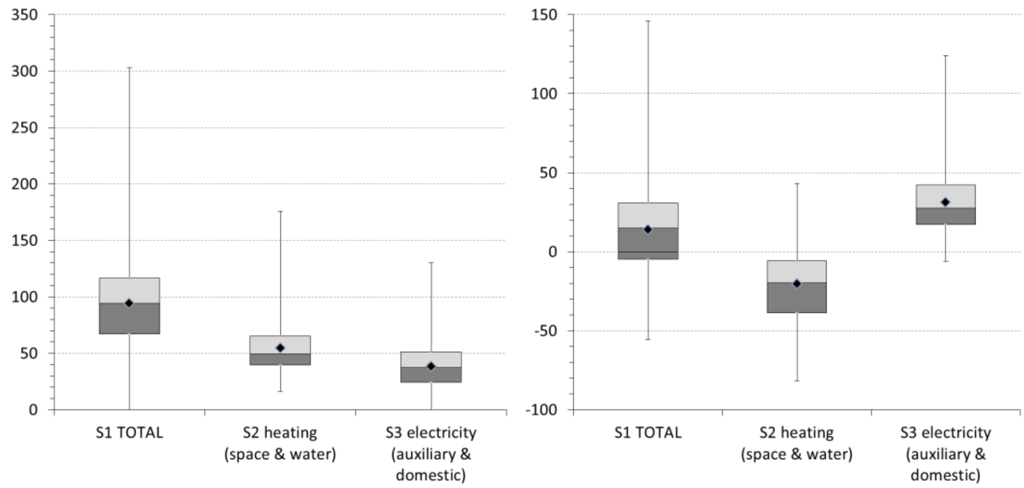

FIG 2. Yearly primary energy use per floor area [kWh/(m².y)]: (a) real values and (b) discrepancy with predictions

4.2 Heating & sanitary hot water

While an undeniable, positive correlation was found between the real and the predicted heating-energy use, there was no close fit between both. On average, heating energy use appeared overestimated by the EPBD-method. Furthermore, this gap between predicted and real values showed large variations, depending on the specific house and household. Four parameters were identified as a significant cause for these variations. Two of them are building related and two are user related.

4.2.1 Air tightness

The air tightness of the houses, or rather the way the air tightness is implemented within the calculation, proved to greatly influence the gap between real and predicted energy use. Within the EPBD-calculation, one can chose to perform the energy calculation with a default value for the air tightness, or with a measured value, based on an air tightness test performed after completion of the building. The overestimation of the heating energy use proved to be the largest for calculations using the default value. This seems to indicate that the real air tightness levels of the houses that were not measured, are better than that default value. This would also be in agreement with the most recent studies on air tightness of Belgian houses (Laverge et al.). However, statistical regression analysis on this or similar datasets cannot prove this, nor can they prove that the heat losses due to air infiltration are correctly modelled in the EPBD-method. The statistical analysis only proves the strong relative influence of choosing to use the default rather than a measured value.

The magnitude of this influence can be explained by the size and typology of the house and the unit used for the default air tightness. The default air tightness is expressed in v50-value, in cubic meter air infiltration rate at 50Pa pressure difference per square meter of envelope area [m³/(h.m²)]. Therefore, any difference with the real air tightness value is magnified within the EPBD-calculation by the large envelope area of the large, detached houses in this sample. The influence of the assumed air tightness rate was such that the calculations had to be corrected towards a more realistic default value, before performing further analyses.

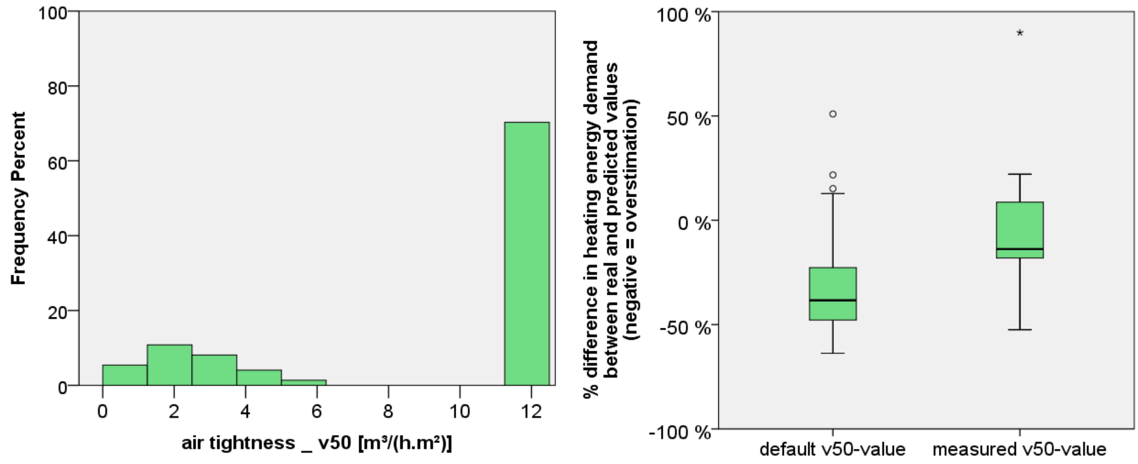

FIG 3. (a) Air tightness rates taken into account in the calculation (v50 in [m³/(h.m²)]) and (b) its effect on the gap between real and predicted heating-energy use

4.2.2 Gas boiler efficiency

The efficiency of the gas boilers, according to the EPBD-files, proved to be significantly, negatively correlated with both the absolute and the relative overestimation of the heating energy demand. The negative correlation with the absolute overestimation can be explained by the fact that a lower heat production efficiency would amplify any overestimation of the net heating demand. However, this would not explain the correlation with the relative overestimation. Three possible explanations were formulated, though none can be proven by statistical analysis on this type of data. (1) The formula used in the EPBD-method to correct the partial load efficiency from the manufacturer's data, based on the real return temperature of the system, might be flawed. (2) When a high performing boiler is chosen, one might be more inclined to use a lower return temperature to take full benefit of the investment and, consequently, to use that lower temperature in the EPBD-calculation, instead of keeping the fixed default value of 70°C. (3) Many houses had a combi-boiler, used both for space heating and for sanitary hot water. Due to the relatively low space heating demand of these houses, the boilers would have to be sized based on the hot water demand. This could result in a lower, effective efficiency when the boilers are used for space heating only and have a larger, relative effect on the boilers with the highest theoretical efficiency. Further analysis on this problem is needed to identify whether its cause is related to the physical EPBD-model, to the varying scrupulousness of the EPB-assessor, to incorrect or imprecise installation on site or to any combination of these or other possible factors.

4.2.3 Heating profiles

The importance of user behaviour on energy use is generally acknowledged, as discussed e.g. by Guerra Santin (2010). However, the influence of the different heating profiles on the real energy use could not be proved directly from the answers to the surveys. Many different combination of heating profiles occurred within the sample, due to variations in daily heating times and heating set points over the different rooms of each different house, having also its own thermal time constants. Considering the size of the dataset, the amount of parameters for the regression analysis had to be reduced. This was achieved by clustering the daily heating times, set points and time constants of the buildings, using the simplified corrections formulas from EN 7120, resulting in one instead of three parameters per room. This allowed to identify the heating profiles of the master bedrooms as having the most significant effect on the real energy use. The statistical importance of the master bedroom can be explained by the fact this room is present in all houses (e.g. in comparison to a study or play room) and that its heating profiles showed larger variations than e.g. the living rooms, which almost all households heated to a similar set point.

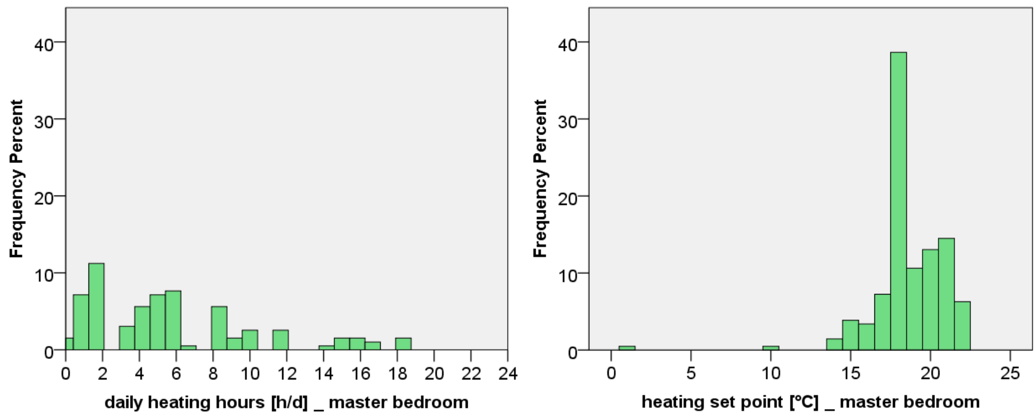

FIG 4. Heating profiles in the master bedrooms: (a) large spread in daily heating times [h] and (b) set points [°C]

4.2.4 Showers & baths

Neither the weekly amount of baths, nor the weekly amount of showers were proven to have a significant effect on the gap between real and predicted heating-energy use. This contra-intuitive finding was explained by the strong, negative correlation that was found between both ways of having a wash. Therefore, similar to the problem of multiple parameters for heating profiles, the parameters for baths and showers were merged. As the average heating-energy use for showers is not equal to that for baths, the weighted sum of weekly baths and showers, per household, was calculated. Based on EN 13203-2, the average energy use was estimated to be 3,6kWh for a bath and 1,4kWh for a shower. Using this aggregated parameter, the weekly amount of baths and showers taken by each household revealed itself as the second most influencing user behavioural factor explaining the divergent gaps between real and predicted heating-energy use.

5. Conclusions & discussion

This study aimed both at investigating the gap between real and predicted energy use in low-energy houses as well as at identifying the most significant parameters influencing this gap. This study proves the influence of both technical as well as user behavioural parameters on the gap between real and predicted energy use. The implementation (default values and formulas) of air tightness and combustion efficiency within the calculation method proved to be significantly correlated with the size of the gap. These issues could partly be tackled by choosing more realistic default values, improving the predictions' accuracy. However, this would oppose itself to the role of conservative default values, namely to admonish building teams to perform better and to prove it, by rewarding these efforts through better energy labels based on measured values. The realistic estimation of user behaviour is an even more complex task within energy performance regulations. The contradiction there lies between choosing a default user behaviour to enable comparison of energy labels on the one hand and delivering accurate predictions on energy use to the future, specific inhabitants and investors on the other hand. Therefore, one might question if it is realistic or even recommendable to aim both at labelling and at an accurate, case-specific prediction based on one single, simplified calculation.

The presented study pointed out some significant parameters. However, the limited representativeness of the sample, as well as the strong, direct correlations between building parameters and household parameters hinder further extrapolation towards building stock levels. These findings question the possibility of accurately predicting the effect of future, tightened building requirements, using data collected from past forerunners. Larger datasets would be needed for further thorough statistical analysis, due to the complexity of the problem, the large amount of influencing variables and the important possible amount of unknowns and contradictions within different datasets. However, collecting such size of datasets appears be in contradiction to the target of such study: the few forerunners.

6. Acknowledgements

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