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Abstract: Buildings account for 40% of total energy consumption and emit 35% of the total CO2 in the EU and there is consequently an enormous energy saving potential. Therefore the EU-directive 2002/91/EU [1] requires from all EU Member States to save energy in this sector. Hence, the drive to reduce the energy consumption of buildings represents an essential component of environmental protection efforts. Furthermore, the new directive 2010/31/EU [2] requires that the Member States tighten national standards and draw up national plans to increase the number of 'nearly zero-energy buildings'. Well planned energy-saving strategies presume knowledge of specific characteristics of the current national building stock. Therefore, the implementation of process to support systematic data collection, classification and analysis of the energy consumptions of buildings will become increasingly important during the coming years.
The following field survey analyzed the energy consumption of 68 school buildings in Luxembourg. A separate collation of electricity and heat energy consumptions allowed a detailed analysis of specific energy parameters. A statistical analysis and interpretation of new buildings differentiated by energy sources was completed as well as the definition of energy relevant parameters such as the energy standard, the purpose of the building or the presence of canteens.

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Detailed Response to Reviewers

We accepted all remarks and modified the manuscript.

Field Study on the Energy Consumption of School Buildings in Luxembourg

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Abstract

Buildings account for 40 % of total energy consumption and 35 % of the total CO_2 emitted in the EU. In consequence, there is an enormous energy saving potential and the European Union requires from all EU member states to save energy in this sector. Hence, reducing the energy consumption of buildings represents an essential component of environmental protection efforts. Furthermore, the new European directive 2010/31/EU requires that the member states tighten national standards and draw up national plans to increase the number of "nearly zero-energy buildings". Well-planned energy-saving strategies presume knowledge of specific characteristics of the current national building stock. Therefore, the implementation of a process to support systematic data collection, classification and analysis of the energy consumption of buildings will become increasingly important during the coming years.

In the field study described below we analyzed the energy consumption of 68 school buildings in Luxembourg. A separate collation of electricity and heat energy consumptions allowed to make a detailed analysis of specific energy parameters. Clustered according to energy sources, the new buildings were analyzed from a statistical point of view. We defined the energy relevant parameters such as energy standards, the purpose of use of the buildings or whether they had canteens.

Keywords

School buildings, Energy consumption, Luxembourg, Benchmark, Regression analysis

1 Introduction

The Kyoto protocol adopted in 1997 [1] was aimed at fighting the constant increase in worldwide energy consumption and, as a result, the increase in greenhouse gas emissions. The leading industrial countries committed to reduce their annual greenhouse gas emissions by an average of 5 % for the period 2008-2010. As buildings account for more than one third of total energy consumption in the European Union and have an enormous energy-saving potential, the EU directive [2] sets national binding targets for CO_2 reductions. Saving energy in the building sector is therefore a central key-point with regard to climate protection.

During recent years the distribution per sector of Luxembourg's energy consumption shifted noticeably in favor of the building sector. In 1990, 71 % of the total domestic end energy consumption was ascribed to the industrial sector and only 20 % to the building sector. The distribution has changed significantly since then and in 2005 the industrial sector contributed only 44 % to the national energy consumption while transport and the tertiary sector (incl. private and public households as well as non-residential buildings) accounted for 25 % and 31 % [3] respectively.

Hence, a non-existent database with the most important benchmarks of the various building types is necessary to define the exact saving potential of the whole Luxembourg building sector. So, the aim and most important research activity were to collect energy values of buildings in order to compile a representative database and make a statistical evaluation. This paper presents the results of the benchmark study for newer schools in Luxembourg and illustrates that, contrary to common expectations, the primary energy consumption of new buildings has increased in recent years as a result of the increased electricity consumption.

2 Energy benchmarks of schools in European countries

In order to rate the energy performance of a building, it must be compared to many other same-category buildings. Therefore, the first step is to establish a database. Many countries already have such benchmark studies of school buildings [17]-[25].

The deviations between countries are mostly not significant as they are used for the same purpose, i.e. education. In most cases, the average heat consumption is about 100 kWh/m^{2}a. Santamouris [25] analyzed 320 school buildings from different regions in Greece, concluding that the average heating energy consumption is of 68 kWh/m^{2}a and that 25 % of all Greek school buildings boasting the lowest values consume less than 32 kWh/m^{2}a. However, a study by the German Fraunhofer Institute [18] determined a maximum average value of 211 kWh/m^{2}a. In contrast, another German study [17] provided very different results. This can be explained, on the one hand, with the sample size ([17] is higher by a factor of ten than the sample size of the Fraunhofer study [18]), and, on the other, with the selection of the buildings (only energy-efficient buildings or a large range of building types). This example shows that many conclusions on energy consumption need to be regarded with caution.

Therefore, benchmark analysis is always necessary in order to know which types of buildings and which boundary conditions (heating degree days, floor area etc.) were used.

According to the existing European benchmark studies [17]-[25], the electricity consumption values of schools vary from 10 to 30 kWh/m²a. The minimum value of 10 kWh/m²a found in German primary schools [17] can be explained by the very low level of technical equipment and the fact that here artificial light uses the majority of the energy.

With regard to energy consumption in schools, British studies analyzed the dependence of special-use areas (e.g. cafeteria) and found that consumption increases by up to 7-10 %. Energy consumption is likely to increase by even as much as 20 % if a gym is taken into consideration when calculating a building's energy consumption [10].

Finally, the various European countries show no significant differences regarding average thermal as well as electricity consumption. Thus, it will be interesting to see how the energy consumption of new Luxembourg schools fit into this set of benchmarks.

3 Analysis of the buildings included in the sample

3.1. Description of the building sample

The following sample includes educational buildings that were constructed, extended or completely renovated after 1996. This year was defined as a threshold because at that time the first thermal insulation regulation in Luxembourg, based on limited U-values, came into effect. This remained to be the reference regulation in Luxembourg until the new energy-efficiency regulation for non-residential buildings [4] came into effect on January 1st, 2011. The sampled objects have a total heated gross area of approximately 400,000 m². The buildings were classified into four different groups depending on the type of use (see Fig. 1):

- preschools including daycare centers
- primary schools
- secondary schools (high schools)
- gyms

There are 49 secondary schools in Luxembourg. However, this number does not reveal the actual total quantity of existing buildings as some schools have more than one building. Buildings classified as "new" were constructed or renovated after 1996, resulting in 16 "new" secondary school buildings in Luxembourg. Twelve of these buildings were analyzed for this field study, representing 75 % of the total population and allowing significant conclusions to be drawn.

The primary and pre-school buildings are similar with respect to the nature of their use and represent the second largest group of educational buildings. In a study [5] conducted by the Ministry of Education in 2008/2009, there was a total of 452 school buildings falling into this category in Luxembourg. Based on information received from the relevant municipalities in Luxembourg, 91 of these buildings can be classified as new objects (year of construction after 1996). Of these 91 school buildings we analyzed the energy consumption of 52 buildings in this study. These represented 55 % of the population and consequently provided a representative sample.

3.2. Definition of the reference values

To compare the energy consumptions measured in the various buildings, the most common benchmarking metric used in the energy sector is based on the gross heated floor area (including the exterior walls) [17], [26], [27]. Furthermore, the climatic boundaries must be specified to neutralize the effect of weather conditions. The thermal end energy consumption of each building collected during this study was altered, based on the average climatic conditions in Luxembourg. In doing so, the portion of thermal end energy, which is dependent on weather conditions, was adjusted to the average climate conditions in Luxembourg with the help of $HDD_{20/15}$:

$$E_{Vhb} = E_{hb} \times \frac{HDD_{20/15m}}{HDD_{20/15}} \qquad (1)$$

where:

E_{Vhb} Normalized thermal end energy consumption of a building relative to average climate conditions

E_{hb} Measured thermal end energy consumption of a building

$HDD_{20/15m}$ Average heating degree days in Luxembourg for the period 1995-2009 (3560 Kd/a)

$HDD_{20/15}$ Heating degree days of the period analyzed

3.3. Thermal end energy consumption

The thermal end energy consumption will become less important in the coming years when compared to the total primary energy consumption of a building. Figure 2 shows the heating consumption, including the domestic hot water supply, of 68 objects with reference to the heated gross area. The different colors represent the various energy sources used to heat the building. The mean value is 93 kWh/(m²a) and therefore significantly lower than the energy consumption of single family houses (131 kWh/(m^2a)) [6]. Some of the buildings analyzed use district heat as an energy source. Thus, the generation and storage losses are not included in the measured energy consumptions of these school buildings. The district heat consumption figures were therefore increased by 10 % in order to come up with more realistic results when being comparing to buildings heated with gas or fuel oil. This estimation of additional losses (10 %) complies with the method of evaluation of a heating system according to DIN 4701-10 [7] and also correlates with the values measured in an internal University of Luxembourg low-temperature boiler study.

The calculated standard deviation (±49 %) is substantial and can be explained by the different types of use and the varying energy standards of these buildings. The list includes small kindergartens as well as large secondary schools with canteen kitchens, gyms and labs. Consequently, a range from 24 to 197 kWh/(m²a) could be measured. Building N° 1 with a thermal heat consumption of 0 kWh/(m²a) is a school building in passive design, heated with a earth-to-air heat pump system. The total energy required to heat the building on a set temperature is electricity and therefore included in the consumption values in Figure 7.

We also evaluated that buildings using a district heating system (average = 77 kWh/(m^2a)) or a pellet boiler (average = 63 kWh/(m^2a)) consume less thermal end energy. Particularly due the small number of pellet boilers used in low-energy or passive school buildings, it was concluded that the reason for these buildings' lower energy consumption does not depend on the energy source but rather on the building's energy standard. Contrarily, the buildings with higher energy consumption still use fuel oil boilers (average = 149 kWh/(m^2a)) and are, generally, older buildings (more than 10 years old) or extensions of existing buildings supplied with heat from the older main building. Hence, it is not the energy source which is determining but the practice and intention of the building owners which have changed in recent years.

Of all buildings analyzed, the lowest consumption value was measured in a very airtight low-energy school boasting low U-values. This specific building does not have a gym or a canteen kitchen, which would influence the thermal end energy consumption. The low heat energy requirement is supplied by the local district heat grid, which uses fossil fuels.

Other building characteristics were also analyzed. The year of construction, an indication for thermal end energy consumption, is one of them. Almost all schools which were constructed after 2005 consume less than 100 kWh/(m^2a) and often less than 50 kWh/(m^2a) of thermal energy. The linear correlation [8], which is a measure of linear dependence between heat consumption and the year of construction, is negative (newer buildings consume less thermal energy) and a very high confidence level was determined, indicating a high probability that both values correlate (s. Chapter 4 and Table 2). An explanation for the decrease in thermal end energy consumption after 2005 is that a new regulation "Fonds pour la protection de l'Environnement" [9] became effective. This allowed all municipalities to apply for financial support when constructing new public passive and low-energy buildings. The present sample contains 40 % of low-energy (21 objects) and passive buildings (6 objects). Different methods of construction being taken into account, the energy consumption analysis shows a positive effect as far as thermal energy consumption is concerned. When comparing standard to low-energy buildings, average thermal end energy consumption decreases by 36 % and by an additional 52 % for passive buildings (Fig 3). When we compared the consumption values to the figures calculated in the planning phase, it can be determined that just 50 % of the actual consumption values correspond to the reference values defined in the Directive [9]. The real mean value exceeds the reference thermal heat consumption figures by 20 % (35 / 30 kWh/m^2a and 72 / 60 kWh/m^2a) (Fig. 3). However, consumption values corresponding to the maximum threshold were a prerequisite for those buildings to be classified as passive and low-energy buildings respectively and to apply for financial support.

For statistical analysis the objects were classified in different categories (Fig. 4) according to their consumptions and compared to a normal distribution, which was determined on the basis of the same mean and standard deviation. There is a visible approximation between both distributions. The hypothesis that the sample is based on a normally distributed population could be verified by means of a χ^2-test [8], which confirmed this basic assumption. As a result, an extrapolation with the “Students t-distribution” was possible and the mean thermal end energy consumption of all new school buildings in Luxembourg was estimated with a 95 % confidence interval at 93 ± 9 $kWh/(m^2a)$.

Figure 5 shows the correlation between the consumption and the gross heated floor area. Being quite small preschools and primary schools, most of the buildings analyzed had less than 10,000 m^2. The school buildings with a heated floor area of more than 10,000 m^2 were all secondary schools. Surprisingly, there isn’t a significant linear correlation between the heat consumption and the building size for the analyzed sample. A significant decreasing correlation was expected as it is typical for very large buildings to have a lower A/V ratio compared to small primary schools with only a few 100 m^2 of heated area. This, however, could not be confirmed and, as a result of this, other construction characteristics are more important than A/V ratio.

3.4. Electricity consumption

We measured the electricity consumption of 64 buildings separately. The arithmetical mean value is 32 kWh/(m²a) ± 15 kWh/(m²a) (or ±47 %) and, of course, is lower than the thermal consumption of the same group of buildings. The positive linear correlation between the year of construction and electricity consumption shows an increase in consumption during recent years – an effect which is of high importance. The distribution resulting from this is more or less a standard normal distribution (Fig. 6) and the “Students t-distribution” can again be used. The mean population figures of newer educational buildings in Luxembourg can be evaluated within a range of 32 ± 3 kWh/(m²a) and a probability of 95 %.

However, the resulting large standard deviation is a consequence of the buildings’ various technical installations. The school (No. 3, Fig. 7) with the lowest consumption (6 kWh/(m²a)) is a primary school without special areas such as a gym or a canteen – a passive building with a ventilation system operating only temporarily during the breaks or after classes to improve the air quality for the following lesson. The consumption values linked to this system could not be measured separately. In addition, a very energy-efficient lighting system with presence detectors and daylight sensors was installed to reduce electricity consumption. The two buildings (No. 33 and No. 14, Fig. 7) presenting a consumption value of more than 70 kWh/(m²a) are primary schools with an in-house “Maison Relais” (daycare center). These buildings have an energy-consuming kitchen with rated power requirements of several kW. It was not possible to conduct a separate energy monitoring of the energy consumption in the kitchen.

Insufficient energy monitoring was a main problem encountered in the field study. For example, the consumption of several buildings with different types of usage was measured using the same meter, which makes an accurate analysis very difficult. Often, there was a canteen or a gym integrated into a school building and the total consumption counted on a single meter. As already mentioned, a British study of school buildings determined that energy consumption in schools providing catering increased by 7-10 %, whereas the energy consumption can increase up to 20 % if the school premises include a gym [10]. Especially the electricity consumption varies more if the school has a large canteen kitchen (Fig. 7). To assess the impact of large kitchens and to estimate the electricity consumption of these kitchens in each building, we had to know the annual number of meals prepared here. According to a Swiss study [11], there are 2.3 to 3.1 kWh required to cook a hot meal in a canteen kitchen. However, Rohatsch [12] published values ranging from 0.7 to 0.8 kWh/meal. The detailed analysis of a Luxembourg school verified the performance of installed kitchen equipment and the average operating times. As a result, a mean energy consumption of approximately 1.5 kWh/meal was estimated for schools which use their canteens only during lunchtime. This value seems realistic and ranges between the reference values found in literature [11], [12]. Knowing the annual number of meals cooked and the average energy consumption per meal, we were able to calculate the energy use of each canteen. After an adjustment regarding the electricity consumption of the whole building, a new mean value of 26 kWh/(m^2a) for those school buildings with a large kitchen was calculated, which corresponds more to the arithmetical mean of all the no-kitchen buildings (29 kWh/m^2a, Fig. 7). Finally, as a result of the present study, the mean electricity consumption of schools providing catering and/or a gym can be increased by 10 kWh/m^2a (35 %) compared to smaller buildings with no kitchen.

3.5. Primary energy consumption

The primary energy consumption can be calculated with help of national conversion factors, which are slightly different in each country. The primary energy factors for Luxembourg are documented in the new Luxembourg Regulation [4] for non-residential buildings. The various factors vary significantly, depending on the energy sources used for heating. Thus, some buildings may show an advantage concerning the primary energy balance which is simply due to the fact that another energy source is used. Therefore, we used unit factors ($e_{p,heat}$=1.1, $e_{p,elec}$=2.66) for the primary energy analysis in order to determine the building's energy standard regardless of the energy vector. Yet, the present study shows quite significant variations in primary energy consumption, ranging from 47 kWh/(m²a) to as much as 320 kWh/(m²a) (Fig. 8). Especially in buildings with exceptionally high electricity consumption, such as No. 14 and 34 (a passive and a low-energy building with a daycare center and primary energy consumptions >250 kWh/m^{2}a), the negative effect of uncontrolled electricity use is noticeable. Nowadays, total primary energy consumptions in educational buildings of around 100 kWh/m²a are feasible, as is shown in Figure 8. This value corresponds to the German Passive House Institute's [14] limit for green [13] as well as passive buildings. With this in mind, the results of our study are disappointing because most Luxembourg school buildings consume a lot more primary energy. Only 7 out of 64 of the buildings surveyed met this threshold more or less. On the other hand, 33 % of all schools needed less than 150 kWh/(m^{2}a) of primary energy which is a positive trend.

Astonishingly, the different types of usage (preschools, primary or secondary schools) do not influence the average values (Fig. 9). Both buildings with a primary energy consumption of less than 100 kWh/(m²a) are primary schools. In contrast, consumption values of less than 150 kWh/(m²a) could be found in all building groups. This illustrates that the type of usage is not a significant parameter but rather the building itself and its respective energy standard. Figure 10 shows the problem of new passive or low-energy standards. The thermal end energy consumption decreases significantly as shown in Figure 3, but at the same time the electricity consumption goes up due to the increasing technical facilities, e.g. mechanical ventilation systems. As a result, the positive effect of passive and low-energy buildings compared to standard buildings is not as significant as assumed. Furthermore, only one passive and one low-energy building meet the reference values as defined in the funding guidelines [9].

Readers should note that the threshold values defined in the funding guidelines consider only the electricity use for HVAC and lighting while the values (Fig. 10) measured include the total electricity consumption of the building.

4 Regression analysis

In addition to the other tests, a multiple regression analysis [15] was conducted in order to find out which of the analyzed factors have the most significant impact on a building's energy consumption. We verified all parameters in correlation with each other and assessed their impact on total energy consumption. At the beginning of the project we had to sample all relevant parameters of all objects as precisely as possible. For the present analysis, the variables which are shown in Table 1 were defined.

In the simplest case it is assumed that the general multiple regression model is linear. There are j independent variables (predictors) and the dependent variable y can be written as:

$$y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \dots + b_j x_{ij} + \varepsilon_i \quad (2)$$

Where:	b_j	regression parameters (estimated)
	ε_i	residuals
	x_{ij}	independent variables / predictors (Table 1)
	y_i	dependent variables (e.g. energy consumptions, Table 1)

The approach to assess the regression parameters is based on the "least squares method". The difference between the empirical and assessed value is to minimize:

$$\sum_{i=1}^{N} \varepsilon_i^2 = \sum_{i=1}^{N} (y_i - \hat{y}_i)^2 = \sum_{i=1}^{N} \left(y_i - \sum_{j=0}^{p} b_j x_{ij}\right)^2 \rightarrow min. \quad (3)$$

where the used regression function was assumed as following:

$$\hat{y}_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \dots + b_j x_{ij} \quad (4)$$

The equation was transformed in a matrix form to calculate the regression parameters b_j.

$$\underline{Y} = \mathbf{X}\,\underline{\beta} + \underline{e} \quad (5)$$

Where: $\underline{\beta} = \begin{bmatrix} b_1 \\ \vdots \\ b_j \end{bmatrix}$ regression parameters b_j

$\underline{e} = \begin{bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_i \end{bmatrix}$ residuals = $(y_i - \hat{y}_i)$, real minus calculated consumptions

$\boldsymbol{X} = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{bmatrix}$ defined independent variables, s. Table 1

$\underline{Y} = \begin{bmatrix} y_1 \\ \vdots \\ y_i \end{bmatrix}$ dependent variables (e.g. energy consumptions), s. Table 1

The derivative of Eq. (5) with respect to β has to be minimized [16] and leads to:

$$\beta = (\mathbf{X}^{\mathbf{T}}\,\mathbf{X})^{-1}\mathbf{X}^{\mathbf{T}}\mathrm{Y} \qquad (6)$$

where $(\mathbf{X}^{\mathbf{T}}\,\mathbf{X})$ is the covariance matrix.

The next step was to analyze how good the model characterizes the real values of the sample. The examination of the calculated coefficient of determination R^2 and the corresponding level of significance P[1] are used to evaluate the best multiple regression model. The level of significance (= error of probability) P checks the calculated correlation coefficients (Table 2) between the dependent (y_i) and independent variables (x_j) with the help of the t-distribution and the so called t-test. The coefficient of determination R^2 (= R*R in case of only one predictor x_j) specifies the part of variance which can be explained by the chosen number of predictors x_j.

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \qquad (7)$$

Where:

$\sum(y_i - \hat{y}_i)^2$ sum of squares of residuals (= part of the variability not explained by the model)

[1] Level of significance/ Error of probability

	P ≤ 0,1 %	high significant (***)
	0,1 % < P ≤ 1,0 %	very significant (**)
	1,0 % < P ≤ 5,0 %	significant (*)
	P > 5,0 %	not significant (n.s.)

$\sum(y_i - \bar{y})^2$ total sum of squares (real individual consumptions minus mean consumption)

An F-test checks if any additional predictor xj helps to improve the part of variance to be explained probabilistically. The final aim is to reduce the number of independent variables x_j to a minimum and to use these to explain a maximum part of variance. For the present study the defined explanatory independent variables and the corresponding values are shown in Table 1. The sample size varies from 58 to 62 educational buildings, because the buildings were only used if all analyzed characteristics were known.

The outputs of the used software tool SPSS show a highly significant single correlation (s. Table 2) when comparing the thermal consumption with the year of construction (x_1) and the energy standard (x_2), which is based on the fact that there is a significant linear correlation between both of these predictors x_1 and x_2. In our case, this was the result of enacting the regulation [9] described above. The very strong correlation between thermal consumption (y_1) and the energy source (x_6) could already be assumed after analyzing the values in Figure 2. All buildings with low energy consumption figures were supplied with district heat in contrast to the inefficient buildings heated with fuel oil boilers. The fact that the buildings were also used for other purposes (x_4) is the only significant independent variable with respect to the electricity consumption (y_2) (s. Table 2). This is not surprising as, above all, the canteen kitchens have a measurable impact of 10 kWh/m^{2}a on average on the electricity consumption of the building referred to in Section 2.4.

The analysis of thermal end energy consumption results in a model with an explanatory percentage of variance of R^2 = 53 %. The calculated coefficient "b_i" of the best fit model to predict the heating energy consumption (y_1) of new schools on the basis of the regression model gives the final regression equation with the independent variables "energy standard" (x_2), "type of use" (x_3) and "energy source" (x_6) (s. Table 3). The following F-Test shows a very high significance, whereas adding of a further independent variable will stop the forward multiple regression as the limit value of significance (P = 5.0 %) will be exceeded and the model with more independent variables will not explain a higher proportion of variance. Therefore the variables “heated gross area” (x_5), “year of construction” (x_1) and “canteen kitchen” (x_4) were excluded.

In summary, the multiple regression analysis shows the same results as expected and couldn’t provide new evidence. The collection of more independent variables like the detailed wall constructions, the installed lighting power or the annual hours of artificial lighting usage (installation of daylight sensors and presence detectors) will perhaps improve the results and also the percentage of variability explained above. The final regression model can help assess the energy consumptions of a new school building in Luxembourg. For instance, a passive school building’s thermal end energy consumption ($x_2 = x_3 = x_6 = 0$) can be assessed with a 95%-confidence interval at 24-65 kWh/m^{2}a, using the estimated regression parameters (s. Table 3), which seems realistic.

5 Conclusion

In the building sector, school buildings make up one of the larger building groups and are significant energy consumers – on a par with residential and office buildings – in Luxembourg. Nowadays, thermal end energy consumption is no longer the main problem as far as primary energy use in a newer building is concerned. The heating demand can be reduced through better airtightness and high wall insulation achieved with relatively simple and widely available constructive solutions. Likewise, there is still enough heat-saving potential as a consequence of the building design, as the extreme range of values presented in Figure 2 illustrates. As a consequence, approximately 17 GWh/a of heating energy can be saved in new school buildings in Luxembourg if the calculated average of 93 kWh/(m^{2}a) is compared to the best figures attaining only 50 kWh/(m^{2}a) and multiplied with the total heated floor size of 400,000 m^2. This results in a saving potential of 1 % of the national annual fuel oil and gas consumption [3] in the tertiary sector (excluding households).

In contrast, the mean electricity consumption has increased in the newer buildings as a result of the presence of canteen kitchens, the use of PCs (>100 W per PC) and video projectors (>300 W per projector) during lessons or the use of mechanical ventilation systems in new low-energy and passive schools. These factors compensate partially for the lower lighting power used in newer buildings as well as the possible thermal savings under the new energy standards. This is a very negative trend in view of primary energy consumption, which is also proven in comparison with international studies. Newer buildings in Luxembourg consume more primary energy than older school buildings in other European countries (Fig. 11). European electricity consumptions vary between 10 to 30 kWh/(m²a) (see [16] to [24]). In older school buildings abroad, lighting is usually the main consumer, whereas the more energy-efficient lighting used in the newer educational buildings in Luxembourg cannot compensate for the rising consumption of building equipment described above. Table 4 gives an overview of the main benchmarks[2] of newer buildings in Luxembourg from the three main building groups previously mentioned. Passive and low-energy schools save a noticeable level of thermal end energy (up to 70 %) compared to standard buildings. The rising electricity consumption minimizes however the positive effect of the new building design, and the average primary energy saving potential measured achieves only 17 to 37 %. Furthermore, the most energy-efficient Luxembourg school buildings consume 50 % less primary energy than the mean value of all new school buildings. These promising results show that saving energy is possible and that there is still an enormous energy saving potential in the building sector.

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Figure Captions

Fig. 1: Quantities of school buildings collected in Luxembourg

Fig. 2: Thermal end energy consumptions (including domestic hot water supply) of new educational buildings in Luxembourg – District heat consumption increased by estimated generation losses (+10 %)

Fig. 3: Thermal end energy consumptions of new educational buildings in Luxembourg sorted by energy standards

Fig. 4: Frequency distribution of thermal end energy consumptions of new educational buildings in Luxembourg – District heat consumption increased by estimated generation losses (+10 %)

Fig. 5: Thermal end energy consumptions of new educational buildings in Luxembourg depend on the heated gross area

Fig. 6: Frequency distribution of electricity consumptions of new educational buildings in Luxembourg

Fig. 7: Electricity consumptions of new educational buildings in Luxembourg with or without canteen kitchens

Fig. 8: Primary energy consumptions of new educational buildings with constant primary factors of electricity (e_p = 2,66) and heat (e_p = 1,1)

Fig. 9: Primary energy consumptions of new educational buildings depend on the type of use

Fig. 10: Primary energy consumptions of new educational buildings in Luxembourg sorted by energy standards

Fig. 11: International comparison of primary energy consumptions of school buildings and gyms – heat e_p = 1.1 and electricity e_p = 2.66 [11], [17]-[25]

Tables

Independent variables of educational buildings				**Dependent variables** of educational buildings		
Variables / Values			Label / Unit	Variable		Unit
Year of construction	x_1	[20xx]	Year of construction	Thermal end energy consumption (district heat +10%)	y_1	[kWh/m²a]
Energy standard	x_2	0	Passive buildings			
		1	Low-energy buildings			
		2	Standard buildings			
Type of use	x_3	0	Preschools, primary schools	Electricity consumption	y_2	[kWh/m²a]
		1	Secondary schools / high schools			
Canteen kitchen	x_4	0	No canteen kitchen	Primary energy consumption ($e_{p,heat}$ = 1,1 or $e_{p,electricity}$= 2.66)	y_3	[kWh/m²a]
		1	Additional canteen kitchen			
Heated gross area	x_5	[xxxx]	Heated gross area [m²]			
Energy source	x_6	0	No fuel			
		1	Fuel			

Tab. 1: Independent and dependent variables defined for school buildings

Linear correlation coefficients R between dependent (y_i) and independent (x_i) variables							
		Year of construction x_1	Energy standard x_2	Type of use x_3	Canteen kitchen x_4	Heated gross area [m²] x_5	Energy source x_6
Thermal end energy consumption (district heat +10%)	y_1	-0.46***	0.52***	-0.28*	-0.09 (n.s.)	-0.11 (n.s.)	0.52***
Electricity consumption	y_2	0.20 (n.s.)	-0.14 (n.s.)	0.21 (n.s.)	0.32*	0.12 (n.s.)	Not analyzed
Primary energy consumption ($e_{p,heat}$ = 1,1 or $e_{p,electricity}$ = 2,66)	y_3	-0.23*	0.33**	-0.09 (n.s.)	0.15 (n.s.)	-0.01 (n.s.)	Not analyzed

Tab. 2: Linear correlation coefficients R between dependent and independent variables

Model		Regression parameters	95 % - Confidence interval for b_j	
		b_j	Lower bound	Upper bound
(Constant)	b_0	45	24	65
Energy standard	b_2	33	20	45
Energy source	b_6	43	20	66
Type of use	b_3	-39	-59	-18

Tab. 3: Multiple regression parameters of the best model to assess the thermal end energy consumption of new educational buildings in Luxembourg

Building categories	Number of buildings	Average thermal end energy [kWh/(m²a)]	Average electricity consumption [kWh/(m²a)]	Primary energy consumption [kWh/(m²a)] Heat (e_p = 1,1), Electricity (e_p = 2,66)	Primary energy saving potential
Single family houses [7]					
• Standard	54	130 ± 32	25	210	
• Low-energy	13	75	20	135	**35 %**
• Passive	5	0	35	93	**55 %**
Educational buildings					
• Standard	41	115 ± 43	30 ± 13	205	
• Low-energy	21	70 ± 29	35 ± 16	170	**17 %**
• Passive	6	35 ± 20	35 ± 24	135	**35 %**
Offices [26]					
• Administration	19	100 ± 42	95 ± 62	365	
• Financial sector	25	150 ± 67	240 ± 104	800	

Tab. 4: Benchmarks of different building categories in Luxembourg with year of construction after 1996

Figure 1

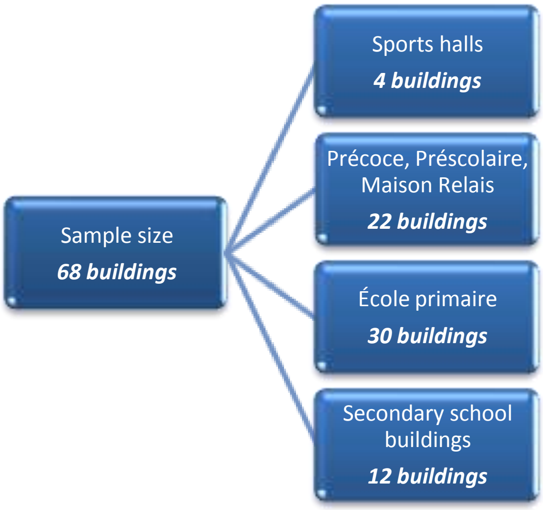
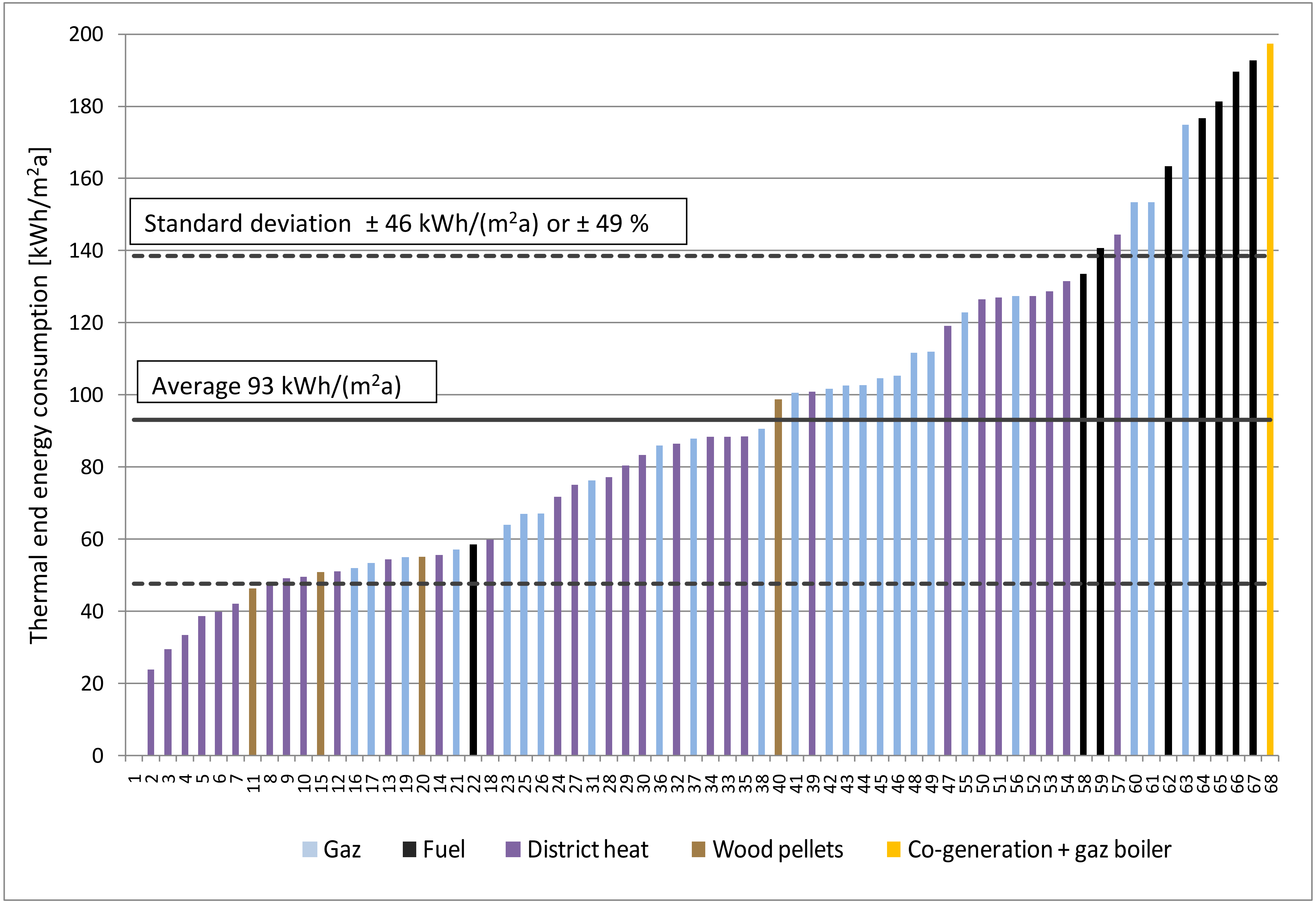
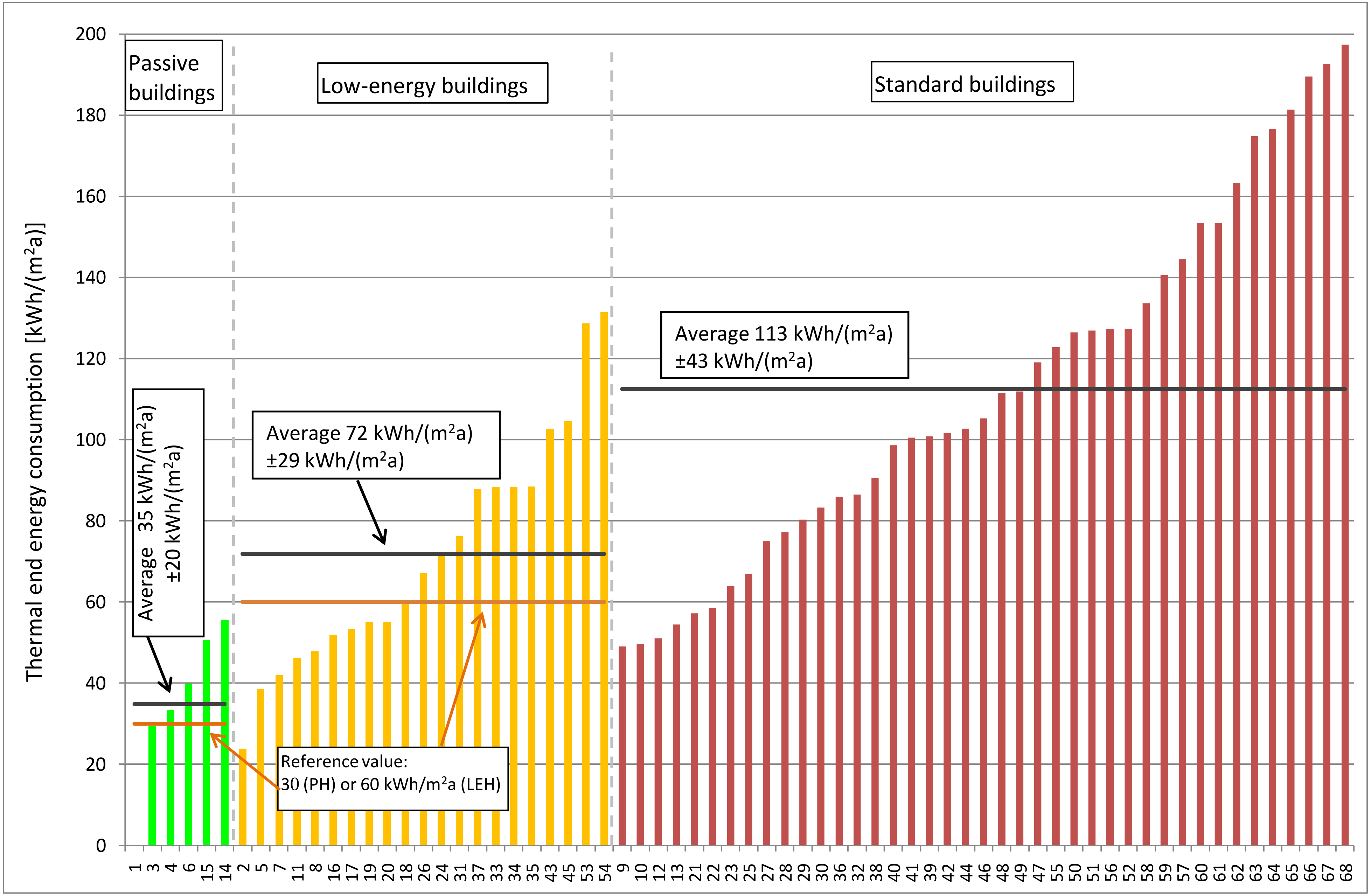

Sample size
68 buildings
Sports halls
4 buildings
Précoce, Préscolaire, Maison Relais
22 buildings
École primaire
30 buildings
Secondary school buildings
12 buildings

Figure 2



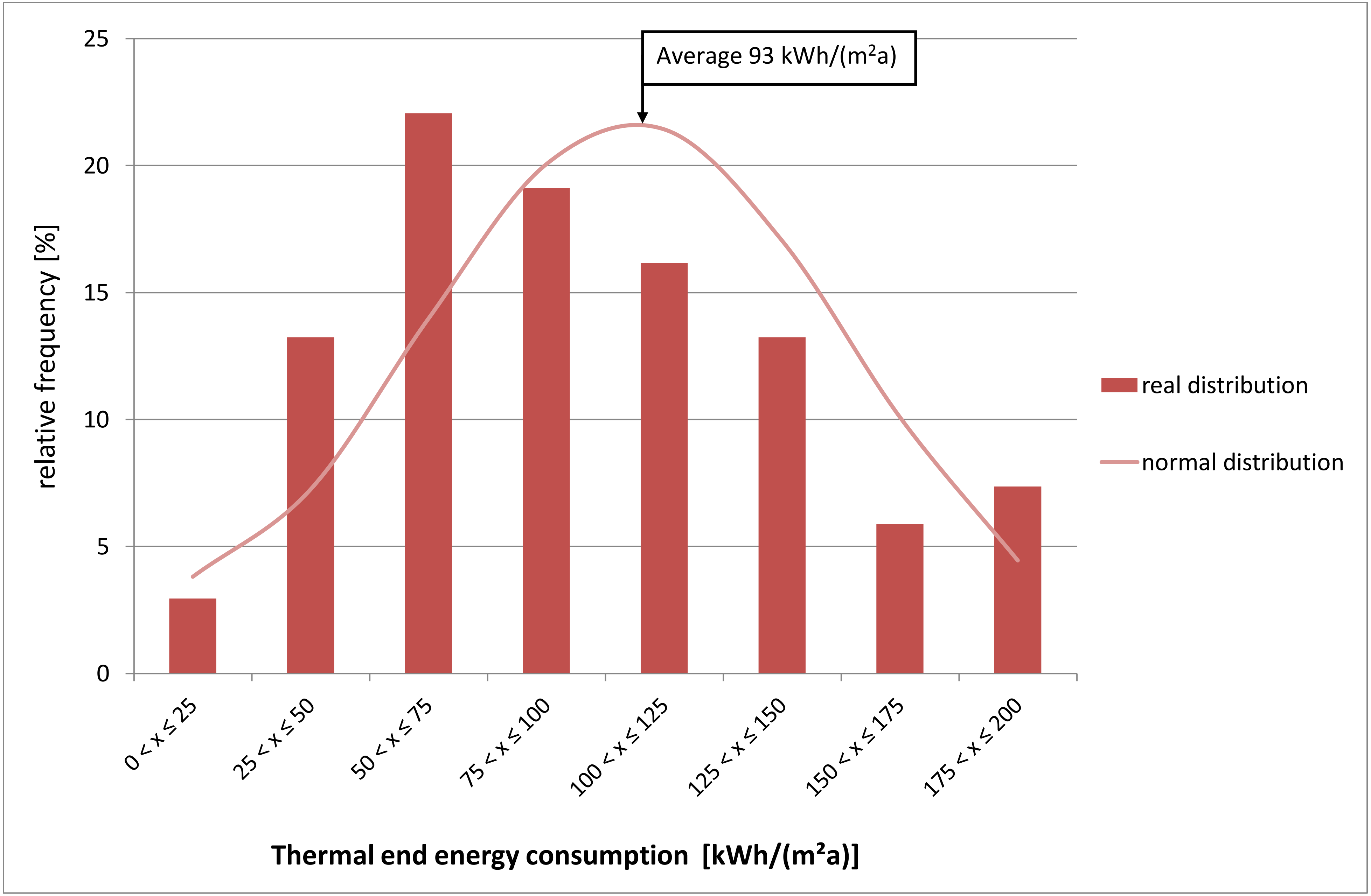
Thermal end energy consumption [kWh/(m²a)]
200
180
160
140
120
100
80
60
40
20
0
Standard deviation ± 46 kWh/(m²a) or ± 49 %
Average 93 kWh/(m²a)
1 2 3 4 5 6 7 11 8 9 10 15 12 16 17 13 19 20 14 21 22 18 23 25 26 24 27 31 28 29 30 36 32 37 34 33 35 38 40 41 39 42 43 44 45 46 48 49 47 55 50 51 56 52 53 54 58 59 57 60 61 62 63 64 65 66 67 68
Gaz
Fuel
District heat
Wood pellets
Co-generation + gaz boiler

Figure 3



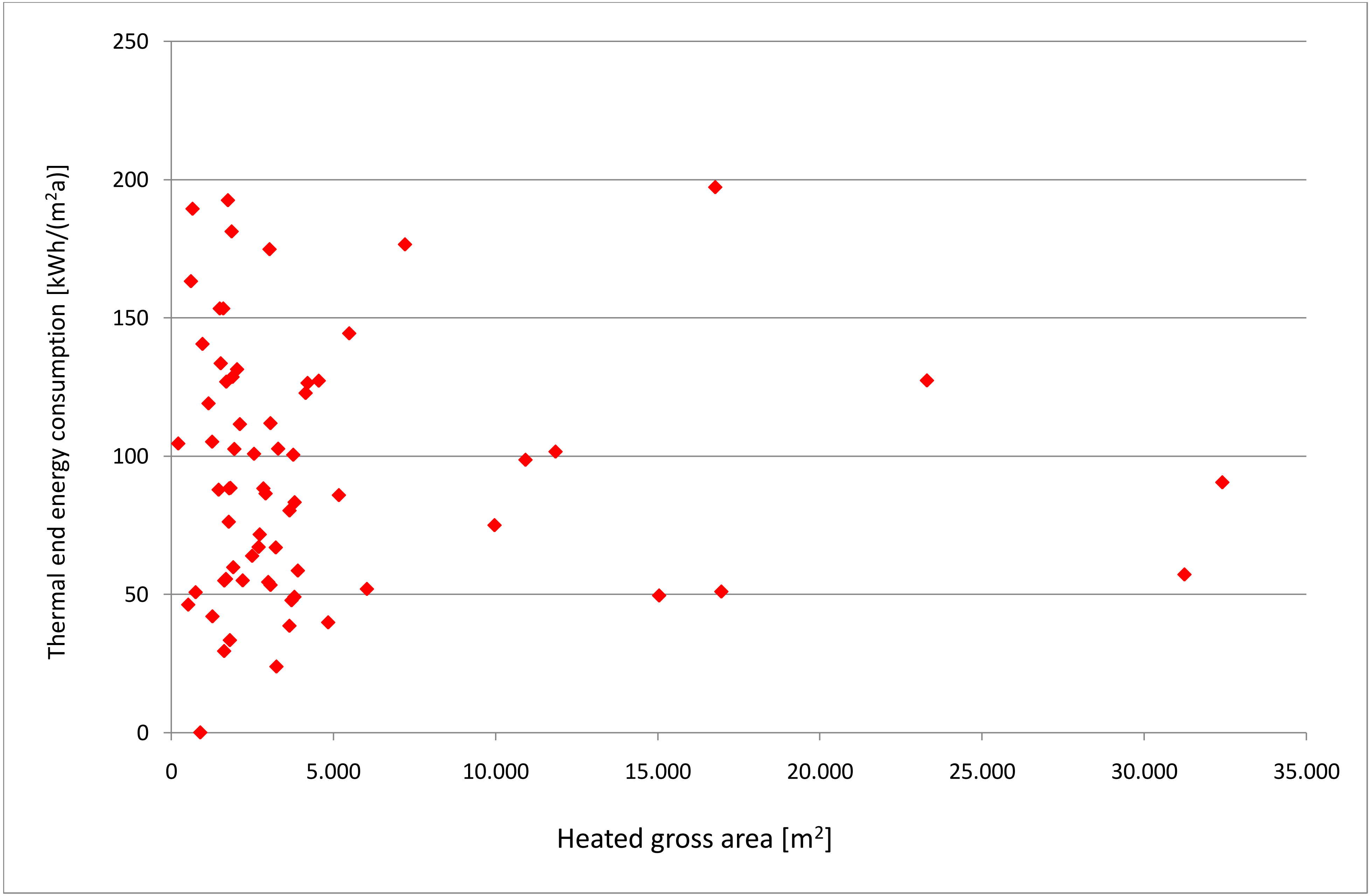
Thermal end energy consumption [kWh/(m²a)]
200
180
160
140
120
100
80
60
40
20
0
Passive buildings
Low-energy buildings
Standard buildings
Average 35 kWh/(m²a) ±20 kWh/(m²a)
Average 72 kWh/(m²a) ±29 kWh/(m²a)
Average 113 kWh/(m²a) ±43 kWh/(m²a)
Reference value: 30 (PH) or 60 kWh/m²a (LEH)
1 3 4 6 15 14 2 5 7 11 8 16 17 19 20 18 26 24 31 37 33 34 35 43 45 53 54 9 10 12 13 21 22 23 25 27 28 29 30 36 32 38 40 41 39 42 44 46 48 49 47 55 50 51 56 52 58 59 57 60 61 62 63 64 65 66 67 68

Figure 4



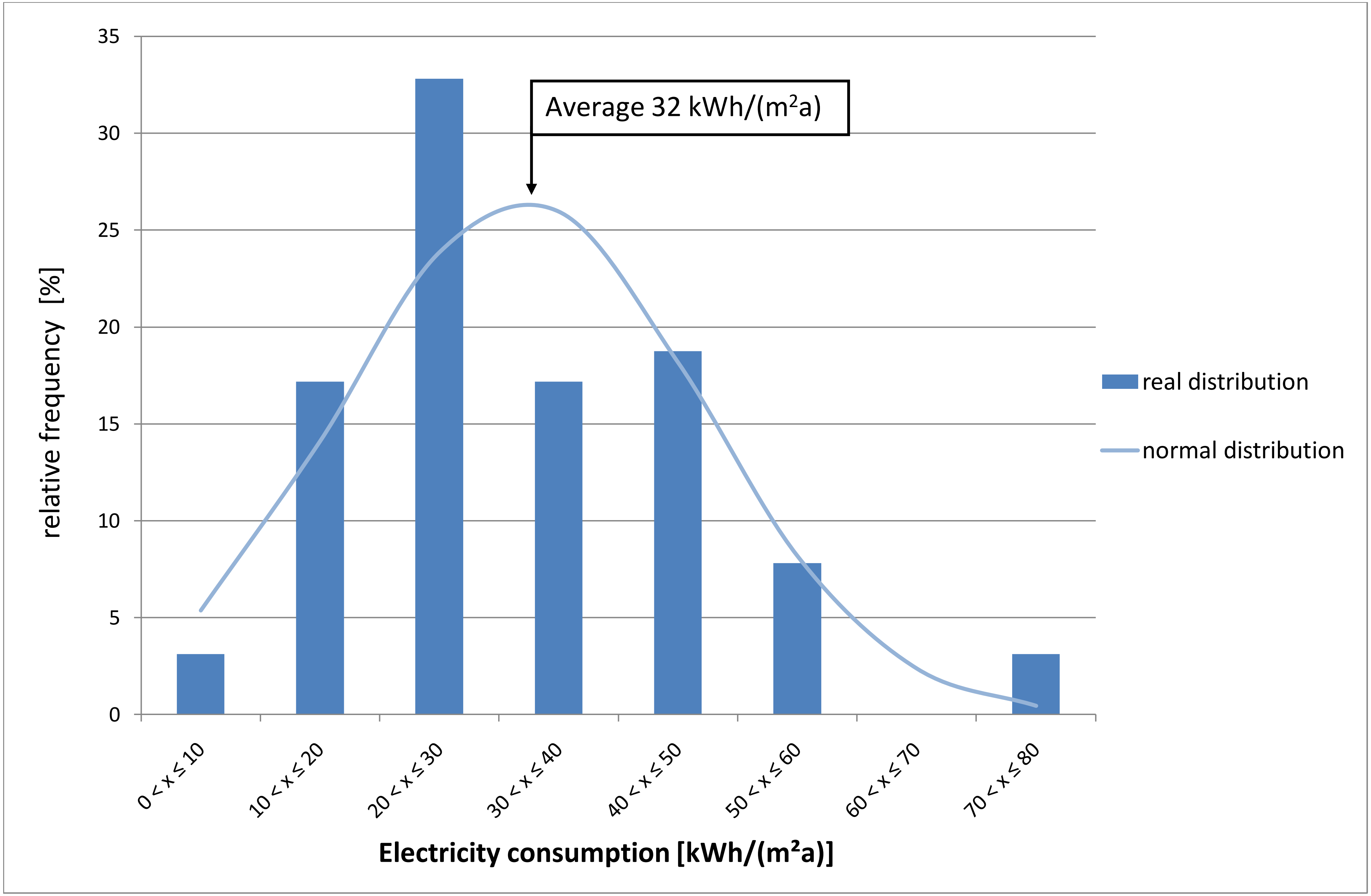
Average 93 kWh/(m²a)
relative frequency [%]
25
20
15
10
5
0
0 < x ≤ 25
25 < x ≤ 50
50 < x ≤ 75
75 < x ≤ 100
100 < x ≤ 125
125 < x ≤ 150
150 < x ≤ 175
175 < x ≤ 200
real distribution
normal distribution
Thermal end energy consumption [kWh/(m²a)]

Figure 5



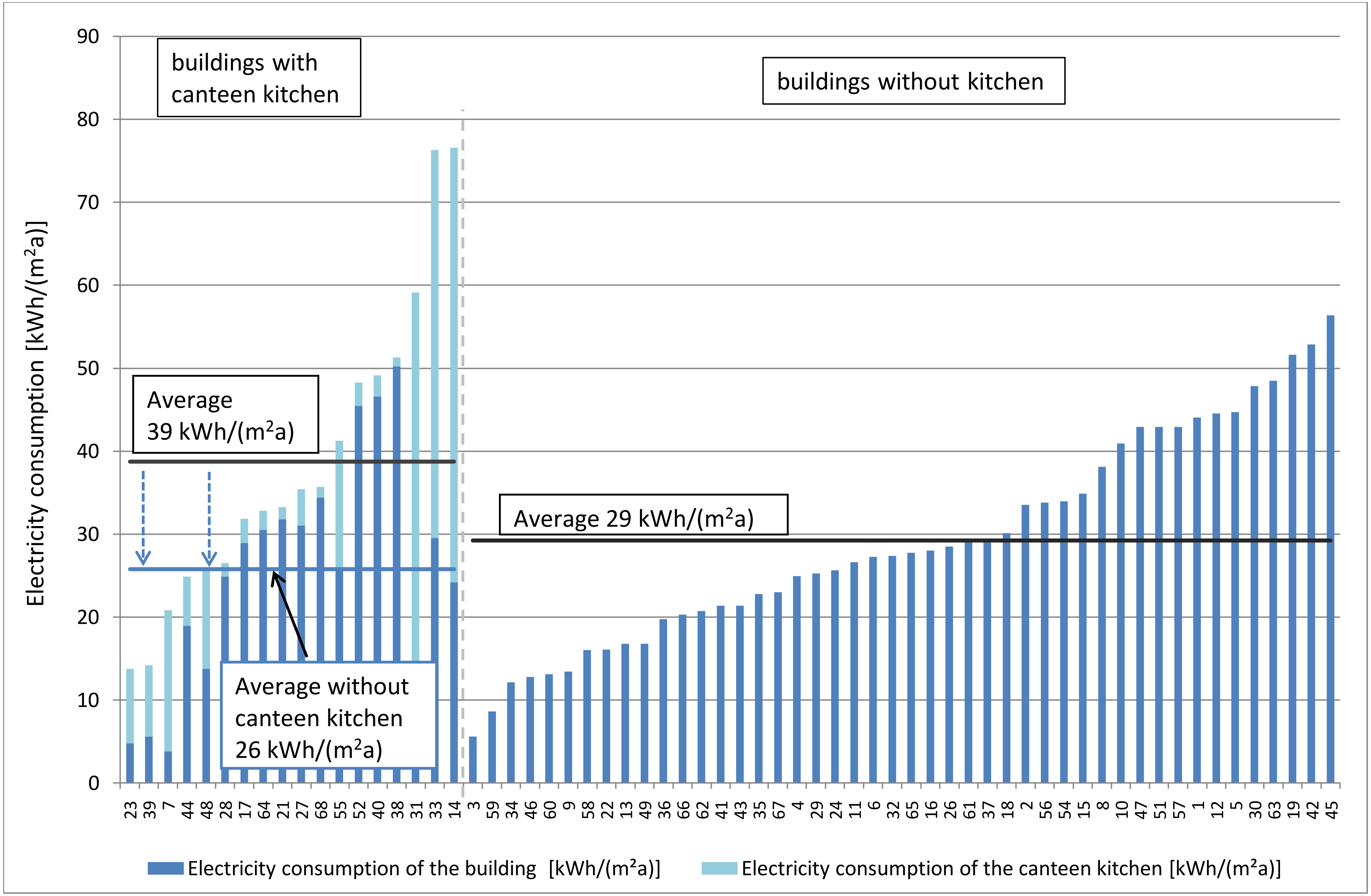
250
200
150
100
50
0
0
5.000
10.000
15.000
20.000
25.000
30.000
35.000
Thermal end energy consumption [kWh/(m²a)]
Heated gross area [m²]

Figure 6



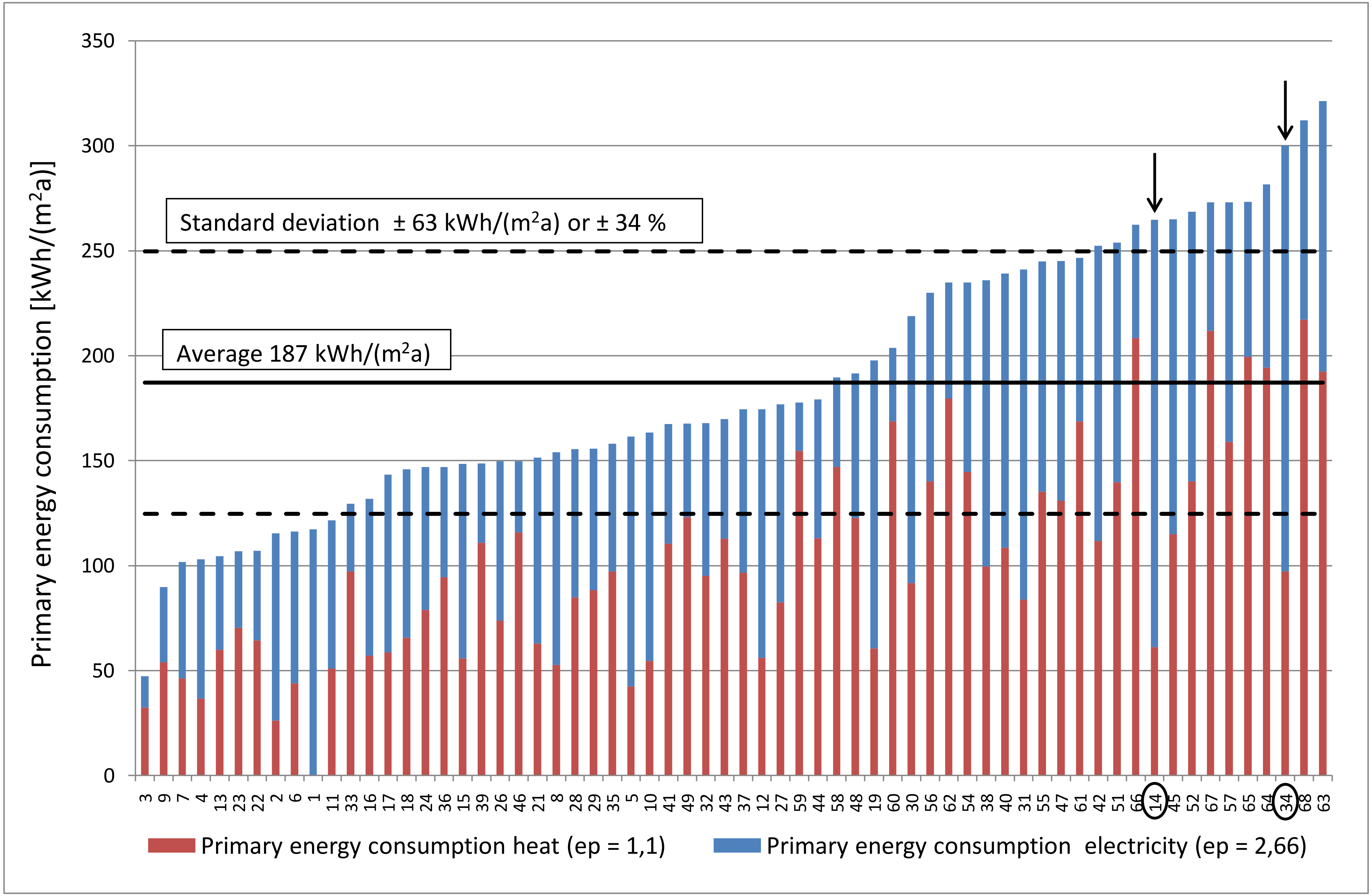
Average 32 kWh/(m²a)
relative frequency [%]
35
30
25
20
15
10
5
0
0 < x ≤ 10
10 < x ≤ 20
20 < x ≤ 30
30 < x ≤ 40
40 < x ≤ 50
50 < x ≤ 60
60 < x ≤ 70
70 < x ≤ 80
Electricity consumption [kWh/(m²a)]
real distribution
normal distribution

Figure 7



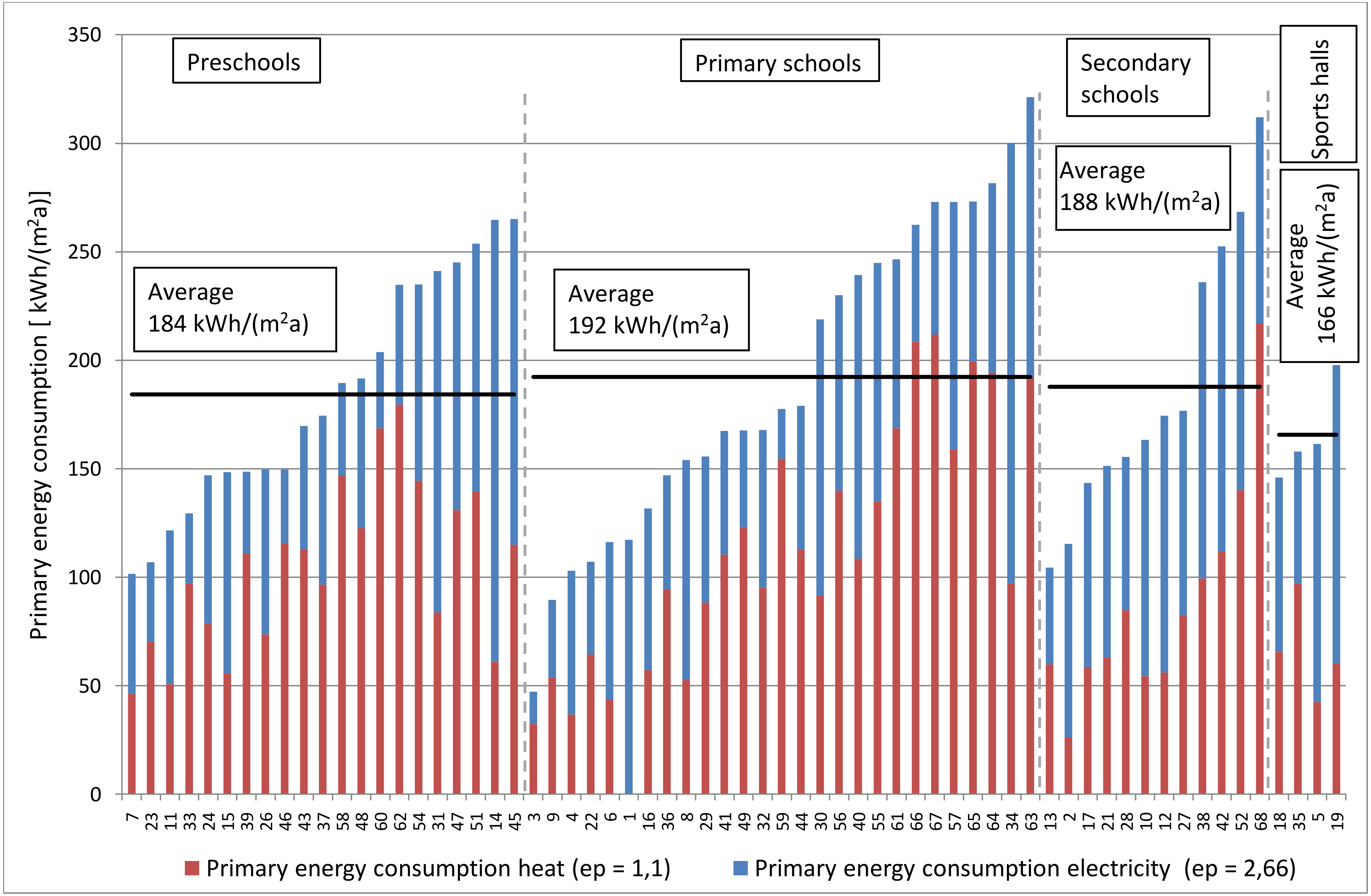
buildings with canteen kitchen
buildings without kitchen
Average 39 kWh/(m²a)
Average 29 kWh/(m²a)
Average without canteen kitchen 26 kWh/(m²a)
Electricity consumption [kWh/(m²a)]
90
80
70
60
50
40
30
20
10
0
23 39 7 44 48 28 17 64 21 27 68 55 52 40 38 31 33 14 3 59 34 46 60 9 58 22 13 49 36 66 62 41 43 35 67 4 29 24 11 6 32 65 16 26 61 37 18 2 56 54 15 8 10 47 51 57 1 12 5 30 63 19 42 45
Electricity consumption of the building [kWh/(m²a)]
Electricity consumption of the canteen kitchen [kWh/(m²a)]

Figure 8



Primary energy consumption [kWh/(m²a)]
350
300
250
200
150
100
50
0
Standard deviation ± 63 kWh/(m²a) or ± 34 %
Average 187 kWh/(m²a)
3 9 7 4 13 23 22 2 6 1 11 33 16 17 18 24 36 15 39 26 46 21 8 28 29 35 5 10 41 49 32 43 37 12 27 59 44 58 48 19 60 30 56 62 54 38 40 31 55 47 61 42 51 66 14 45 52 67 57 65 64 34 68 63
Primary energy consumption heat (ep = 1,1)
Primary energy consumption electricity (ep = 2,66)

Figure 9



Preschools
Primary schools
Secondary schools
Sports halls
Average 184 kWh/(m²a)
Average 192 kWh/(m²a)
Average 188 kWh/(m²a)
Average 166 kWh/(m²a)
Primary energy consumption [kWh/(m²a)]
0
50
100
150
200
250
300
350
7 23 11 33 24 15 39 26 46 43 37 58 48 60 62 54 31 47 51 14 45 3 9 4 22 6 1 16 36 8 29 41 49 32 59 44 30 56 40 55 61 66 67 57 65 64 34 63 13 2 17 21 28 10 12 27 38 42 52 68 18 35 5 19
Primary energy consumption heat (ep = 1,1)
Primary energy consumption electricity (ep = 2,66)

Figure 10

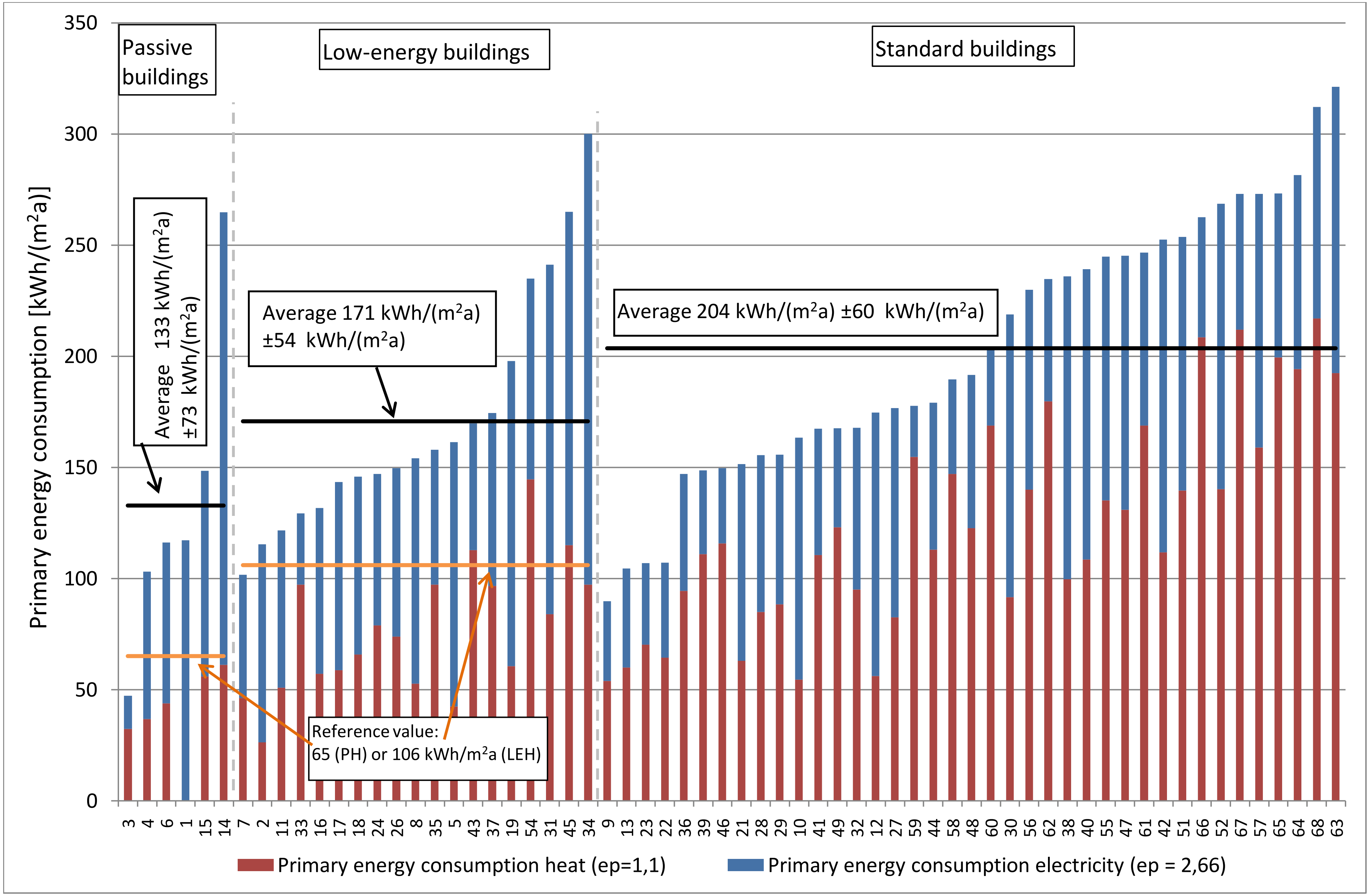
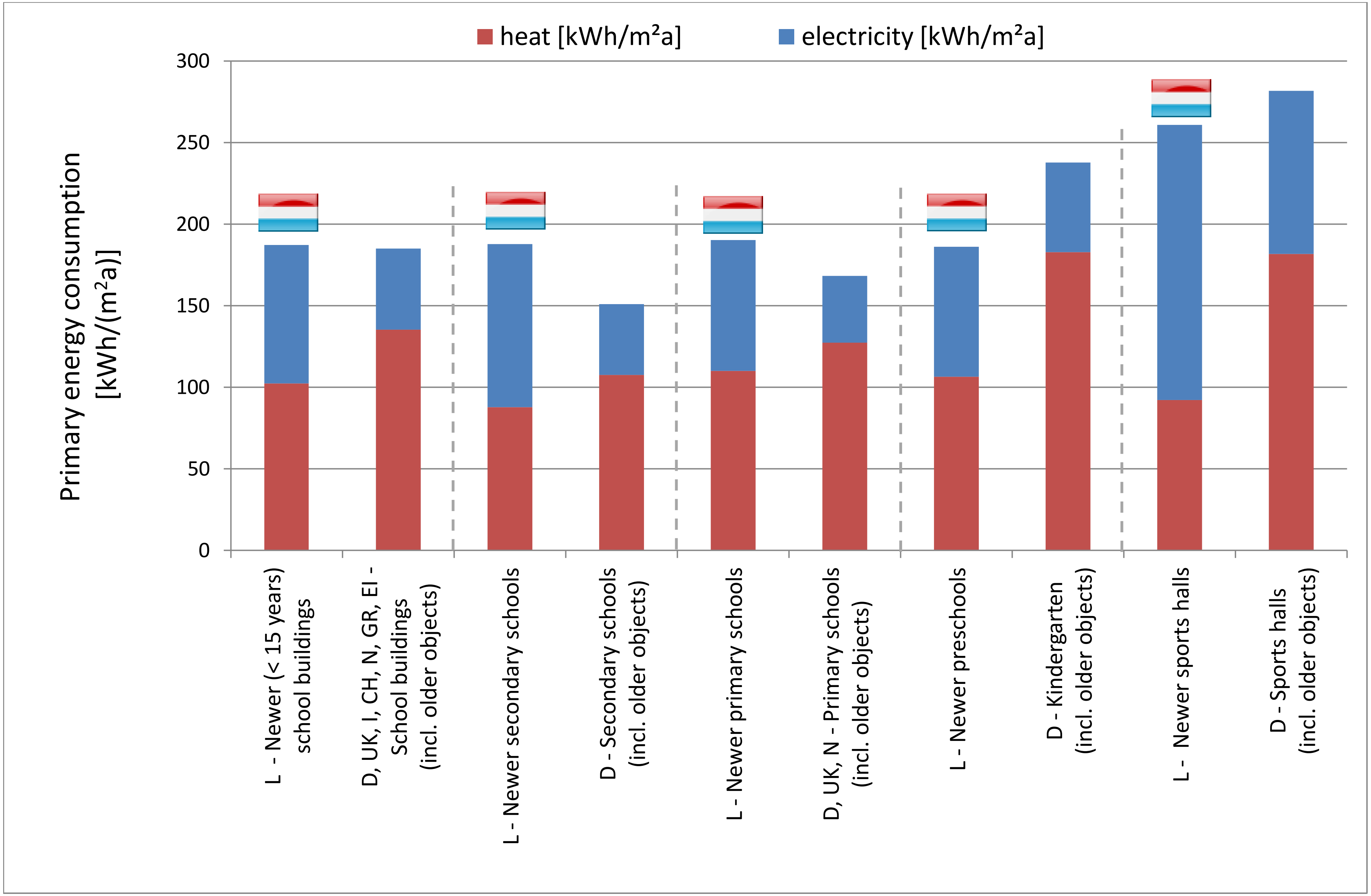

Passive buildings
Low-energy buildings
Standard buildings
Average 133 kWh/(m²a) ±73 kWh/(m²a)
Average 171 kWh/(m²a) ±54 kWh/(m²a)
Average 204 kWh/(m²a) ±60 kWh/(m²a)
Reference value: 65 (PH) or 106 kWh/m²a (LEH)
Primary energy consumption [kWh/(m²a)]
350
300
250
200
150
100
50
0
3 4 6 1 15 14 7 2 11 33 16 17 18 24 26 8 35 5 43 37 19 54 31 45 34 9 13 23 22 36 39 46 21 28 29 10 41 49 32 12 27 59 44 58 48 60 30 56 62 38 40 55 47 61 42 51 66 52 67 57 65 64 68 63
Primary energy consumption heat (ep=1,1)
Primary energy consumption electricity (ep = 2,66)

Figure 11



heat [kWh/m²a]
electricity [kWh/m²a]
Primary energy consumption
[kWh/(m²a)]
300
250
200
150
100
50
0
L - Newer (< 15 years) school buildings
D, UK, I, CH, N, GR, EI - School buildings (incl. older objects)
L - Newer secondary schools
D - Secondary schools (incl. older objects)
L - Newer primary schools
D, UK, N - Primary schools (incl. older objects)
L - Newer preschools
D - Kindergarten (incl. older objects)
L - Newer sports halls
D - Sports halls (incl. older objects)

HIGHLIGHTS

- New schools in LU use more primary energy than older schools in other EU countries
- Passive (PH) and low-energy (LEH) schools consume up to 70 % less thermal energy
- But passive and low-energy school buildings consume approx. 20 % more electricity
- Real thermal consumptions of (PH) and (LEH) exceed the reference figures by 20%