Energy Consumption of non-retrofitted institutional building stock in Luxembourg and the potential for cost-efficient retrofit

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Abstract

The public building stock of a country, consisting of schools, offices, accommodation facilities, single- and multi-family homes, accounts for a high consumption of electrical and heat energy. Therefore, this stock is often object to actions with the goal of lowering this energy usage by increasing the efficiency of those buildings. This is usually done by applying measures to the building envelope like insulation and/or new windows and by using more efficient HVAC technology. But often, in the initial state, the current energy consumption of such a stock is unknown or only known for single buildings. In this case, the calculation of energy and costs savings is either impossible or not exact. This paper shows a way to quantify and categorize the end-energy for heat use of the public building stock in Luxembourg, which consists of 1,744 Mio. m^2 gross area, while the information about this stock was incomplete in the first place. This analysis was done in cooperation with the national administration of public buildings.

A certain amount of sample buildings was analyzed and then separated into three groups of low, normal and high end-energy use. The boundaries of these groups were chosen according to literature values, derived from European retrofit projects, which also served as the source for possible costs of renovations. This data was extrapolated to the whole stock. This information serves as a basis for future decisions concerning the retrofit of those buildings and makes a

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calculation of costs possible.

As a result, the type of buildings with the highest potential for retrofit measures was identified. Schools, offices and accommodation facilities with "high" consumption of more than 190 kWh/(m^2a) show the highest economic potential with retrofit costs of 0.04 to 0.08 EUR/kWh if their energy consumption is lowered to values around 90 to 100 kWh. Other groups of buildings show higher costs of around 0.07 to 0.19 EUR/kWh.

Keywords: Retroft, Public Building Stock, Retrofit Scenarios, Energy Efficiency

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1. Introduction

In the national energy efficiency plan of Luxembourg [1], retrofitting of old buildings plays an important role. Especially the big stock of institutional buildings, built before the first national energy regulation for buildings in 1995 [2], shows big potential to lower its energy consumption. The stock consists of single- and multi-family homes, schools, commercial buildings and accommodation facilities. In order to develop retrofit strategies, the consumed end-energy referring to heated gross area has to be captured and interpreted. Since there was no data concerning the heated gross area, the building age distribution and the energy demand available for those buildings, the analysis is based on a number of sample buildings, for which these parameters were either known or measured on site. With this data, an extrapolation towards the totality of the public buildings is achieved and an estimation of the condition of the public building stock in Luxembourg becomes possible. These values are compared to the results of a literature study of different European publications, in which the end-energy use of different building types and stocks are presented. In the following, all mentioned area data is defined as gross area (external). If there was another reference area used in the European studies, the values were translated according to available geometrical data in those studies. If only the net area was known, a factor of 1.25 was used to calculate the gross area.

2. Literature Study

Single- and multi-family homes. In a data collection of [3] it is shown, that in the class of buildings constructed in Germany between 1919 to 1978, the end-energy use of non-retrofitted single-family homes is more or less the same and the mean value is 195 kWh/(m^2a). After the oil crisis and the new German thermal insulation regulation in 1977 the mean value decreases to 144 kWh/(m^2a) in the period between 1979 to 1987, while newer buildings after 2002 consumed only 78 kWh/(m^2a). The same situation accounts for Luxembourg, where buildings up to 1970 show a mean value between 185 kWh/(m^2a) [4] and 195 kWh/(m^2a) [5]. Newer buildings after 2000 show lower values between 95 kWh/(m^2a) [5] and 122 kWh/(m^2a) [4]. Buildings, built after 2000 with focus on energy efficiency, showed even lower mean values of 73 kWh/(m^2a) [6]. Thus, by retrofitting, the saving potential for old buildings lies between 60 and 120 kWh/(m^2a). For multi-family homes the situation is similar. According to [3], buildings before 1978 which havent been retrofitted, show a mean end-energy consumption of 158 kWh/(m^2a). Residences in Slovenia [7], Switzerland and Denmark [8] show similar energy consumptions. Old buildings in France and the Netherlands show slightly higher mean values of around 210 kWh/(m^2a). In Luxembourg, multi-family homes until 1970 show values between 140 kWh/(m^2a) [5] and 151 kWh/(m^2a) [4]. Again, old buildings until 1970 did not show any decreases of the end-energy consumption throughout the construction years from 1918 to 1970. Newer buildings later than 2000 show mean values between 100 kWh/(m^2a) [4] and 128 kWh/(m^2a) [5]. In Germany, new multi-family homes after 2002 showed even lower values with a mean of 82 kWh/(m^2a) [3].

Commercial Buildings. There exist several databases in Germany about the end-energy use of commercial buildings, but without distinguishing between construction year. According to [9], the mean value across all building ages is 128 kWh/(m^2a) which corresponds to the mean value of the category low-technological buildings of another German study [10]. Bulgarian and Luxemburgish buildings show similar mean values around 130 kWh/(m^2a) [7], while the mean value for low-technological buildings in Luxembourg is 56 kWh/(m^2a) [11]. The more complex the technology in a building, the more likely is a consumption of electrical end-energy of more than 100 kWh/(m^2a) [12]. To lower the end-energy use of commercial buildings, it seems, that it is crucial to lower heating and cooling loads, while keeping the complexity of building technology as low as possible to avoid a substitution of heating energy with electrical energy, resulting in high primary energy values [10].

Schools. As for the commercial buildings, there exist several studies in Europa for the end-energy use of schools, unfortunately again not distinguishing between the construction years. Mean values of three studies in Germany vary widely. While the schools in [9] show a mean end-energy use for heat of 120 kWh/(m^2a), which is close to the mean values of new Luxembourgish schools of 113 kWh/(m^2a) [11], [13] calculates a value of 211 kWh/(m^2a) and [10] of 160 kWh/(m^2a). A British study showed a mean value of 175 kWh/(m^2a) [14]. Even if those values are mean values across all building ages, a saving potential between 45 and 100 kWh/(m^2a) compared to the level of new Luxembourgish schools can be assumed. Luxembourgish schools which were built according to the low-energy standard show an even lower mean value of 72 kWh/(m^2a) [10]. The end-energy consumption of electricity is fairly low compared to those of commercial buildings with values between 14 and 30 kWh/(m^2a) across all studies. Nonetheless, in the case of retrofitting it is recommended to keep the complexity of technology rather low, in order to avoid effects such as encountered in commercial buildings.

Accommodation facilities. According to five studies which include facilities like day-cares, nursing homes, dormitories and kindergartens, the mean value lies between 160 and 220 kWh/(m^2a) [15],[13],[16]. Again, no difference was made between older and newer facilities. In more recent studies [17], the mean value decreases to about 125 kWh/(m^2a), which is due to the higher share of modern buildings in the sample. The end-energy use of electricity was between 20 and 30 kWh/(m^2a) and is only small, compared to the end-energy for heat.

Costs for retrofit. If possible, the costs for a retrofit should be refinanced by the savings of energy costs. One way to lower the heat demand of a building, is to lower the transmission losses by applying insulation of the building envelope. The optimal thickness of this insulation layer depends on assumptions and the current state of the building. When short calculation times are assumed, the optimum lies between 6 and 9 cm [17],[18],[19]. When longer time periods are considered, the optimum is between 10 and 20 cm. If there are any actions to be taken anyhow, like a retrofit of the plaster, an insulation of the envelope becomes more attractive and an insulation thickness of over 20 cm is economically valuable [19]. Unfortunately, other construction parts have longer lifetimes than plaster, so not every retrofit can be coupled with other actions. Nonetheless, the insulation of the upper floor ceiling and basement ceiling in most cases are economically worthwhile, even if full costs are considered [17],[20] Other possible actions are the renewal of the heating system, e.g. replacement of old boilers with condensing boilers, or the replacement of old single-glazed windows with multiple-glazed windows which frames are also more airtight. According to a study by [21], the retrofit of single-family homes with a end-energy demand of 230 kWh/(m^{2}a) to a demand of 85 kWh/(m^{2}a) can be economically feasible. This retrofit includes insulation of the facade, the upper flor ceiling and basement ceiling, as well as the replacement of the old boiler with a condensing one. A change of windows, even if a replacement of windows is necessary because of other reasons, is almost never worthwhile [21],[22]. In a Belgium study, the insulation of the upper floor ceiling is considered to be the most economically action, followed by the insulation of the basement ceiling and a replacement of the boiler, while the insulation of the facade and the change of windows do not show any economical potential [23]. The reason for this contradictory statement concerning the insulation of the facade could be, that [21] combined the action and costs with a renewal of the plaster, while [23] considered full costs for the insulation. In a study of [24], single family homes were retrofitted. Starting with a end-energy use of 199 kWh/(m^{2}a) for all buildings, a reduction to 46 kWh/(m^{2}a) with costs of 245 EUR/m^2 (standard insulation, double-glazed windows, no mechanical ventilation), a reduction to 47 kWh/(m^2a) with costs of 288 EUR/m^2 (thicker insulation, exhaust ventilation system) and a reduction to 36 kWh/(m^2a) with costs of 334 EUR/m^2 (thicker insulation, triple-glazed windows, ventilation system with heat recovery) were achieved. When the primary energy is considered, the buildings are on the same level, due to the electricity use of the ventilation system in the third building. Despite of different efforts to retrofit, the result was more or less the same. Of course, the influence of the user has to be considered, which can be assumed as about one third of possible deviation around the mean value [5]. [25] takes a look on multi-family buildings, which were retrofitted between 1995 and 1997. The actions included 12 cm insulation of the facades, 8-16 cm insulation of the upper floor ceilings and double-glazed windows. By these actions, the initial end-energy use between 140 and 173 kWh/(m^2a) could be reduced to values between 92 and 110 kWh/(m^2a). The costs, depending on the building, were between 90 and 191 EUR/m^2. Another multi-family home showed high end-energy use pre-retrofit of 361 kWh/(m^2a) and post retrofit of 144 kWh/(m^2a) for costs of 132 EUR/m^2. A complete retrofit including heat distribution, new radiators and the measures named above is even more expensive. Such a retrofit lowered the end-energy demand of a multi-family home from initially 271 kWh/(m^2a) to 134 kWh/(m^2a) with costs of 377 EUR/m^2 [25]. Another complete retrofit, including extensive means like mechanical ventilation and solar water heating, monitored by [26], led to a decrease of end-energy use down to 41 kWh/(m^2a) for the costs of 350 EUR/m^2. Also the retrofitting of schools and accommodation facilities shows high potential. [27] reports a reduction in end-energy use from 177 kWh/(m^2a) to 63 kWh/(m^2a) for costs of 129 EUR/m^2. Also, [28] monitors a reduction from 210 kWh/(m^2a) down to 55 kWh/(m^2a), costing 189 EUR/m^2. Both projects included the renewal of the heating systems, new windows and insulation of the envelope. In [29] a retrofit including new windows, insulation and the construction of an atrium between the two building parts, led to a decrease from 283 kWh/(m^2a) to 61 kWh/(m^2a). Unfortunately, now cost data was specified. A day nursery was retrofitted for the costs of 300 EUR/m^2 and a reduction from

209 kWh/(m^{2}a) to 100 kWh/(m^{2}a) achieved by insulation, new windows and the hydraulic balancing of the heating system [30]. According to the literature study, the end-energy use of retrofitted buildings, built before the 1970s, can be decreased to around 60 kWh/(m^{2}a) by standard means of insulation, new windows and renewal of building technology. Mean costs vary between 140 and 250 EUR/m^2. If less expensive measures are used, as shown in [29], the end-energy use can only be lowered to values around 90 to 110 EUR/m^2. But, there is no direct correlation between the retrofit costs and the achieved energy savings. The reasons is the great variety of measures and their effects. A fairly cheap retrofit does not necessarily leads to only small energy savings and vice versa.

Summary. According to a literature study, buildings constructed before the early 1970s do not show any differences in end-energy use for heat. A reason could be rising indoor temperatures for comfort reasons in contrast to the decreasing u-values of the facades. A classification should therefore not depend on the building age, but on end-energy use. This classification could separate the buildings into groups of low, medium and high demand. The literature study of several best-practice retrofit projects leads to the estimations of the costs per m^2 as shown in 1. The retrofit of the envelope including windows of single family homes comes with costs of about 120 to 150 EUR/m^2 [24],[3], while a retrofit of all building components including the heating system etc., easily leads to costs of around 290 to 350 EUR/m^2. The costs for retrofitting a single family home with high demand and a retrofit goal below 100 kWh/(m^{2}a) is roughly estimated with 235 EUR/m^2. For buildings with a normal use of end-energy it is assumed that they already have been partly retrofitted. The costs of a total retrofit are therefore reduced by 40 EUR/m^2, which is equivalent to the costs of a renewal of windows [24]. The envelopes of multi-family homes can be retrofitted for costs between 90 and 150 EUR/m^2. If building technology is also considered, prices go up to 210 to 250 EUR/m^2. For offices, same numbers are assumed. For buildings with a normal consumptions, again a reduction of retrofit costs of 40 EUR/m^2 are assumed. As shown before, schools were retrofitted to values down to 60 kWh/(m^2a) for costs of 129 to 189 EUR/m^2. The mean values of 160 EUR/m^2 is used for the estimation of retrofitting buildings with initially high consumption. Buildings with normal consumption again are considered to be partly retrofitted and a cost reduction of 60 EUR/m^2 is considered. For accommodation facilities, values close to the ones of multi-family homes were considered, since their building structures can be assumed similar. [30] describes the retrofit of such a building to an end energy use of 100 kWh/(m^2a) with costs of 300 EUR/m^2. Retrofit without building technology causes costs of about 90 EUR/m^2 as for multi-family homes. Again, buildings with low initial end energy use, are considered to be partly retrofitted, thus the mean costs are reduced by 40 EUR/m^2 to 155 EUR/m^2. In 1, the resulting categorizations are summarized.

Table 1: Estimated end-energy for heat incl. hot water use and costs of retrofit (excl. VAT) based on literature study

	Single family home	Multi family home	Offices	Schools	Accommodation facilities
End-energy incl. hot water [kWh/(m^{2}a)]					
Low consumption	$\leq$ 130	$\leq$ 115	$\leq$ 105	$\leq$ 90	$\leq$ 130
Normal consumption	130-190	115-160	105-150	90-160	130-180
High consumption	$\geq$ 190	$\geq$ 160	$\geq$ 150	$\geq$ 160	$\geq$ 180
Costs of retrofit [EUR/m^2]					
Normal consumption	195 $\pm$115	130 $\pm$80	130 $\pm$80	60 $\pm$15	155 $\pm$105
High consumption	235 $\pm$115	170 $\pm$80	170 $\pm$80	160 $\pm$30	195 $\pm$105

3. Public building stock in Luxembourg

In this chapter, the stock of public old buildings managed by the Administration des Batiments Publics in Luxembourg is analyzed in terms of energy efficiency, in order to provide an overview and to estimate possible retrofit potential and costs. In Figure 1 we can see the different categories and total numbers of buildings.

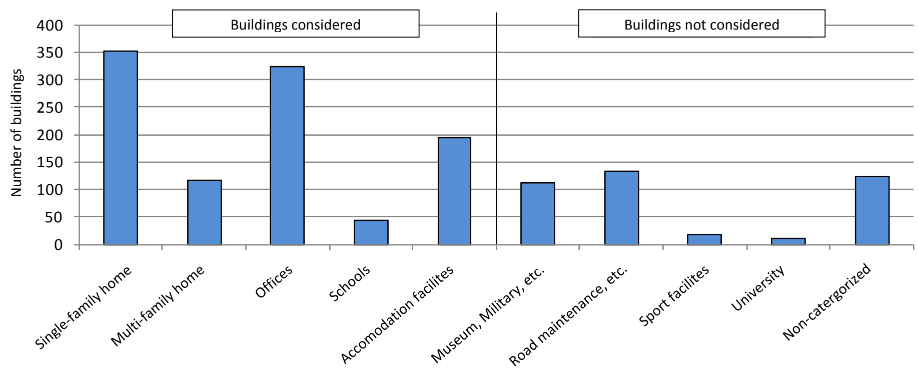


Figure 1: Number of public buildings in Luxembourg, constructed before 1995, categorized by use.

Since values about the energy demand, the age and the size of these buildings were not centrally recorded, these values for a certain amount of sample buildings had to be captured on site or in cooperation with facility managers in order to estimate mean values to be relevant for the whole stock. The end-energy demand including hot water was derived by analyzing the bills from several years if available or on-site meter data.

First, the heated gross area of the sample buildings were identified and the mean value calculated. According to the Kolmogorov-Smirnov-Test the samples were not normally distributed [31]. However, assuming a normal distribution of building stock as a whole, a t-test was used to calculate a confidence interval in which the real mean value of the whole building stock lies with a probability of 95 % [31]. The results are presented in Table 2.

Table 2: Building samples for building structure analysis

	Amount of sample buildings	Total amount of buildings	Mean heated gross area of sample incl. 95%-confidence interval
Single-family homes	206	353	195±5 m^2
Multi-family homes	72	118	760±135 m^2
Office	114	325	1,865±592 m^2
Schools	25	45	15,400±4,000 m^2
Accommodation facilities	105	194	1800±583 m^2

To calculate the total gross area of the whole building stock, this mean value and its confidence interval boundaries were then simply multiplied with the total number of buildings of each category. While the total number of single family homes are the biggest group within the stock, the schools represent the biggest total heated gross area as seen in Figure 2.

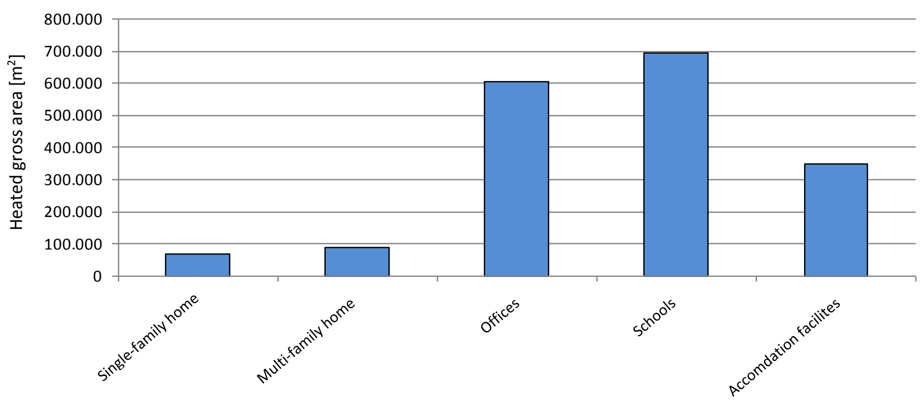


Figure 2: Heated gross area of public buildings in Luxembourg, constructed before 1995.

In a second step, the end-energy use for heat including hot water was derived for a number of sample buildings. The mean value of those sample buildings and its standard deviation are then calculated and used as a basis for the calculation of the total end-energy demand for heat of the whole public building stock (see Table 3). The samples of every building group was normally distributed according to the Kolmogorov-Smirnov-Test. The heat demand of buildings with district heating was increased in calculation by 10 % to count for the process of the heat production [37]. The data was adapted to the degree days Gt20/15 of the mean value over several years in Luxembourg. As for the area, the gross value was considered, as it is easy to determine by the outer dimensions of the buildings.

Table 3: Building samples for end-energy use for heat including hot water

	Amount of sample buildings	Total amount of buildings	Mean end-energy for heat use incl. hot water of sample incl. standard deviation
Single-family homes	30	353	181±31 $kWh/(m^2a)$
Multi-family homes	31	118	171±32 $kWh/(m^2a)$
Offices	20	325	176±59 $kWh/(m^2a)$
Schools	26	45	161±71 $kWh/(m^2a)$
Accommodation facilities	16	194	229±49 $kWh/(m^2a)$

Table 4 shows the total consumed end-energy for heat including hot water by building type and the gross area per building type.

Table 4: Consumption of end-energy of analyzed building types

	Heated gross area [m^2]	Consumption of end-energy for heat incl. hot water [GWh/a]
Single-family homes	69,000	12.5
Multi-family homes	90,000	15.4
Offices	606,000	106.7
Schools	696,000	111.6
Accommodation facilities	349,000	19.9
Total	1,744,000	326.1

The heated gross area of each building category can then be seperated in classes of low, normal and high consumption. This process is presented in detail using the example of the single family homes.

With a total number of 353, the single family homes count for a fairly big share of public buildings in Luxembourg. For 206 of them, the buildings structure, age and gross area was known (according to Table 2). For 30 of them (9 % of the total amount), the end-energy use was derived (according to Table 3). The typical single family home is of 195 m^2 heated gross area (standard deviation 33 m^2) and consumes 181 kWh/(m^{2}a) (standard deviation 31 kWh/(m^{2}a)) of end-energy for heat. This goes along well with the results of other studies [3], [4],[5],[6]. In Figure 3 the frequency distribution and the classification into low, normal and high consuming buildings according to Table 1 is shown.

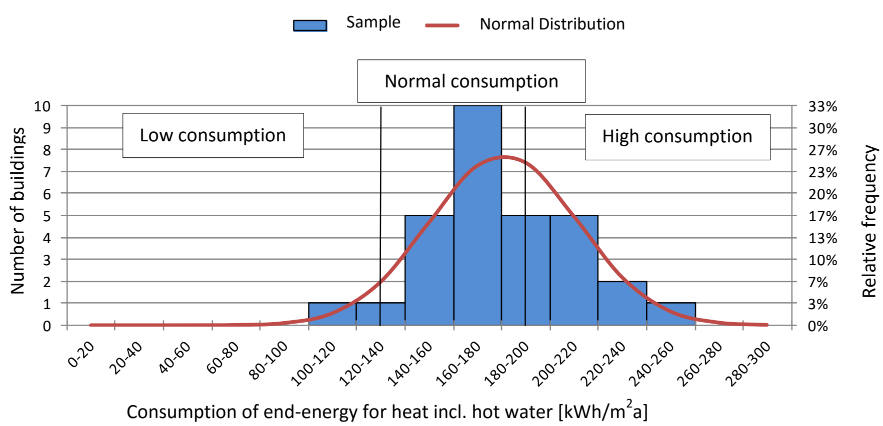


Figure 3: Frequency distribution of end-energy consumption of old single family homes built before 1995 in Luxembourg.

Most of the single family homes, which in total account for 69,000 m^2 (or about 4 % of the total gross area of all the public buildings), show a normal consumption, while only 3 % are in the group of low consumption and 37 % in the group high consumption. The mean end-energy consumption in the high consumption group is 214 kWh/(m^{2}a). If this group of buildings would be retrofitted and their consumption decreased to 100 kWh/(m^{2}a), then the total decrease of end-energy consumption for the whole stock would be 3 Mio. kWh/a, at costs of about 6 Mio. EUR (estimated costs according to Table 1). The same is possible for the buildings with normal consumption. Here, for costs of about 8 Mio. EUR, the total end-energy saved would be approx. 2.6 Mio kWh/a.

The same analysis was done for all building types. The results are presented in Figure 4 and Table 5. Old buildings with low consumption are rare (green), while most of the single family homes and schools belong to the group of buildings with energy normal consumption (blue). For the other building types, the biggest group consists of buildings with high consumption (red).

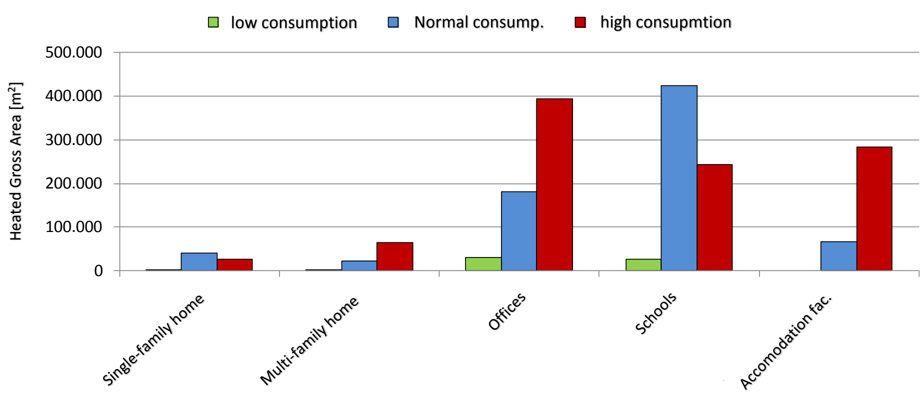


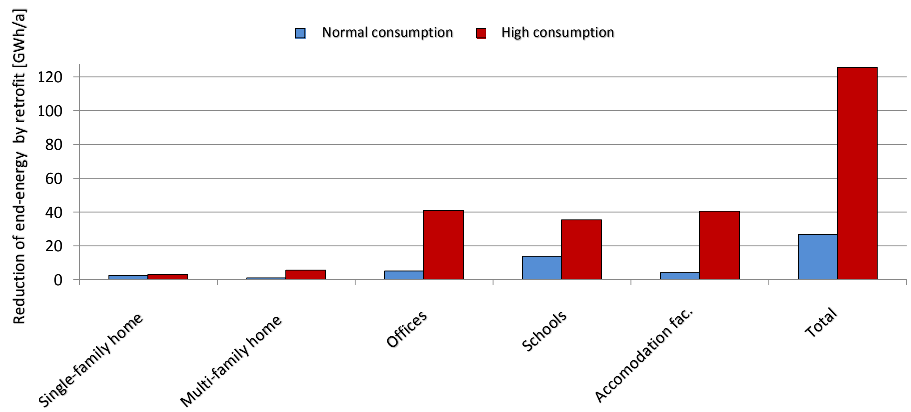
Figure 4: Heated gross area of old public buildings divided by consumption.

The target value of a retrofit is 90 kWh/(m^{2}a) for schools and 100 kWh/(m^{2}a) for all other building types. In Table 5, the estimated costs of a retrofit of buildings with normal and high consumption are presented.

Table 5: Total possible reduction in consumption and costs of retrofit of analyzed building classes

	Decrease in Consumption through retrofit [GWh/a] of classes "normal" and "high"	Costs of retrofit [Mio. EUR]
Single-family home	5.6	14
Multi-family home	6.4	14
Offices	46.1	91
Schools	49.5	64
Accommodation facilities	44.8	65
Total	152.4	248

As can be seen in Figure 5, a retrofit of buildings with high consumption leads to the highest energy savings, while buildings with normal consumption often show only less potential for savings, compared to the costs of their retrofit. In numbers, that means for buildings with initially normal consumption, costs of retrofit are between 0.07 to 0.19 EUR/kWh, if an amortization period of 25 years and no interest rate is considered. For buildings with initially high consumptions, these costs are only 0.04 to 0.08 EUR/kWh. For economic reasons, the retrofit should focus on the buildings with the highest consumption of end-energy.



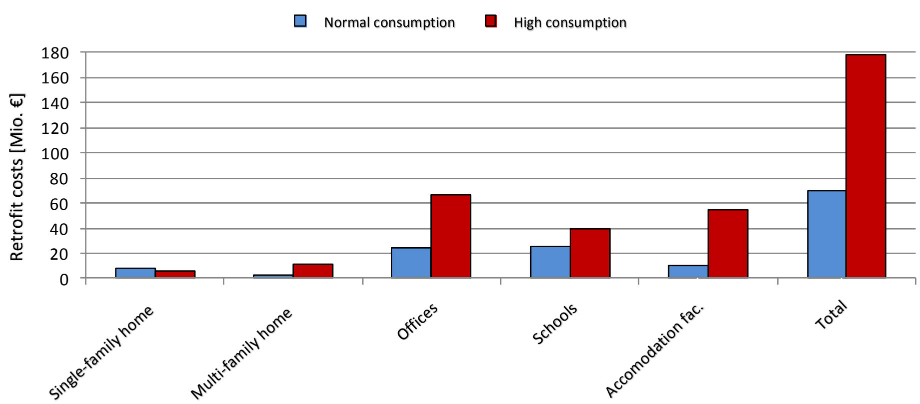


Figure 5: Possible reductions in consumption and costs of retrofit subdivided by building types and consumption classes.

4. Discussion & Conclusion

The project objective was to quantify and categorize the end-energy use of the public building stock in Luxembourg and to estimate the costs of retrofit actions. This data serves as a basis for future retrofit scenarios and enables the administration of those buildings the calculation of costs for possible future actions. Data derived from a literature study is the starting point in order to categorize the buildings into three categories of low, normal and high end-energy consumption. Since the end-energy use for buildings built before the early 1970s do not vary significantly by building age, a categorization should be done by end-energy use. Buildings with low consumption show an end-energy use between 90 and 130 kWh/(m^2a), while the highly consuming buildings show values between 150 and 190 kWh/(m^2a). The buildings in between are called normal. Costs for retrofit range from 60 to 235 EUR/m^2, depending on the retrofit measures. For buildings with normal consumption, only constructional changes of the building envelope are considered for retrofit, e.g. the insulation of the envelope, the ceiling and new windows. A renewal of the heating system was only considered for the retrofit of buildings with high consumption, resulting in higher retrofit costs. Partly retrofitted buildings on the one hand make fewer actions necessary to reach low energy use values, but on the other hand, show less saving potential, making a renovation possibly less cost effective. Several studies showed, that with rising complexity of the building technology, comes the risk of higher primary energy demand. A retrofit of the HVAC technology should therefore carefully be planned, commissioned and maintained. The Luxembourgish stock with a total heated gross area of 1.744 Mio m^2 was then categorized into those three classes of low, normal and high energy use. While most single family homes and schools where in the class normal, most of the multi-family homes, offices and accommodation facilities are to be found in the class high. By gross area, schools make up for the biggest part of the total gross area, followed by offices and accommodation facilities. Therefore, those three building types would have the biggest effect on the energy demand of the total stock when retrofitted to a target value of 90 to 100 kWh/(m^2a). It is more cost efficient to retrofit the class of buildings with high consumption, since the costs per one kWh savings here are between 0.04 to 0.08 EUR, while retrofitting the class normal would be more expensive with values between 0.07 to 0.19 EUR/kWh (considering an amortization time of 25 years and no interest rate). A possible future cost-effective retrofit strategy should therefore first focus on the buildings which were categorized into the class with high consumption and account for a big part of the total stock floor space. An insulation of the basement ceiling and upper flow ceiling are the most economically measures. The insulation of the facade, change of windows and especially the renewal of the heating system as well as the installation of a mechanical ventilation system has to be carefully calculated for every single case.

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