Complex Analysis of Energy Efficiency of public buildings: case study of VGTU

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Introduction

Buildings consume approx. 40 % of the whole final energy consumed in the European Union (EU) [1]. Therefore the energy efficiency is at the heart of the EU's 2020 strategy for smart, sustainable and inclusive growth [2]. Energy efficiency is seen as one of the biggest EU's energy resources. Meanwhile, the biggest energy saving potential lies in buildings and high attention should be paid to the existing old buildings, which need to be refurbished [3, 4].

Directive 2010/31/EU (EPBD) [1] requires construction just nearly zero energy buildings starting from 2020, there are also energy efficiency requirements for the refurbished buildings. It should be mentioned that scope of the directive is just energy efficiency. But there exist also other issues related to climatic zones, urbanistic traditions, and economic indicators to be considered in the regions when developing sustainable buildings. International Energy Agency [5] for analysis of the future sustainable buildings proposed a Globally Optimised, Locally Designed (G.O.L.D) principle. Similar approach is also proposed in "Concept of Moscow city "green" construction" [6] and by Dall'O' et al. [7]. It is easier to implement these principles in new built buildings and for the existing inefficient buildings these principles can be partly implemented through energy audit – one of the key elements of the process of refurbishment.

The energy audit is a versatile assessment of the present condition of the building, evaluation of the gained results in terms of the energy efficiency and proposition of economically and ecologically efficient, socially acceptable organizational and technical measures pursuing to reduce energy consumption. Beggs [8] found analogy between building and a complaining patient, and energy auditing is the research work very similar to the research work of the medical doctor. Therefore, the right way to make energy audit is firstly to examine the building, state problems and then to suggest measures to eliminate these problems.

There exists a problem that at the process of energy audit such parameters as internal temperature, air change rate and thermal characteristics of envelopes usually are presumed theoretically based on the auditor's experience or standards. Therefore, incorrect assessment of one parameter impacts other parameters and the overall result. That in consequence may skew the savings expected after the refurbishment. The scientific task of the research presented in this paper was solution of this problem – creating more precise energy auditing methodology.

Researchers of Vilnius Gediminas Technical University (VGTU) have been participating in the EEI project "USE Efficiency" since 2009 [9, 10] and in frames of that project they have significantly contributed to the promotion of the energy audit. The project is oriented towards students, efficient energy use and implementation of energy efficiency measures in university buildings.

Young researchers were encouraged to perform audits of analyzed buildings as more precise and original as possible and thus they were gaining experience in the performance of the audits. Therefore the high attention was paid to the estimation of the real parameters of the building as well as proper selection of measured parameters, points of measurements, methods to be used, duration and time of measurements. These tasks enabled students to go more deeply into the energy audit as well as analyze energy characteristics of the university buildings, identify existing problems and their scale.

For this purpose, the equipment of the newly established VGTU Center of Civil Engineering Sciences was used. The kit consists of the measurement devices used to define real energy consumption, characteristics of the building, user behavior and indoor climate conditions.

Methodology

In the frames of the project, each university, participating in the project USE Efficiency, had to perform two level's audits for its buildings [11]. 1st level audit was performed according to the operational energy consumption of the building. This kind of audit enables to identify the critical buildings. Such identification is an important step, if investor has a limited amount of money and wants to refurbish a building, especially when country has no benchmarks for energy efficiency of buildings. And this is the case of Lithuania.

Total energy consumption of the building is influenced by construction and equipment of the building, building management, building use and building users (see Fig. 1), meanwhile asset rating enables to evaluate just energy consumption related to constructions and equipment. Therefore the most appropriate way to make energy audit of the building is to take into account both operational and asset rating energy consumption and make a balance between them. Thus many unknown values should be found. If possible, the best way to find them is measurement. Construction of the precise balance of the energy consumption enables to make precise evaluation of energy saving measures.

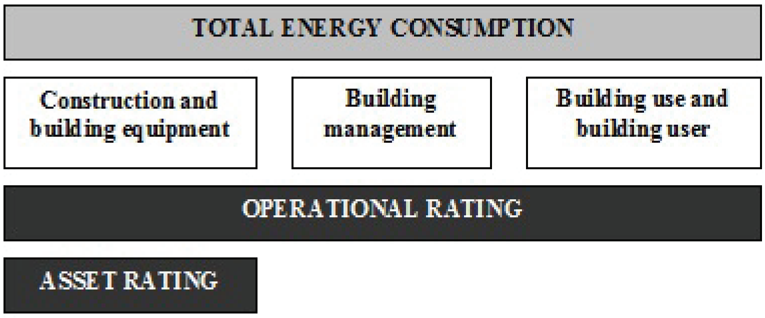

Figure 1. Rating of energy consumption of the building

The 2nd level detailed energy audits of 6 VGTU buildings (Fig. 2) were performed. Methodology of such level of accuracy is usually applied in industrial processes auditing (including mechanical and electrical systems, energy processes, supply systems, etc.) [12]. Such complex energy audits are also recently used in USA for public buildings [13]. The main features of the detailed (complex) energy audit are the next:

1) description of all energy using systems, no matter if energy savings are found or not;
2) it is allowed to ignore some less important areas just after the whole energy balance is found;
3) presentation of all profitable energy saving measures;
4) performance of the detailed calculation of energy savings and investments;
5) performance of the diagnostic evaluation of each energy using system and specification of the energy consumption;
6) description of the alternative energy saving measures, object, energy production and consumption, related schedules and balances.

Some authors [14] claim that energy auditing has to be a systematic continuous process (energy management).

When performing energy audits for the VGTU buildings, following tasks were set and realized:

1) analysis of the current state of the building and collection of the data;
2) measuring of the energy related parameters and data processing;
3) technical analysis of the heating energy consumption and related expenses as well as formation of the energy balance of the energy consumption;
4) recalculation of the actual heating energy consumption according to the heating season of the standard year;
5) selection of the energy saving measures and calculation of the expected savings;
6) evaluation of the economical efficiency of the energy saving measures.

Some authors, instead of performing sufficient number of measurements, supplement their detailed energy audits with occupants' surveys or building energy simulations [15-17]. Tronchin and Fabri [18] concluded that using dynamic energy simulations is preferable for energy audits because of their accuracy.

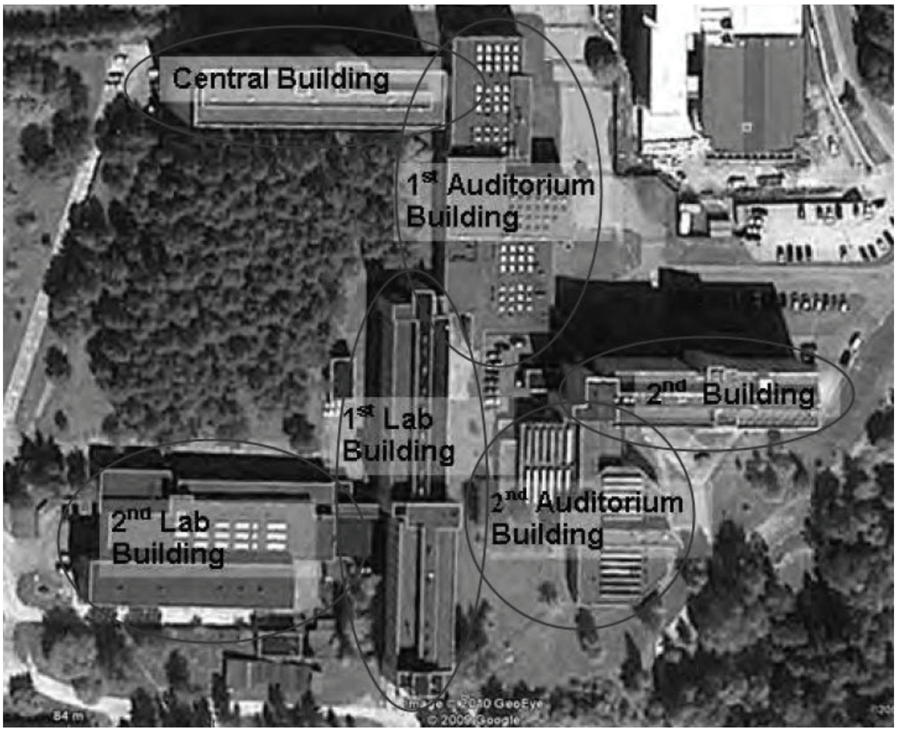

Figure 2. Analysed buildings of VGTU campus

Working in groups and consulting with the supervisor for one semester, young researchers (Master students) proposed simple, but clear sequence of the energy audit performance (Fig. 3). In the data collection phase researchers were collecting information about physical characteristics (dimensions of walls and windows, dimensions of rooms, etc.), structure of the elements (walls, floor, roof, etc.). Also at this stage they performed measurements of thermal characteristics of building's elements (thermal conductivity of walls, windows, the roof and the floor; exploration of the ventilation system, etc.) and indoor conditions (temperature, relative humidity, lighting levels, CO_2 concentrations, air exchange rates).

Figure 3. Energy audit chain

Afterwards (step 2) the results of measurements were structured, processed and analysed comparing them with analogical results (for example, with the data of the other room). Main final results gained were: average temperature and humidity for the measured period, actual U-values (heat transmittance), actual air exchange rate and lighting level.

When these characteristics are defined, it is possible to perform calculations (step 3) with the purpose to form the energy balance of the building. The main equation used for this (1):

$$\sum Q_{SV,f} = \left(\sum A_i \cdot U_i + c \cdot \rho \sum V_j \cdot n_j\right)\left(\Theta_{i.f.} - \Theta_{e.f.}\right) \cdot z - \psi_P \left(Q_{P,ext} + Q_{P,\text{int}}\right) - Q_{RES} - \\ - \sum \sum \psi_{R,k} \cdot Q_{NR,k} + \sum Q_{Nf,k} \, . \quad (1)$$

In this equation, variables, which usually are not exactly known and are changed in order to make balance between actual and theoretically defined energy consumption, are: U_i – heat transmittance of elements, W/(m²·K); n_j – air exchange rate, h^{-1}; $\Theta_{i.f.}$ – internal temperature, °C; Ψ_P – heat gains coefficient; Q_{RES} – renewable energy, kWh; $\Psi_{R,k}$ – heat exchanger efficiency. In this case, measurements enabled to have quite precise values of the most of these parameters. That fact made balancing much easier and more precise.

After energy balance is formed, the final results are analysed (step 4) in order to define the problematic parts of the building's systems and to define, where the highest potential for savings after implementing certain energy saving measures is.

Finally (step 5), the action plan with the packages of energy saving measures was proposed. Measures are listed according to their priority – from the highest priority to the lowest. For each proposed package savings are defined as well as technical difficulties of their implementation and changes of the indoor conditions. This phase also includes evaluation of the economical effect of the proposed measures – definition of the simple payback period, discounted pay-back period and saved energy cost.

Measurements

Performed audits were supported by VGTU Centre of Civil Engineering Sciences, which allowed young researches to use newly bought measuring equipment: ALMEMO [19], TinyTag and HOBO data loggers, HOBO meteorological station, Thermacam FLIR B660, thermocouples, CO_2 sensors, blow door, etc.

Before the auditing, each group has got a thermovision picture of the analyzed building (see example in Fig. 4). These pictures gave the possibility to define the problematic places of the building and to choose points for measurements. Totally in all analysed buildings measurements of indoor climate parameters were carried out in 24 premises and thermal characteristics of 18 elements were measured.

The main measured parameters were: internal temperature and relative humidity and heat transmittance of different elements. It is most common to change these parameters when heat balance of the building is formed. Less attention was paid to the measurement of CO_2 concentration; it was used for measurements during lectures. Observing the time, when CO_2 concentration drops down to the initial level, the air exchange rate was calculated and the value was used for further energy consumption calculations.

When performing indoor climate parameters measurements, it was decided to keep data loggers in laboratories, auditoriums and offices for 3–5 days, with the measurement time step – 30 minutes, as a result drawing the graph and defining average dominant value of the measured parameter. When measuring heat transmittance, data loggers were connected according to the scheme showed in Fig. 5.

In this case data were measured and stored by data loggers every 5 minutes. Data of each measurement were analysed graphically, defining the night time interval with the highest measurement reliability and the smallest fluctuations of parameters. During the day, the heat flow is highly influenced by internal heat gains related to occupants and external solar heat gains; therefore, the best period for measurement is night. When having the measured parameters, the actual heat transmittances were calculated.

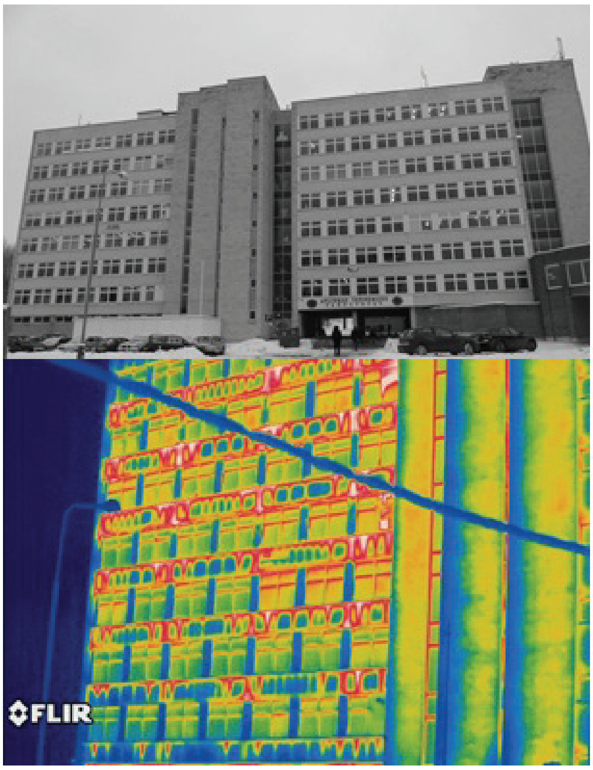

Figure 4. Pictures of 2nd (SRK-II) building

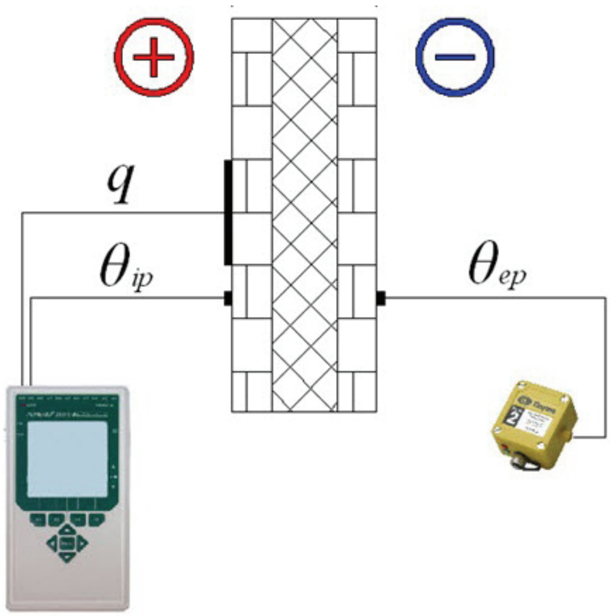

Figure 5. Measurement of heat transmittance

Results

1st level audit enabled to compare buildings according to thermal and electrical energy consumption in one common diagram (see Fig. 6). The comparison was made both per the area unit and volume unit, but since university has many premises with high ceilings – the correct way to compare energy consumption is per volume unit.

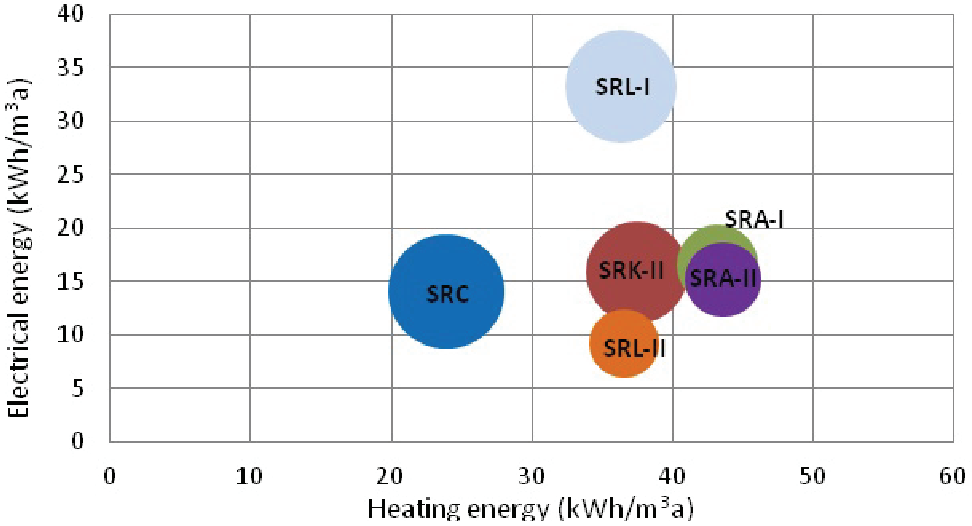

Figure 6. Energy use per volume unit

It can be seen (Fig.6) (size of the circle corresponds to the volume of the building) that SRL-I building has relatively high electrical energy consumption. This can be explained by the fact that in the building dominate laboratories with a lot of electricity using old and ineffective experimental stands and other equipment. Also, a distinguishing building, as can be seen, is – SRK-II. These two buildings mentioned above are the critical ones.

Results of measurements have shown that in all 6 buildings the average internal temperature varies between 14.9 °C and 20.0 °C, meanwhile the relative humidity varies from 25.2 % to 36.3 %. According to the national norm [20], the internal temperature for the heating season must be 20–22 °C and the relative humidity – 40–60 %. Thus, it can be stated that practically in all analysed buildings standard requirements are not satisfied.

CO_2 and blow door tests have shown that, when the difference between external and internal air pressure is 4 Pa (condition of natural ventilation), the air exchange rate is less than 0.2 h^{-1}. Such a small air exchange rate is explained by a non-functioning mechanical ventilation system and new tight plastic frame windows. Fig. 7 shows the measured parameters of one classroom (in the 2nd (SRK-II building)) during the lecture. Classroom was occupied from 10:20 till 11:55. During this period, the lecture was held, therefore CO_2 concentration increased. Before the lecture CO_2 concentration was about 700 ppm, while after the lecture it has increased to 1900 ppm. So in the end of the lecture CO_2 concentration rate exceeded the permissible one 1.9 times.

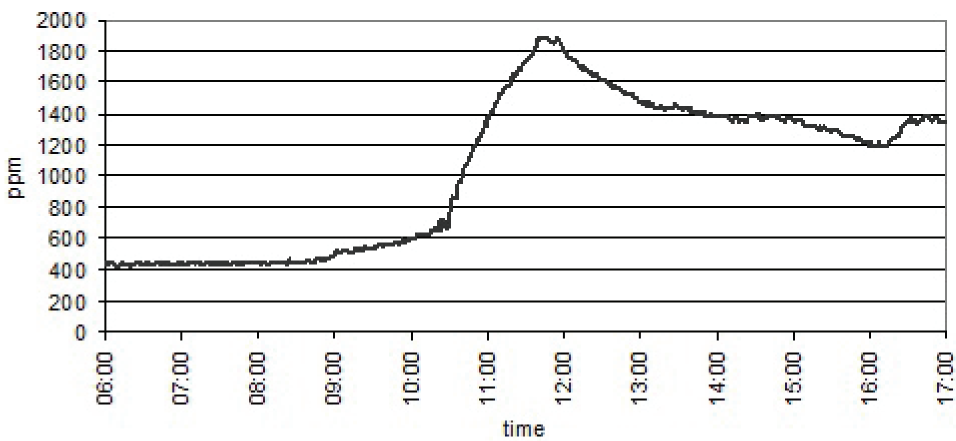

Figure 7. CO_2 concentration measured in the classroom

Other indoor climate characteristic – air exchange rate – can be calculated using CO_2 concentration measurement data. Air exchange rate is calculated using (3.1) equation:

$$n = \frac{(\ln(c_p - c_e) - \ln(c_g - c_e)) \cdot 3600}{t}, \quad (2)$$

where n – air exchange rate, h^{-1}; c_p – measured CO_2 concentration at the beginning, (1803 ppm); c_g – measured CO_2 concentration at the end, (1193 ppm); c_e – outdoor air CO_2 concentration, (400 ppm); t – time of measurement.

According to the national hygienic norm [20], air exchange rateis 0.7 h^{-1}, while the calculated one is 0.14 h^{-1}. So air exchange rate is 5 times smaller than required.

The defined actual U-values correspond to the design values and calculated theoretical values (when design values were unknown) with a deviation of ±10 %. As an example, measurement results of one classroom's U-values are shown in Fig. 8. The two ordinate axes (one with external temperature and the other with calculated U-values) enable to show the dependency of the U-value on the internal and external heat gains. Therefore, three nights with time intervals from 01:00 h to 05:00 h were used for the calculations.

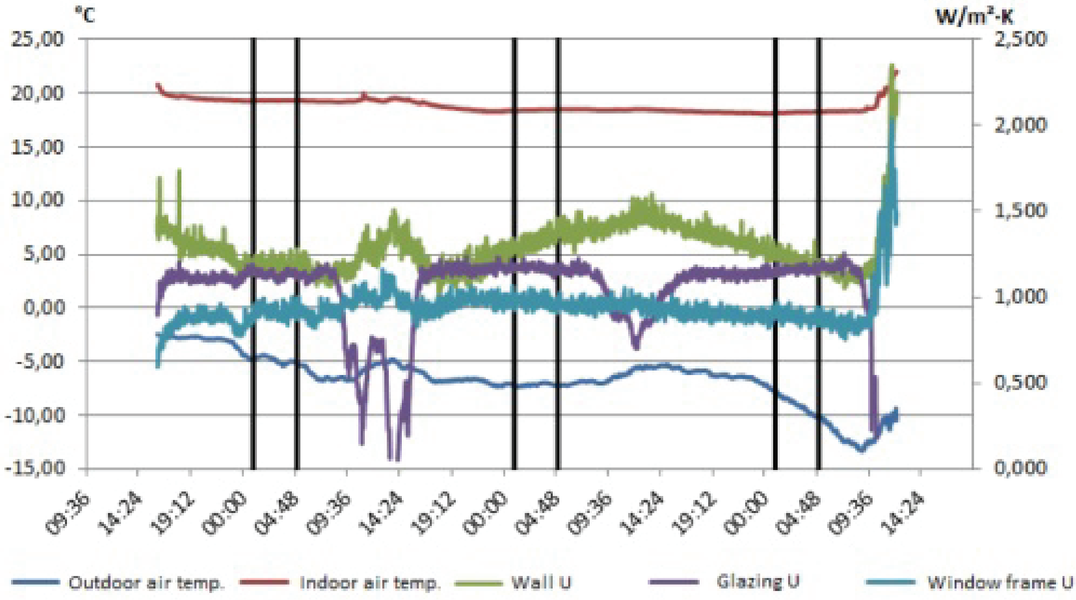

Figure 8. Results of measurements of envelopes thermal characteristics

When having main parameters measured, there were no difficulties to form the heat balance for each building. For example, for 2nd (SRK-II) building the discrepancy between measured (by heat counter) actual heat consumption and calculated was just around 7 % and this value satisfies the requirement of the national auditing methodology [21], which allows difference up to 8 %.

Finally, the groups of researchers proposed packages of energy saving measures. The greatest attention was paid to the reduction of heating energy demand. For all buildings, the same as for the critical 2nd building, the most common proposed energy saving measure was insulation of external envelopes (walls, basement, and roof) to satisfy requirements of current standards. And also all of the groups have considered the possibility of installing effective mechanical ventilation system to increase the comfort.

For the 2nd building, as the most efficient, proposed measures were: insulation of the envelope, renovation of the heating system and combination of both of these measures as complex renovation. Insulation of the envelope gives highest energy savings – up to 53 % and just renovation of the heating system gives quit small savings – 14 %, since its effect is higher just if envelope is also insulated. Therefore the most efficient renovation is when both measures are applied together. Then we have 60 % energy savings (see Fig. 9). To make a final decision, economical evaluation of these measures is needed.

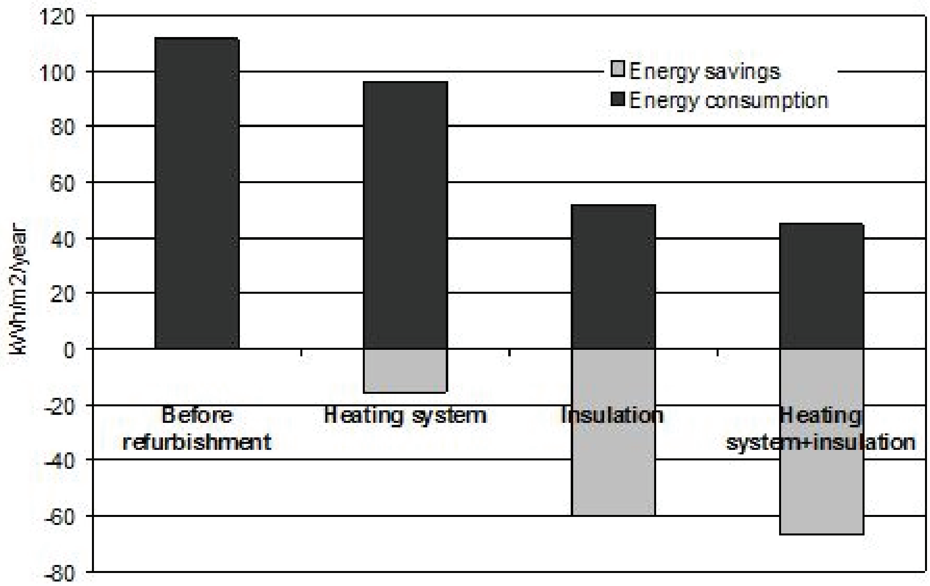

Figure 9. Energy consumption and savings before and after the refurbishment

Economical evaluation of the energy saving measures

The proposed energy saving measurements were assessed according to the following indicators:

- Simple pay-back period (SPB);
- Discounted pay-back period (DPB);
- Saved energy cost (SEC).

Simple pay-back period of separate energy saving measures or their package is a simple indicator of economical efficiency. Simple pay-back period (SPB) gives a number of years in which individual energy efficiency measures or pack of them saved energy funds will cover the initial investment, but this method ignores the time value of money perspective. Meanwhile, discounted pay-back period (DPB) enables to evaluate length of time required to recover the initial cash outflow from the discounted future cash inflows. Discounted pay-back period is calculated:

$$DPB = \frac{-\ln\left(1 - d \times \frac{I_o}{\Delta S}\right)}{\ln(1+d)}, \tag{3}$$

where I_o – investment on the first year of the of the value, €; d – discount rate (-0,0741); ΔS – planned annual savings, €.

Saved energy cost criterion (SEC) can also be used for the assessment of energy efficiency measures cost-effectiveness. This criterion assesses measures life time and the cost of borrowing money. Saved energy cost is calculated:

$$SEC = \frac{I}{Q_S} \times \frac{d}{1-(1+d)^{-n}}, \tag{4}$$

where I – investment, €; Q_s – saved energy per year, MWh; n – life time of the measure, year.

If SEC exceeds current price of energy, then energy saving measure is considered as economically efficient.

Economical indicators for the critical building SRK-II are shown in the table below.

Table 1. Economical indicators for the 2nd building (critical)

	Investment, €	Planned savings, €/year	SPB	DPB	SEC
Thermal envelope insulation	121714	17191	7,1	10,1	3,69
Heating system renovation	102984	8785	11,7	>15	6,11
Complex renovation	169512	28035	6,0	8,2	3,15

As it is seen from the Table 1, insulating just envelopes seems acceptable option, but such pay-back period (10,1 years) is considered by some authors as unattractive (too long) [15, 22]. Renovation of the heating system without renovation of the envelopes without any doubts is unattractive option since it pays back more than after 15 years. Complex renovation requires more investments than just renovation of the heating system or envelope. But such complex renovation enables to save more energy thus making investments more attractive if taking into account discounted payback time which is 8.2 years. Some authors, when selecting energy efficiency measures, are already taking into account climate change [23, 24]. Pay-back of energy saving measures is also dependent not just on location [25], but also on the climate change. Example of the dependency of energy efficiency saving measures discounted pay-back time on climate change in Moscow is shown in [24].

Conclusions

Energy audits of 6 University buildings enabled to define their weak points, operational energy consumption and characteristics of the elements as well as to propose relevant energy saving measures. Used measurement devices enabled to define very detailed parameters related to building elements and indoor climate. That made further calculations much easier and precise. The methodology presented in the paper is also recommended to use in all public buildings.

It was defined that in different buildings average dominant internal temperature is from 14.9 °C to 20.0 °C, and relative humidity – from 25.2 % to 36.3 %. Such values do not satisfy requirements of the hygienic norms. Air exchange rate in buildings is around 0.2 h^{-1}. Such value is not sufficient to ensure indoor comfort. Measured heat transmittance coefficients of envelopes differ from the theoretically calculated values just by ~10 %. But still these heat transmittance coefficients do not satisfy requirements of current regulations.

The analysis of the different energy saving measures and their combination, as well as different payback periods calculations showed that complex renovation requires more investments than just renovation of the heating system or envelope. But such complex renovation enables to save more energy thus making investments more attractive.

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Key words

Energy efficiency;public buildings; energy audits; indoor climate; elements thermal characteristics; measurements;economical evaluation.

Abstract

The purpose of this work was to make analysis of energy efficiency of Vilnius Gediminas Technical University (VGTU) buildings. The survey was performed within the frame of the Intelligent Energy – Europe (IEE) project "Use Efficiency" – Universities and Students for Energy Efficiency.

The methodology of the detailed auditing proves that energy audits must be performed with the maximum use of measurements. When having main parameters measured, it is much exact and easier to form energy balance of the building.

It has been inferred that performing detailed energy audits with the support of measurements enable to asses building's present energy efficiency very precise and consequently savings, related to the proposed energy saving measures, can be assessed more realistic than just analytical calculations.

The analysis performed consists of 2 levels: the 1st and the 2nd level audits. During the 1st level audits, according to the operational energy, critical buildings were identified. The 2nd level audits contain a detailed analysis of the energy efficiency of the buildings and are based on different measurements and analytical calculations (performed according to the national methodology). This analysis could be a guideline for others performing this type of investigations.

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