Retrofitting of fire stations in cold climate regions

A. Borodinecs*, A. Prozuments, A. Zajacs, J. Zemitis
Riga Technical University, Riga, Latvia
* E-mail: borodinecs @rtu.lv

Abstract. Most of the urban housing stock in European cities consists of multi apartment buildings. Improvement of energy efficiency of the existing building stock is the key priority across the world. As such, unclassified buildings including fire stations present a significant potential for application of innovative energy efficient measures. Despite the fact that fire stations account for a rather insignificant share on the scale of the total building stock, it is vitally important to ensure optimal thermal comfort as well as reduce energy consumption in those buildings. This in turn contributes in minimizing maintenance and running costs for municipalities. This paper analyses typology of Latvian fire stations and their energy consumption. Standardized IFC model was developed to evaluate effect of implementation of energy efficiency measures in a selected fire station. The study results showed that the proposed theoretical thermal energy consumption of developed standardised model correlates with the measured data. The measured average annual energy consumption including electricity for fire stations was 317 kWh/m^2 and thermal energy for space heating – 135.4 kWh/m^2. Based on theoretical model, different retrofitting scenarios were evaluated using IDA-ICE dynamic energy simulation software. The results of this study can be expanded and applied to other types of unclassified buildings (in countries with cold climate) such as police departments and prisons.

1. Introduction

Energy efficiency of buildings as well as sustainable development of construction sector has been put forward among major priorities in the European Union [1]. Moreover, countries such as USA, China and Russia are consistently improving and tightening their legislation on buildings energy performance [2–4]. For example, Russia has tightened its legislation with regards to heat resistance requirements for opaque elements of building envelope by 200 % [5]. Despite the increased focus on implementation of energy efficient measures in buildings, the world's energy consumption is increasing at a rate of approximately 10 % per year [6]. It should be noted that the main contributors to this dynamic are the developing countries. The main target group for implementation of energy efficiency measures in building sector are multi apartment and public buildings, which are major contributors to CO_2 emissions [7]. Meanwhile the energy efficiency in so called unclassified buildings is not being adequately addressed, as these buildings are not part of governmental subsidies. Unclassified buildings include army barracks, warehouses, police departments, fire depots, prisons etc. These buildings constitute approximately 1 % of the total building stock share. Nevertheless, when it comes to energy conservation, even this small building share should not be neglected. Unclassified buildings are typically occupied 24/7 and consume up to 5 times more energy than a regular apartment building per floor area. Retrofitting of such buildings would ensure not only reduction of energy consumption but also allow for an improvement of thermal comfort and indoor air quality. This is very important for occupants residing for an extended time in one building. For instance, when staying inside the fire stations, firefighters are exposed to polycyclic aromatic hydrocarbons [8]. The main reasons for that are insufficient (or in many cases non-existing) ventilation, poor quality of a building or improper retrofitting. It should be noted that it is mainly fire stations constructed before 1990s that are not well maintained and do not have energy efficient solutions [9]. While the residential sector in the EU countries has a high potential for saving energy by lowering the heating demand through properly insulating building envelope [10], the retrofitting packages for the fire stations should have a stronger focus on upgrading the mechanical systems and incorporating renewable energy sources. Modern fire fighter trucks have electric equipment that use 12 V batteries. These batteries are usually charged in between the emergency callouts through an electric grid. In

such cases installation of PV arrays could have a positive effect on overall energy performance profile of the fire stations.

A recent study analysed five typical mid-scale fire stations, whose lighting bills came out to 9500$ annually per station [11]. The same study estimated that the potential energy saving due to an increased thermal insulation of external building envelope would be in the ballpark of 20 %. However, the application of thermal insulation may not be enough to ensure sustainable retrofitting. Such issues as poor indoor air quality, unsatisfactory thermal comfort and environmental impact should also be addressed when it comes to fire stations. Another study [12] analysed the use of green-rating system (LEED) to assess overall sustainability of fire stations. The results showed the importance of implementation of green-rating system which allows municipalities to take adequate design measures on future maintenance and retrofitting strategies.

A typical fire station is a low-rise building. There are several cost optimal solutions for the construction and retrofitting of low-rise buildings [13] which can be easily applied to fire stations. However, retrofitting of the fire stations is more complicated in comparison to residential and public buildings. This type of buildings have specific requirements on ventilation due to firefighting truck exhaust pipes and hot water consumption pattern, that has explicit peak loads on staff shifts change. This requires an installation of a more powerful hot water boiler. Retrofitting packages should also include measures for moisture control [14].

The main objective of this study is to evaluate current energy efficiency of non-renovated buildings and to perform an indoor air quality analysis in order to evaluate working parameters of heating, ventilation and air conditioning systems as well as airtightness of the building envelope. Based on acquired results standard energy retrofitting measures will be offered and analyzed in terms of both energy reduction and operation cost reductions. For this purpose, real fire stations under operation in Latvia were selected. Latvia is situated in Northern Europe along the Baltic sea region and represents a country with mildly cold climate. Several studies on buildings' energy efficiency in Baltic sea region [15, 16] have shown that estimations of energy reduction in Latvia can be used and adopted in this region. Other studies have shown that climatic conditions and building typology in Latvia are very similar to major Russian cities such as St. Petersburg, Leningrad district and Moscow.

2. Methods

Research methodology lies on the development of theoretical building model which was validated based on real on-site measurements. Validated model was used to evaluate different retrofitting scenarios. In addition, real indoor air parameter measurements were conducted to identify critical points.

The method of the energy consumption evaluation for unclassified buildings is based on the analysis of the real measured thermal energy consumption in fire stations. In total, the dataset on 40 fire stations was analysed. All analysed buildings were connected to district heating systems. Data was provided by the maintenance organizations of those buildings for the time period 2016–2019. In addition, on-site IAQ measurements and technical inspection was performed. EXTECH CO2/Humidity/Temperature dataloggers were used. These loggers have the following technical parameters:

✓ CO₂ range 0 to 4000 ppm; resolution 1ppm;

✓ Temperature range 0 to 50 °C; resolution 0.5 °C;

✓ Humidity range 10 to 90 %; resolution 0.1 %;

Dataloggers were installed in different rooms to evaluate indoor air quality.

For theoretical evaluation of energy consumption and effect of different retrofitting packages, the dynamic energy simulation tool Indoor Climate and Energy (IDA-ICE) 4.8 was chosen. This software allows to estimate energy consumption with one-hour interval and includes a detailed evaluation of heat balance, indoor air temperature, operative temperature etc. In addition, it takes into account human comfort level and metabolic rate.

IDA-ICE dynamic energy simulation tool was validated in accordance with ISO 13791:2012 [5] and [6]. Climate data was derived from ASHRAE 2013 which differs from ASHRAE 2017 data only by 2.5 % [15]. The accuracy of this software simulations was proved by studies [8, 9].

In general, calculations of the annual thermal energy demand for a prototype building can be determined by the equation adopted from [17]:

$$E_{annual} = \frac{\left(\Sigma U_i A_i + \Sigma \psi_j l_j + \Sigma \chi k + \left(V_{air} \cdot c \right) \right) \cdot 24 \cdot Dheat \cdot \left(T_{in} - T_{out} \right)}{1000 \cdot A_b} - \eta \cdot \left(Q_{int} + Q_{sol} \right), \quad (1)$$

where U_i is heat transfer coefficient of the building construction element (W/(m²·K));

A_i is the area of the respective construction element of the building prototype model (m²);

Ψ_i is heat transfer coefficient of the linear thermal bridge (W/(m·K));

l_i is length of the linear thermal bridge (m);

χ_k is heat transfer coefficient of the point thermal bridge (W/·K);

V_{air} is ventilation air volumetric flowrate (m³/h);

c is air heat capacity per volume = 0.34 (Wh/(m³×°K));

D_{heat} is number of heating days;

T_{in} is average set-point temperature in the assessment (heating or cooling) period (°C);

T_{out} is average external temperature in the calculation period (°C);

A_b is total floor area of the building (m²);

η is gain use coefficient for heating in accordance with Paragraph 99 of this Regulation or Standard LVS EN ISO 13790:2009 L;

Q_{int} is interior gains of the whole building in the assessment period t (kWh/m²);

Q_{sol} is solar heat gains (kWh/m²).

$$Q_{sol} = \frac{\sum A_{sol} \cdot E_{sol}}{1000 \cdot A_b}, \tag{2}$$

where A_{sol} is area of collecting useful solar energy of the building (m²);

E_{sol} is solar irradiation in the assessment period t per area A_{sol} (Wh/m²).

3. Results and Discussion

3.1. Typology of fire stations

During the period before the year 1940, 15 % of buildings currently serving as fire stations were built (with the total area of 2553.7 m²). From 1945 to 1970, 45 % of all fire station buildings were built with the total area of 11251.1 m². From 1971 to 1900, 25 % of fire stations buildings were built with the total area of 8208.0 m². After 1991, the remaining 15 % of all fire stations buildings were built with the total area of 4098.1 m². A typological overview of several Latvian fire stations is provided in Figure 1.

| a) 1973 | b) 1934 | c) 1960 |

| d) 1965 | e) 1993 | f) 1989 |

Figure 1. A review of typical Latvian fire stations.

As shown in Figure 1, all fire stations were built according to individual projects. However, a typology of the analysed depots indicates to common construction principles. Namely, the first floor is used for parking fire-fighting vehicles whereas the second floor is used for staff needs and administration. For the purpose of this research a unified fire station building model was developed in Industry Foundation Classes (IFC) data model format (Figure 2) in order to evaluate different retrofitting scenarios. However it should be noted that theoretical estimations are not always achieved in practice, and therefore a certain degree of deviation may occur between the theoretical model and the actual fire stations [18].
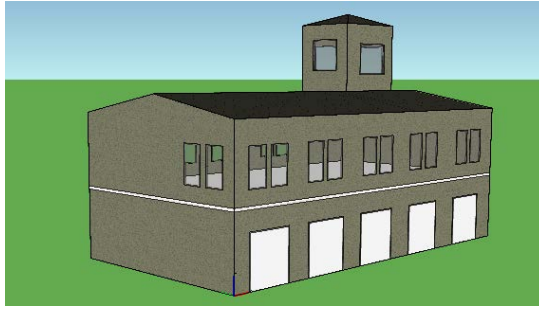
Figure 2. Industry Foundation Classes (IFC) data model for a typical Latvian fire station.

Using the 3D model, it is possible to evaluate the efficiency of various energy performance improvement measures and their conformity with the specific nature of fire stations. Similar layout and construction features can be found in many post-soviet countries including Russian Federation, where brick walls are historically widely used for such buildings.

3.2. Measurements of indoor air quality in a non-renovated fire station

The analysed building was constructed in 1910. There is not any mechanical ventilation and central hot tap water system installed. An exhaust ventilation system is installed to extract the exhaust gas from the firefighting truck exhaust pipes. Indoor air quality measurements were conducted in two different premises: a) a break room of a firefighting depot staff and b) a repair shop in the same building. Measurement results showed the diurnal changes of the indoor environmental parameters for the break room (Figure 3). In total 8000 measurements were recorded with 10-minute intervals.
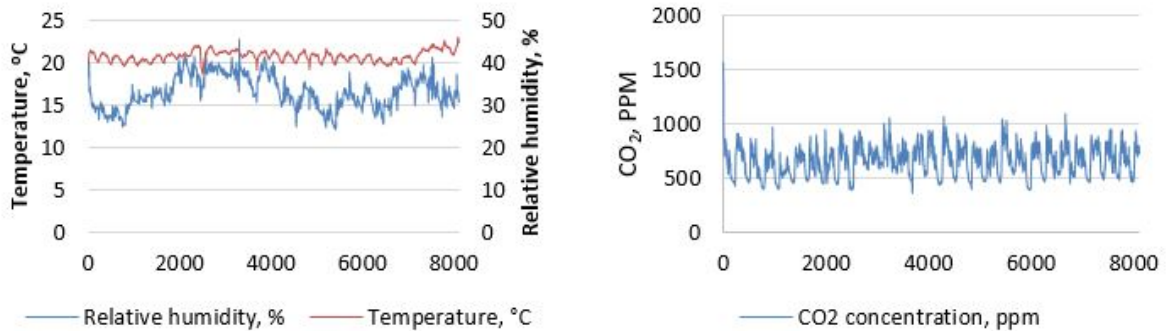

Figure 3. Indoor air quality measurements for the break room.

Analysis of the graphs in Figure 3 shows that the indoor air temperature ranges from 18 to 23 °C with an average of 20.7 °C. It can be concluded that the indoor air temperature fits the recommended temperature range for human thermal comfort set forth by Latvian Building Norms and commonly referred international industry recommendations, such as ASHRAE [19]. Changes in temperature follow a diurnal pattern with peaks in indoor air temperature during the second part of the day.

Relative humidity ranges from 25 to 45 % with an average of 33 %, which is below the recommended values for human comfort. Similarly to indoor air temperature, relative humidity peaks are observed primarily during the afternoon hours.

The average concentration values of carbon dioxide CO_2 came out to 662 ppm which is below the limit of 1000–1200 ppm set forth by industry standards. Concentrations of CO_2 peaks at around 900–1000 ppm during the second part of the day.

Results regarding the changes of indoor environmental parameters for the repair shop can be seen in Figure 4.
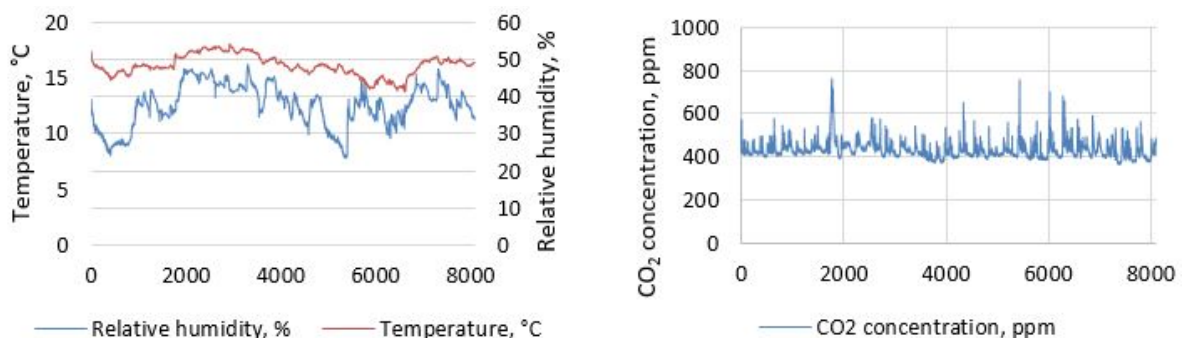

Figure 4. Indoor air temperature and relative humidity measurements for the repair shop.

Бородинец А., Проземент А., Заяцс А., Земитис Ю.

The average concentration of carbon dioxide CO_2 came out to be 430 ppm which is below the limit set forth by industry standards. Concentrations of CO_2 ranges from 360–760 ppm during with peak during the second part of the day.

Given that the analyzed building didn't have any kind of controlled ventilation system, while CO_2 was kept within acceptable limits and the relative humidity was low, it can be concluded that the airtightness of the external building envelope was not sufficient.

3.3. Analysis of thermal energy consumption and technical conditions

The measured average annual energy consumption including electricity for fire stations was 317 kWh/m^2. The relationship curve showing the link between fire stations' energy consumption and the year they were constructed is shown in Figure. 5.
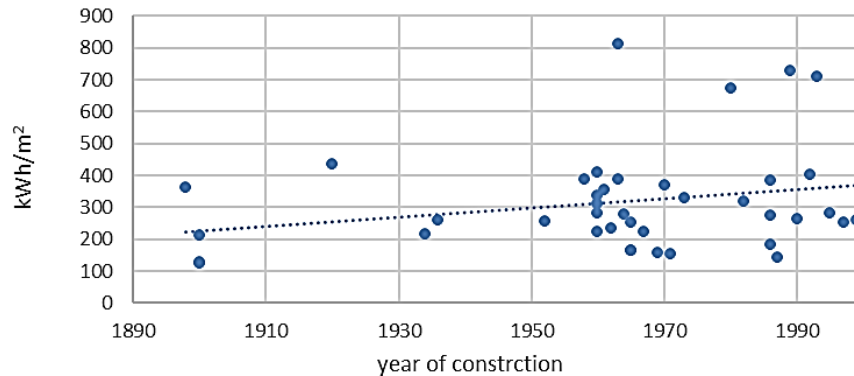

Figure 5. Measured average total annual energy consumption.

As it can be seen in Figure 5, there is no strict correlation between energy consumption of the building and its' year of construction. A more detailed analysis of thermal energy consumption in fire stations located in the City of Riga is shown in Figure 6.
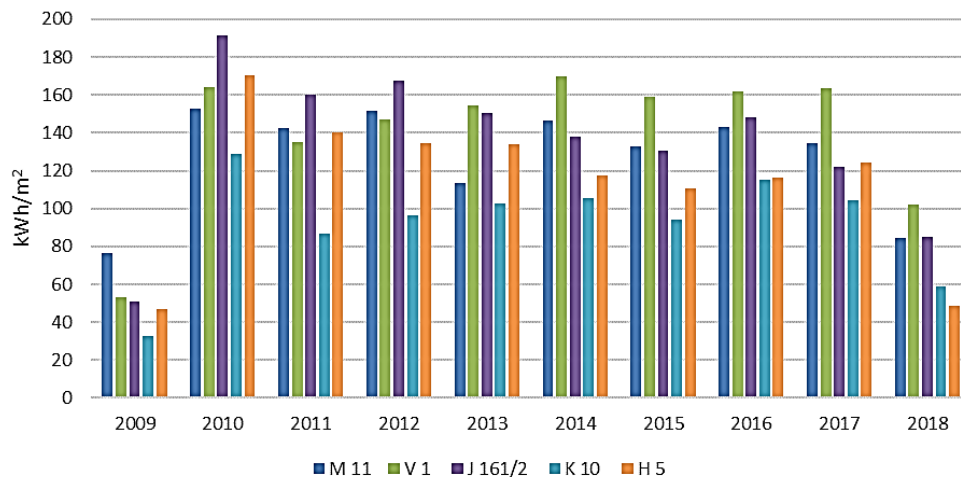

**Figure 6. Annual heat energy consumption of fire station
(address information is deliberately hidden).**

The investigated buildings have poor thermal performance, which is due to the fact that those buildings were constructed before 1990 when the normative U‾values stipulated by the national building code were not nearly as strict as they are today. The study results showed that the average annual heat consumption for fire departments is 135.4 kWh/m^2 within the timeline of 2010 to 2017. Data on the total annual energy consumption was not available for 2009 and 2018. Results are rather similar to typical Latvian multi apartment buildings, which annually consume 190 kWh/m^2 for heating and hot water preparation. It is also important to note that in contrast to residential buildings majority of the fire stations do not have central hot tap water systems. Instead, the electric hot water boilers are used.

During the energy audit, it was found that the existing hot tap water system is in poor technical condition and does not ensure sufficient supply of hot water.

Borodinecs, A., Prozuments, A., Zajacs, A., Zemitis, J.

3.4. Energy consumption estimation in different Latvian cities

In this chapter a theoretical estimation of energy consumption was performed for Latvian climatic conditions, which is similar in Baltic Region and in Western regions of Russian federation, in order validate dynamic energy calculations and to evaluate different retrofitting scenarios. For this purpose a typical Latvian fire station was selected (Figure 2). As a first step, a non-renovated building was analyzed. Table 1 presents data on Energy consumption of non-renovated buildings with the activity level of 2.0 MET, 1.4 CLO in garage and 1.2 MET, 0.85 CLO in office part. The energy consumption for hot tap water was not taken into consideration.

Table 1. Energy consumption of non renovated buildings, kWh/m².

	City of Riga	City of Liepaja	City of Gulbene	City of Daugavpils
HVAC electricity	0	0	0	0
District heating	136.2	123.2	160.7	151.5

As it can be seen in the table the obtained results for the City of Riga are in a good agreement with the measured data. The discrepancy is less than 10 %. It can be concluded that this model can be used for further estimation of the impact of retrofitting scenarios on final energy consumption.

In the scope of this study three retrofitting scenarios were analysed. Scenario 1 «basic» includes thermal insulation of building envelope in accordance to Latvian legislation [16] and installation of mechanical ventilation system without exhaust air heat recovery. Scenario 2 is similar to scenario 1, however, it is enhanced by the installation of the exhaust air heat recovery unit. Third scenario is a deep retrofitting approach which is suitable for Latvian climatic conditions [20, 21]. It includes installation of more efficient exhaust air heat recovery unit, better airtightness of building envelope and an extra thermal insulation that meets the passive house standard requirements.

Table 2. Description of retrofitting scenarios.

	U-values, W/m²K	Ventilations rate, n⁻¹	Exhaust air heat recovery, %	Airtightness of building envelops q_{50}, m³/(m²h)
Scenario 1 "basic"	Opaque elements – 0.2Windows – 1.3 Doors 1.8	Garage – 2Office part – 0.9	0	3.5
Scenario 2 – "basic plus"	Opaque elements – 0.2Windows – 1.3 Doors 1.8	Garage – 2Office part – 0.9	85	2
Scenario 3 "advanced"	Opaque elements – 0.10Windows – 0.7 Doors 1.2	Garage – 2Office part – 0.9	92	1

Table 3. Energy consumption of renovated buildings, kWh/m².

	Scenario 1				Scenario 2				Scenario 3			
	Riga	Liepaja	Gulbene	Daugavpils	Riga	Liepaja	Gulbene	Daugavpils	Riga	Liepaja	Gulbene	Daugavpils
HVAC electricity	25.7	25.7	25.7	25.7	25.1	25.1	25.1	25.1	25	25	25	25
District heating	229.0	215.1	265.9	252.9	63.2	54.5	83.9	80.1	46.1	39.1	64.7	62.14

Figure 7 shows annual comparison of thermal energy consumption before and after retrofitting.

The results of this study indicate that an installation of mechanical ventilation system without exhaust air heat recovery unit significantly increases energy consumption even for a well-insulated building. Installation of an exhaust air heat recovery unit, on the other hand, ensures a reduction of thermal energy consumption by 165.8 kWh/m² or by 72 %. However, there is a significant increase in electricity consumption to run an air handling unit which on average adds 25 kWh/m². The average district heating price in Riga is 62.8 Euro/MWh while the electricity price is 160 Euro/MWh. The economic benefit in this case would not be justified, as the financial benefit of energy saving measures of deep retrofit would not outweigh the cost of electricity consumption to run the AHU. Energy savings for thermal energy is 10.4 Euro/m² and increase for electricity use is 4 Euro/m². This would make an overall energy cost reduction 6.4 Euro/m².
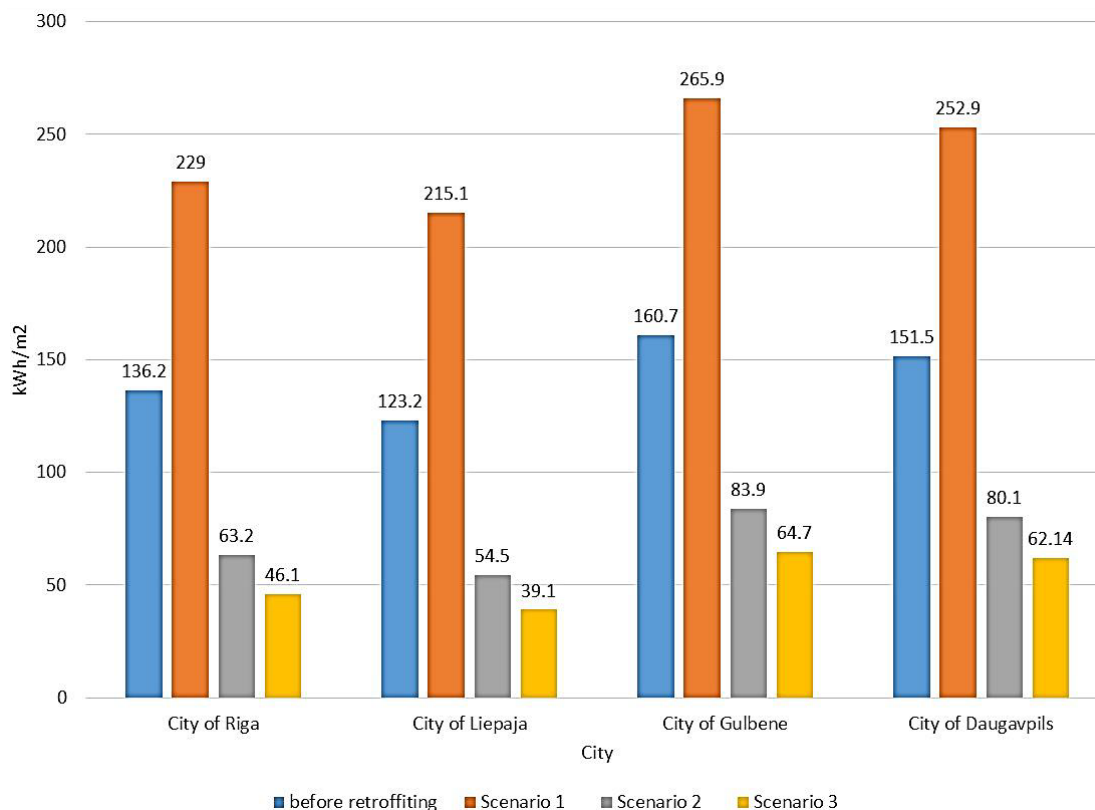
Бородинец А., Проземент А., Заяц А., Земитис Ю.

Figure 7. Comparison of energy consumption for heating before and after renovation.

4. Conclusions

In scope of this study a detailed analysis of indoor air quality and energy consumption for Latvian fire stations was performed. Acquired results can be expanded and applied in other countries and regions located in cold climate zone. Analysed buildings represent typical brickwork construction widely used before 1990ies not only in Latvia but in majority of the post-soviet countries.

1. Despite the increased focus on implementation of energy efficient measures in buildings, the world's energy consumption is constantly increasing. The main target group for implementation of energy efficiency measures in building sector are multi apartment and public buildings. Meanwhile the energy efficiency in so called unclassified buildings is not adequately addressed, as these buildings are not part of governmental subsidies. However, energy consumption of such buildings as fire stations should not be neglected. Firstly, majority of these buildings were constructed before 1990ies without substantial thermal insulation. Secondly, fire stations are operating 24/7 and should provide an adequate thermal comfort and indoor air quality for their personnel. Currently, the thermal comfort conditions can be ensured only in renovated airtight buildings

2. In scope of this study the indoor air quality measurements were performed in non-renovated fire station depot which is located in City of Riga, representing cold climate zone. Analysis had shown that the average indoor air temperature was 20.7 °C, average relative humidity – 33 % and CO_2 concentration 662 ppm. It can be concluded that non renovated external building envelope can be characterized by a high uncontrolled air infiltration rate. Extra air infiltration is compensated by extra heating load.

3. The paper presents the results of calculated and measured data of the energy consumption for fire stations that were built before 1990s. The measured data for these buildings show that average measured total thermal energy consumption is 135.4 kWh/m^2 while the total energy consumption including electricity was about 317 kWh/m^2.

4. Dynamic energy simulation for typical fire station has shown a good correlation with measured data. Based on the dynamic energy simulation the theoretical energy savings were evaluated for three different scenarios. Typical deep retrofitting package allows for 66 % reduction of thermal energy for space heating. Installation of mechanical ventilation system without heat recovery increases energy consumption by 72 % in comparison to renovated building without any mechanical ventilation.

5. Acknowledgements

Borodinecs, A., Prozuments, A., Zajacs, A., Zemitis, J.

References

1. D'Agostino, D., Mazzarella, L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. Journal of Building Engineering. 2019.

2. Shaffer, B., Flores, R., Samuelsen, S., Anderson, M., Mizzi, R., Kuitunen, E. Urban Energy Systems and the Transition to Zero Carbon – Research and Case Studies from the USA and Europe. Energy Procedia, 2018.

3. (DOE) US Department of Energy. An Assessment of Energy Technologies and Research, 2015.

4. Amecke, H., Deason, J. Buildings Energy Efficiency in China, Germany and the United States. Clim. Policy Initiat., 2013.

5. Gorshkov, A.S. The energy efficiency in the field of construction: questions of norms and standarts and solutions for the reduction of energy consumption at buildings. Magazine of Civil Engineering. 2010. 11(1). Pp. 9–13.

6. Rueda, R., Cuéllar, M.P., Pegalajar, M.C., Delgado, M. Straight line programs for energy consumption modeling. Appl. Soft Comput. J. 2019.

7. Karatasou, S., Santamouris, M. Socio-economic status and residential energy consumption: A latent variable approach. Energy Build. 2019.

8. Oliveira, M. et al. Polycyclic aromatic hydrocarbons at fire stations: firefighters' exposure monitoring and biomonitoring, and assessment of the contribution to total internal dose. J. Hazard. Mater. 2017.

9. McCormac, Declan. Dublin City Council Fire Brigade Survey. Display Energy Certificate: Advisory Report. Dublin, 2011.

10. Aydin, E., Brounen, D. The impact of policy on residential energy consumption. Energy, 2019.

11. K. Forward, D. Nahill, and Jeffrey Stokes, «City of Boston's Firehouse Energy Efficiency» 2011.

12. Rokde, P., Valdes-Vasquez, R., Mosier, R. The Green Status of Fire Stations in the United States: An Analysis of LEED-NC V3. J. Green Build., 2019.

13. Golova, T.A., Denisova, A.P. Energy efficiency of the Rural Wall multi-layer structure in low-rise building design. Magazine of Civil Engineering. 2014.52(8). Pp. 9–19. (rus). DOI: 10.5862/MCE.52.2.

14. Peregrine Energy Group. Energy Efficiency Opportunities For Fire Department Facilities West Ossipee, New Hampshire. Boston, 2011.

15. Baranova, D., Sovetnikov, D., Borodinecs, A. The extensive analysis of building energy performance across Baltic sea-region. Sci. Technol. Built Environ. 2018. Pp. 1–45, Apr.

16. Borodinecs, A., Zemitis, J., Sorokins, J., Baranova, D.V., Sovetnikov, D.O. Renovation need for apartment buildings in Latvia. Magazine of Civil Engineering. 2016. 68(8). Pp. 58–64. DOIi: 10.5862/MCE.68.6

17. Danilevsky, L.N., Danilevsky, S.L. The algorithm and accuracy of definition of heattechnical indicators of buildings. Magazine of Civil Engineering. 2017. 73(5). Pp. 49–61. doi: 10.18720/MCE.73.5.

18. Korniyenko, S. Analysis of energy consumption levels for energy efficiency estimation in buildings. Energy-Safety and Energy-Economy, 2017.

19. ASHRAE. ASNI/ASHRAE STandard 62.1 – 2007: Ventilation for acceptable indoor air quality, 2010.

20. Kalamees, T. et al. What kind of heat loss requirements NZEB and deep renovation sets for building envelope? CESB 2016 – Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future, 2016.

21. D'Agostino, D., Mazzarella, L. Data on energy consumption and Nearly zero energy buildings (NZEBs) in Europe. Data Br., 2018.

Contacts:

Anatolijs Borodinecs, +37126079655; anatolijs.borodinecs@rtu.lv

Aleksejs Prozuments, 26079655; aleksejs.prozuments@rtu.lv

Aleksandrs Zajacs, 003719874677; aleksandrs.zajacs@rtu.lv

Jurgis Zemitis, +37128369940; jurgis.zemitis@rtu.lv