OPTIMIZATION OF EXTERNAL WALLS THERMAL INSULATION TECHNOLOGIES CONSIDERING COSTS AND TIME OF EXECUTION

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Abstract

Buildings constructed several decades ago do not meet the energy efficiency requirements of current legislation and therefore needlessly consume great amounts of energy for heating. Most often their energy performance is improved by applying additional thermal insulation layers on buildings external walls. Research presented in this paper analyzes construction technologies of various thermal insulation types and corresponding time needed for work execution and related costs. Economic analysis of proposed thermal insulation materials in this study is done by using the simple payback period. This paper presents a systematic approach for optimization of insulation material type and thickness. The optimization is based on implementation costs and time required for construction works. This case study is done by using database obtained from several single family houses in Croatia which have undergone a process of energy certification and which currently do not have insulation layers on their external walls. Two insulation materials are considered in this study, rock wool and polystyrene insulation and various thickens of those insulation. Research results presented in this paper can be useful in the selection of thermal insulation material and insulation thickness when considering not only buildings energy efficiency improvements but also time spent for applying insulation layer on external walls and cost effectiveness of selected insulation.

Key words

construction technologies; economic analysis; energy efficiency; optimization; thermal insulation

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1 INTRODUCTION

Residential sector, as the biggest individual energy consumer, has a significant impact on energy consumption and high potential for energy efficiency gains [1]. In Croatia, residential sector accounts for approximately 86% of total building stock [2]. Approximately 40 % of residential buildings are constructed before 1970, the year when first actual regulations addressing energy efficiency of building where set and 75% before 1987 [2]. The main problem of these buildings constructed several decades ago is that they lack the adequate thermal insulation, according to the current legislation, and therefore consume massive amounts of energy for heating and cooling.

Studies have shown that the average heat loss in buildings which are constructed several decades ago ranges mainly between 180 and 250 kWh/m^{2}a [3]. Great amount of energy in these buildings is lost through buildings' envelope i.e. un-insulated external walls, since in most residential buildings walls constitute the largest surface of the opaque envelope. Considering the fact that buildings' envelope and its condition, together with a building form, have an important impact on the energy efficiency and thermal performance of the building, the use of the thermal insulation is essential.

In order to reduce energy consumption and improve the energy efficiency and energy performance of new and existing buildings, Croatia has implemented policies of Energy Performance Building Directive - EPBD. One of the requirements of this Directive is that all new and existing buildings must have an Energy rating certificate. The purpose of energy certification of buildings procedure is to provide information of the energy efficiency of buildings and to give cost-effective recommendations (measures) on how to improve buildings' energy efficiency. Every proposed measure in Energy rating certificate has a calculated simple payback period. Further, according to the Directive minimum energy performance requirements for new and existing buildings that are being reconstructed have been set, as well as the minimum energy performance requirements for building envelope elements [4].

The most important parameter for determining heat loss through the building envelope for different building forms is thermal transmittance coefficient (U-value). At this point, maximum value of thermal transmittance coefficient (U-value) for external walls, which needs to be met, has been set to 0.30 W/m^{2}K for continental part of Croatia where an average monthly air temperature of the coldest month is less or equal to 3°C [4].

Regarding the above mentioned, and the fact that the heat loss through walls accounts for 35% of the total loss [5], one of the most effective and common measures, provided in *The Ordinance on energy audits of construction works and energy certification of buildings*, is the improvement of thermal performance of the envelope by applying thermal insulation. Since insulation materials have low thermal conductivity, the proper selection and use of thermal insulation can significantly improve buildings' energy efficiency and reduce annual energy needs for heating and thus the greenhouse gases emission.

This paper studies rock wool and polystyrene insulation, as the most commonly used materials in Croatia. The research is carried out with a purpose to determine the most cost-effective insulation and its optimum thickness, considering the time of execution. Furthermore, it estimates potential improvement in terms of energy savings and greenhouse gas emission. For this purpose, four single family houses are analysed with the insulation layer placed on the outer side of the building envelope.

Nomenclature	
A	Surface area of the heated building section
f_0	Building shape factor
V	Volume of heated air
$Q''_{H,nd,ref}$	Specific annual energy needs for heating for referential climatic data
λ	Thermal conductivity coefficient

2 THERMAL INSULATION TECHNOLOGIES

Thermal insulation is a material or combination of materials used on the building envelope [6]. The purpose of these materials is to reduce energy consumption in buildings, to prevent heat loss and heat gain through the building envelope, as well as to protect and provide thermal comfort for the occupants [7]. When selecting thermal insulation material it is necessary to take into account many characteristics such as: fire resistance, durability, water vapour permeability, density, moisture resistance and thermal conductivity. However, thermal conductivity of insulation material is the most important parameter for determining effectiveness of material in conducting heat.

In Croatia, most commonly used materials for thermal insulation of walls are rock wool (MW) and expanded polystyrene (EPS). In terms of energy savings and thermal protection of external walls, these materials are used as a part of external thermal insulation composite system – ETICS in accordance with HRN EN 13499 and HRN EN 13500 standards. The structure of external thermal insulation composite system – ETICS consists of several components – wall, adhesive mortar, thermal insulation layer, mortar reinforcement layer, alkali-resistant fiberglass mesh and finishing decorative plaster. The insulation layer is usually done with rock wool panels, rock wool lamellas or EPS panels. The main difference between panels and lamellas is construction technology and the need of additional strengthening.

The thermal insulation technology of ETICS system with EPS panels or rock wool panels consists in the application of panels onto the outer side of the wall, then the installation of a mortar layer with reinforcing fiberglass mesh, and finally, the application of the finishing layer made of thin - coat render [8]. Adhesive mortar is applied directly onto the board using "strip - point" method and not onto the substrate. The characteristic of these systems with panels is that it is additionally mechanically strengthened usually with mechanical fasteners with plastic pins/anchoring nails. The problem with this kind of reinforcement is that it causes dotted heat loss. Example of dotted heat loss is presented in Figure 1.

Fig. 1: Example of dotted heat loss on a buildings' facade

Unlike these systems, thermal insulation technology of ETICS system with rock wool lamellas does not require additional strengthening to the insulation thickness of 20 cm with the height of buildings of up to 22 m. The difference is also in the application of adhesive mortar that is, in this system, applied directly onto the whole surface of a panel.

The selection of thermal insulation materials in this paper was done with regard to *Technical Regulation on the Rational Use of Energy and Thermal Insulation in Buildings* [4] restrictions regarding U-value of reconstructed building elements and in accordance with the requirements of EN 13163 standards for expanded polystyrene and HRN EN 13162 standards for rock wool. The main characteristics of used materials are shown in Table 1. Regarding the technology of application, two types of rock wool insulation (panels and lamellas) and one type of expanded polystyrene insulation are considered. The common feature for these three materials is approximately the same value of thermal conductivity coefficient, λ.

Tab. 1: Main characteristics of insulation materials [4, 9, 10]

Insulation type	**Thermal conductivity, λ [W/mK]**	**Density [kg/m^3]**	**Fire resistance class**	**Water vapour permeability, μ**
Expanded polystyrene panels	0.037	21	E	60
Rock wool panels	0.035	100	A1	1.10
Rock wool lamella	0.040	85	A1	1.10

3 CASE STUDY BUILDINGS

This case study analyses four single family houses. All four of these houses have undergone a process of energy certification and currently do not have insulation layers on their external walls. The buildings are located in Osijek-Baranja County, in Osijek or near Osijek.

Some of the buildings' major characteristics are listed in Table 2. Buildings are built between 1964 and 2002. All of these buildings have natural ventilation and central heating system which utilizes gas as an energy source for heating. Buildings A, B, and D have several exposed facades, and building C only one. Further, buildings A, B and C have external walls constructed of full clay bricks and building D of hollow clay bricks which have a somewhat lower value of thermal conductivity coefficient. The difference in material used for the construction of walls lies in the year of construction and the most commonly used materials for that period.

Tab. 2: Buildings' major characteristics

Characteristics	**Building A**	**Building B**	**Building C**	**Building D**
A [m^2]	380.12	279.83	358.26	234.44
V [m^3]	439.23	172.27	235.96	193.31
f_0	0,66	1.23	1.15	0.92
Year of construction	1971	1970	1964	2002
Orientation	N-E-W	SE-NW	NE-SW	NE-SW
Wall area [m^2]	172.76	77.35	109.69	59.11

Since all buildings have undergone a process of energy certification the values of annual energy consumption, annual emissions of greenhouse gases and annual heating costs have been determined as well as building energy efficiency rates, as shown in Table 3. In Croatia, energy efficiency rate goes from A+ to G and currently depends on $Q''_{H,\,nd,\,ref.}$

Tab. 3: Buildings' energy consumption before refurbishment

Characteristics	Building A	Building B	Building C	Building D
Annual energy consumption [m3]	4,939.09	2,274.9	4,982.47	2,121.85
Heating costs [€]	3,565.66	1,642.31	3,596.97	1,531.82
Annual emissions of CO_2 [kg]	10,556.13	4,862.06	10,648.85	4,534.95
$Q'_{H,nd,ref}$ [kWh/(m^{2}a)]	235	259	395	209
Building energy efficiency rating	F	G	G	F

One of the proposed measures, for all four buildings, is a setup of thermal insulation on exterior walls as considered in this case study. For each building, three different types of insulation and three different levels of thickness of each are analysed.

4 ECONOMIC ANALYSIS AND CASE STUDY RESULTS

Economic analysis for the proposed thermal insulation materials in this study is done by using the simple payback period. The payback period is defined as the time taken for the total initial investment of a product to be recovered by the total accumulated savings [11]. It is calculated as a ratio of an invested capital for a proposed measure and savings achieved with that measure. It is usually expressed in years.

For the current level of complexity and current legislation of energy certification procedure, simple payback period is a good indicator of the viability of the proposed energy efficiency measures [12]. To estimate the simple payback period, building energy performance i.e. annual energy consumption and annual heating costs must be determined.

In this paper, simple payback period is calculated for each proposed insulation material. In order to determine an impact of the insulation thickness on the simple payback period in this case study, thickness was varied in three steps for each type of insulation, as shown in Table 4. Thickness of insulation materials was determined with regard to *Technical Regulation on the Rational Use of Energy and Thermal Insulation in Buildings* [4] restrictions, regarding the U-value of the reconstructed building element. Before the calculation of the simple payback period, annual energy consumption and annual heating cost have been determined after a setup of each type and thickness of insulation, as shown in Table 4. The gas price used for the heating cost calculation, in this case study, was 5.40 kn/m^3, i.e. 0.7219 € calculated by using the Croatian National Bank exchange rate list on May 24, 2016. Investment costs (total price) of each thermal insulation type were calculated based on the quantity of work (wall area) and work and material unit prices for each building, obtained from various manufacturers of the insulation material, Table 4. Once savings in heating cost and investment cost were determined simple payback period was calculated for each building and proposed measure, Table 4.

Tab. 4: Annual gas consumption, annual gas price, investment cost, achieved savings and simple payback period for each type and thickness of insulation material

Characteristics	Building A	Building B	Building C	Building D
Expanded polystyrene panels, 16 cm				
Annual energy consumption [m3]	2,761.87	1,725.62	3,332.26	1,825.95
Heating costs [€]	1,993.86	1,245.76	2,405.64	1,318.20
Unit price of investment [€/m^2]	16.63	16.63	16.63	16.63
Total price [€]	2,872.25	1,286.00	1,823.67	982.74
Savings [€]	1,571.79	396.54	1,191.33	213.62
Simple payback period	**1.8**	**3.2**	**1.5**	**4.6**
Expanded polystyrene panels, 18 cm				
Annual energy consumption [m3]	2,724.01	1,714.25	3,303.6	1,817.28
Heating costs [€]	1,966.53	1,237.56	2,384.95	1,311.94
Unit price of investment [€/m^2]	17.82	17.82	17.82	17.82
Total price [€]	3,079.19	1,378.65	1,955.06	1,053.55
Savings [€]	1,599.13	404.75	1,212.03	219.88
Simple payback period	**1.9**	**3.4**	**1.6**	**4.8**
Expanded polystyrene panels, 20 cm				
Annual energy consumption [m3]	2,692.96	1,704.6	3,279.98	1,809.89
Heating costs [€]	1,944.11	1,230.60	2,367.90	1,306.60
Unit price of investment [€/m^2]	19.02	19.02	19.02	19.02
Total price [€]	3,286.14	1,471.30	2,086.46	1,124.35
Savings [€]	1,621.54	411.71	1,229.07	225.22
Simple payback period	**2.0**	**3.6**	**1.7**	**5.0**
Rock wool panels, 15 cm				
Annual energy consumption [m3]	2,770.37	1,728.52	3,338.36	1,828.08
Heating costs [€]	2,000.00	1,247.86	2,410.05	1,319.73
Unit price of investment [€/m^2]	22.08	22.08	22.08	22.08
Total price [€]	3,815.04	1,708.11	2,422.27	1,305.32
Savings [€]	1,565.66	394.44	1,186.93	212.08
Simple payback period	**2.4**	**4.3**	**2.0**	**6.2**
Rock wool panels, 16 cm				
Annual energy consumption [m3]	2,749.34	1,722.17	3,322.06	1,823.24
Heating costs [€]	1,984.81	1,243.28	2,398.28	1,316.24
Unit price of investment [€/m^2]	22.97	22.97	22.97	22.97
Total price [€]	3,968.63	1,776.88	2,519.79	1,357.87
Savings [€]	1,580.84	399.03	1,198.69	215.57
Simple payback period	**2.5**	**4.5**	**2.1**	**6.3**

Rock wool panels, 18 cm				
Annual energy consumption [m3]	2,712.44	1,711.07	3,294.21	1,814.75
Heating costs [€]	1,958.18	1,235.26	2,378.18	1,310.11
Unit price of investment [€/m^2]	25.01	25.01	25.01	25.01
Total price [€]	4,319.92	1,934.16	2,742.84	1,478.07
Savings [€]	1,607.48	407.04	1,218.80	221.71
Simple payback period	**2.7**	**4.8**	**2.3**	**6.7**
Rock wool lamellas, 14 cm				
Annual energy consumption [m3]	2,739.03	1,721.58	3,312.57	1,821.25
Heating costs [€]	1,977.37	1,242.85	2,391.43	1,314.81
Unit price of investment [€/m^2]	40.86	40.86	40.86	40.86
Total price [€]	7,059.14	3,160.60	4,482.04	2,415.29
Savings [€]	1,588.28	399.46	1,205.54	217.01
Simple payback period	**4.4**	**7.9**	**3.7**	**11.1**
Rock wool lamellas, 16 cm				
Annual energy consumption [m3]	2,699.13	1,709.55	3,282.33	1,812.11
Heating costs [€]	1,948.57	1,234.17	2,369.59	1,308.21
Unit price of investment [€/m^2]	43.24	43.24	43.24	43.24
Total price [€]	7,469.33	3,344.25	4,742.48	2,555.64
Savings [€]	1,617.09	408.14	1,227.38	223.61
Simple payback period	**4.6**	**8.2**	**3.9**	**11.4**
Rock wool lamellas, 18 cm				
Annual energy consumption [m3]	2,666.55	1,699.57	3,258.04	1,804.48
Heating costs [€]	1,925.05	1,226.97	2,352.06	1,302.70
Unit price of investment [€/m^2]	45.61	45.61	45.61	45.61
Total price [€]	7,880.21	3,528.21	5,003.36	2,696.22
Savings [€]	1,640.61	415.34	1,244.91	229.12
Simple payback period	**4.8**	**8.5**	**4.0**	**11.8**

Table 3 and 4 show that specific annual heating energy needs for referential climatic data for building C have decreased for 33%, but in order to increase the energy efficiency rating of this building, it is necessary to implement a comprehensive reconstruction. Considering the wall area of the observed buildings, as expected, the specific annual heating energy needs for referential climatic data after implementation of each type of thermal insulation decreased the most, approximately 44%, for building A. Further, for building B the energy needs decreased around 24 %, for building C around 33% and for building D around 14%. The annual greenhouse gas emission has decreased in the same percentage. Nevertheless, lowering of the annual greenhouse gas emission due to installation of thermal insulation layers should be analysed more thoroughly by taking into account the greenhouse gas emission generated as a result of production of the analysed insulation materials.

After the implementation of each type of the thermal insulation, the efficiency rating of building A increased from F to D for all three thickness levels observed in this case study.

The same was with buildings B and D where for all three types of insulation material and thickness levels, the energy efficiency rating increased from G to E for building B, and for building D from F to E. The only building where the energy efficiency rating did not change was building C, given the fact that it is the oldest one in this study, and was also in the worst condition.

Further analysis evaluates the time required for construction works. Regarding the construction technology of insulation materials, time of execution for the use of expanded polystyrene panels was found to be 1.25 h/m^2, 1.42 h/m^2 for the rock wool panels and 1.47 h/m^2 for the rock wool lamellas. Specified time for construction works was obtained from various manufacturers of the insulation materials.
Results regarding investment cost and heating costs are presented graphically in Figure 2.

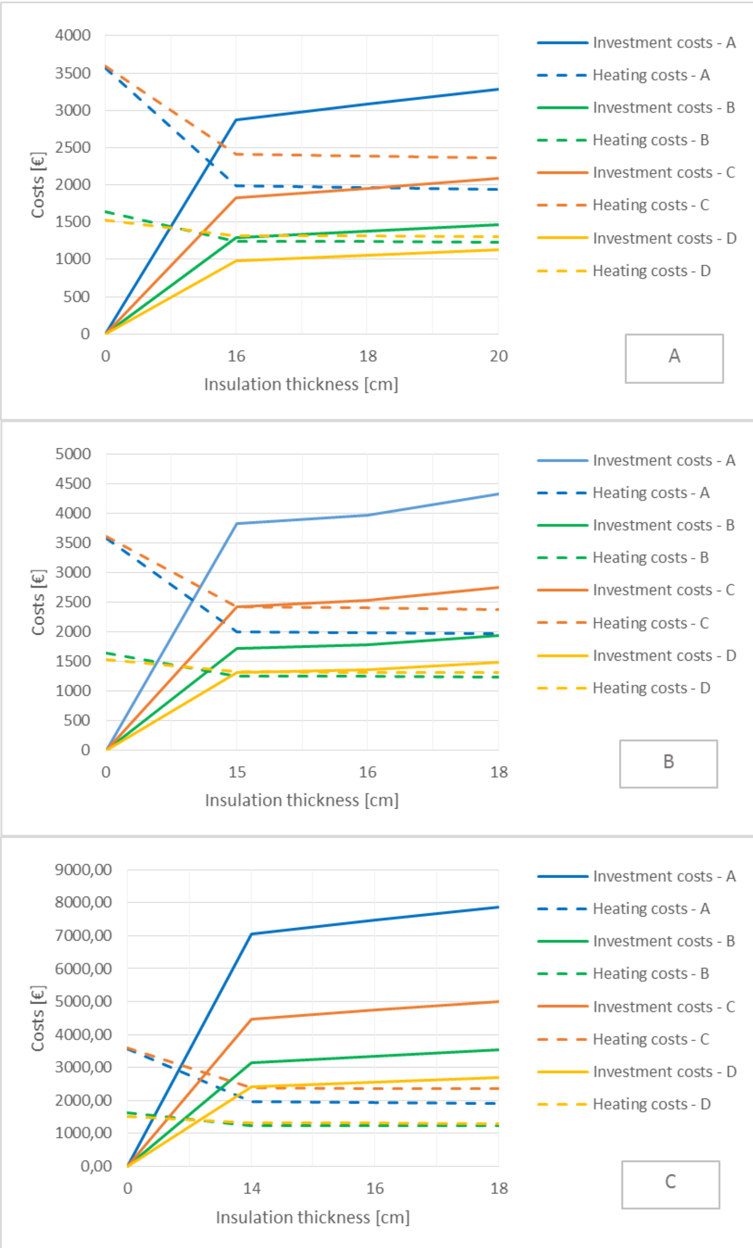

Fig. 2: Investment and heating costs versus insulation thickness; A) expanded polystyrene panels, B) rock wool panels, C) rock wool lamellas

It is obvious and expected that with the increase of insulation thickness, the investment costs of the insulation material also increase, while the cost of energy consumption decreases. On the other hand, the energy cost decrease declines slower with the increase of the insulation thickness compared to the increase of the insulation costs.

Increasing the thermal insulation thickness causes the increase of the investment costs at the rate of approximately 5% while on the other hand, the costs of energy consumption are decreasing at the rate of approximately 1.50%.
The optimum insulation thickness is the thickness at which the total cost is minimum [13]. Regarding the time of execution, simple payback period and costs, under the conditions given in this case study, expanded polystyrene appears to be the most cost effective material type with an optimum thickness of 16 cm.

5 CONCLUSION

In order to determine optimum insulation thickness and material type applied on buildings´ external walls this study analyzed the costs and time of execution. For this purpose, rock wool panels, rock wool lamellas and expanded polystyrene panels were evaluated when applied on external walls in four typical single family houses. The calculation of simple payback period, that is mandatory according to *Ordinance on energy audits of construction works and energy certification of buildings* when conducting the buildings' energy certification procedure, was used for the economic analysis. Simple payback period was calculated for each type and thickness of insulation materials. The annual energy consumption and annual heating costs before and after the implementation of thermal insulation on external walls, were input for the calculation of this period. Since it is no longer a question whether thermal insulation should be used on the building envelope, optimum thickness and material type regarding the cost and time of execution can significantly help the owners in conducting the energy efficiency refurbishment.

For each type of the insulation material, thickness was varied in three steps. As expected, the costs of investment i.e. thermal insulation are found to increase with the increase of insulation thickness. On the contrary, with the increase of insulation thickness, the costs of energy decrease.

Since all elements of the building envelope must fulfil restrictions regarding the U-value during the energy efficiency refurbishment, and as a consequence of the complexity of thermal insulation technologies, it was found that, under the given conditions in this case study, the optimum insulation material is expanded polystyrene with the thickness of 16 cm.

REFERENCES

[1] OECD/IEA, A. (2008)., *Promoting Energy Efficiency Investments – Case Studies in the Residential Sector*. Paris: OECD/IEA.

[2] *Dugoročna strategija za poticanje ulaganja u obnovu nacionalnog fonda zgrada Republike Hrvatske*. Vlada Republike Hrvatske, 2014.

[3] UNDP, *Prirucnik za energetsko certificiranje zgrada-1 dio*, 2010, Program UN-a za razvoj: Zagreb.

[4] *Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama (Translation: Technical Regulation on the Rational Use of Energy and Thermal Insulation in Buildings)*. „Narodne novine“ broj 128/15; Available from: http://narodne-novine.nn.hr/clanci/sluzbeni/2014_08_97_1938.html.

[5] *Energy efficiency in traditional buildings*, ed. J. Donnelly. 2010: Government of Ireland

[6] Al-Homoud, D.M.S. (2005). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment*, 40(3): p. 353-366.

[7] Al-Sanea, S.A., M.F. Zedan, Al-Hussain, S.N. (2012). Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. *Applied Energy*, 89(1): p. 430-442.

[8] Zakon o energiji. „Narodne novine“ broj 102/15; Available from: http://narodne-novine.nn.hr/clanci/sluzbeni/2012_10_120_2583.html.

[9] Schiavoni, S., et al. (2016). Insulation materials for the building sector: A review and comparative analysis. *Renewable and Sustainable Energy Reviews*, 62, p. 988-1011.

[10] Program energetske obnove obiteljskih kuća za razdoblje od 2014. do 2020. godine s detaljnim planom za razdoblje od 2014. do 2016. godine. „Narodne novine“ broj 36/15; Available from: http://narodne-novine.nn.hr/clanci/sluzbeni/2014_04_43_793.html.

[11] Wong, I.L., P.C. Eames, Perera, R.S. (2007). A review of transparent insulation systems and the evaluation of payback period for building applications. *Solar Energy*, 81(9): p. 1058-1071.

[12] Krstić, H., M. Teni, Šandrk Nukić, I. (2015). Sensitivity analysis of cost-effective recommendations for improving building energy efficiency, in *12th International Conference Organization, Technology and Management in Construction*, Conference Proceedings, Croatian Association for Construction Management and University of Zagreb, Faculty of Civil Engineering: Primošten. p. 16-29.

[13] Al-Sanea, S.A., M.F. Zedan. (2002). Optimum insulation thickness for building walls in a hot-dry climate. *International Journal of Ambient Energy*, 23(3), p. 115-126.