Optimization of thermal insulation to achieve energy savings

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Abstract:

Due to the current environmental situation, saving energy and reducing CO_2 emission have become the leading drive in modern research. For buildings that require heating, one of the solutions is to optimize a width of their thermal insulation layer and thus improve energy efficiency and reduce energy needs. In this paper, for a small residential house in Serbia, an optimization in the width of its thermal insulation layer is investigated by using EnergyPlus software and Hooke-Jeeves direct search method. The embodied energy of thermal insulation is taken into account. The optimization is done for the entire life cycle of the house. The results show what optimal thickness of thermal insulation yields the minimum primary energy consumption.

Keywords:

Energy efficiency, Thermal insulation, Hooke-Jeeves optimization, CO_2 emissions, EnergyPlus, life cycle

1. Introduction

Current environmental situation requires increased research in energy efficiency and energy savings in built environment due to reduced conventional fuel resources and increased CO_2 emissions, which create greenhouse effect. Therefore new projects are financed from local governments and European Union to improve energy use, increase energy production from renewable resources and decrease greenhouse gas emissions [1].

To save energy and improve energy efficiency, investigations of thermal insulation materials and their embodied energy in buildings accelerates. Monahan and Powell [2] (2011) discussed embodied energy and energy analysis during the life cycle of a house. The research included all materials that the house is built from, with part of paper that deals with thermal insulation. Yu and Kang [3], Upton [4], Thormark [5] and Gustavson [6] investigated materials, their embodied energy and greenhouse gas emission during their life cycles. Milutienė (2010) inspected embodied energy included in zero–net energy house design [7]. However, they did not optimize the thermal insulation thickness for the minimum total primary energy consumption during the life cycle of the house taking into account the embodied energy of the thermal insulation.

This paper reports a research in energy saving through an optimal use of different types of thermal insulation in a residential house. Different types of thermal insulation may be used in the house; however they have different amounts of embodied energy. The objective is to minimize the sum of the primary energy used for heating during the life cycle and the embodied energy of applied thermal insulation. The final result is the optimized thermal insulation thickness for the residential house. EnergyPlus software is used to simulate energy flows in the house. Using GenOpt code programs the objective function. The optimization routine is an algorithm of Hooke-Jeeves optimization.

2. Scope of research

2.1. Thermal and geometrical description of the residential house

The residential house has two-storeys and four rooms. On the first storey, it has one large living room and one toilet, while on the second storey, it has two bedrooms (Figure 1).

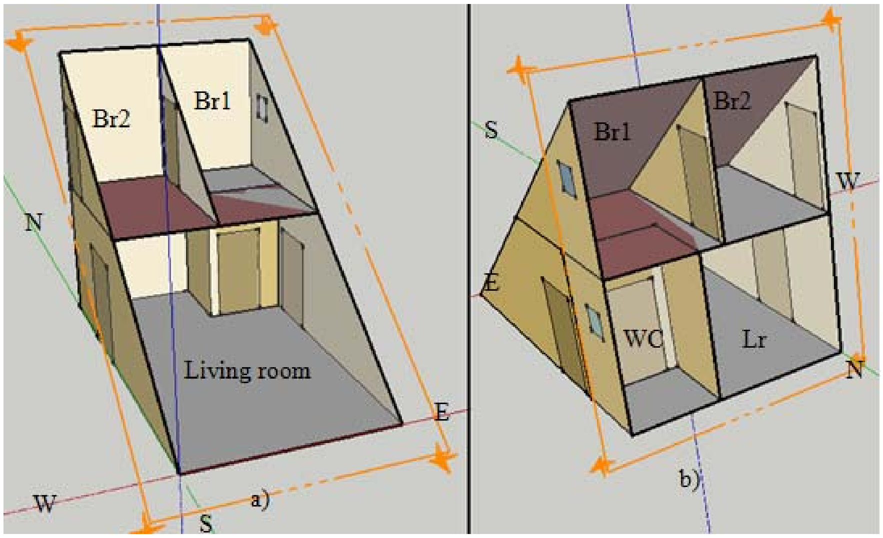

Figure 1: Geometrical definition of the residential house (Br-bedroom, Lr-Living room, WC-Bathroom) (a) South side; (b) North side.

In table 1, geometric data for area of floor by rooms are given. There is no south wall because of the sloped roof, which is under an optimal angle for a PV power generation.

Table 1. The characteristics of the used insulation material

	Floor area (m^2)	External wall area (m^2)
Living room	31.46	-
Toilet	2.95	-
Bedrooms (x2)	8.6	-
Roof	-	43.37
North wall	-	26.4
East and west wall (each)	-	23.46
Total	51.61	73.32 + 43.37

Regarding fenestration, the house has two windows, one in the bathroom and one in the bedroom 1, and it has seven doors from which three are external. The bedroom 1 is oriented toward the east, and the bedroom 2 toward the west.

2.2. Space heating of the house

According to the Serbian heating codes [8], the desired air temperatures are set in the living room and the bedrooms at 20°C, and the bathroom at 22°C, respectively. Electrical heaters with thermostatic valves heat the entire house. The heating system is designed according to the standard procedures defined in [8]. In most cases, the desired air temperatures are met in the first half of an hour of heating start. The thermostatic valves thus save energy by turning off the heaters when the air temperature is above the desired value, and then by turning on the heaters when the air temperature falls below the desired value.

3. Software used for simulation and optimization

3.1. EnergyPlus

To simulate heating, cooling, lighting, ventilation, water network and other energy flows in a built environment, EnergyPlus can be used [10]. EnergyPlus takes into account all factors that influence thermal loads in the building, such as they are electricity devices, lighting, pipes in the building, solar radiation, wind, infiltration, and shading [11]. This software is used to simulate energy behavior of the investigated house. For this house, the geometry is defined outside EnergyPlus by using Google SketchUp with an OpenStudio plug-in [12]. In the Google SketchUp environment, this geometry is shown in Figure1.

3.1.2 Mathematics

The embodied energy, in general practice, is not considered when a building is designed, specified and constructed. The embodied energy of a low-energy house is likely to contribute a greater proportion of its overall life cycle primary energy consumption during than that would be for a conventional house [2]. The embodied energy, E_{em} represents an amount of the primary energy used to create one kilogram of a material. Here, the embodied energy was calculated by using the following equation:

$$E_{emti} = A_{ti} \cdot \delta_{ti} \cdot \rho_m \cdot E_{em} , \qquad \text{(Eq. 1)}$$

Where A_{ti} is the area of thermal insulation (the area of the exterior walls and the roof) and in this case, it is 116.69 m^2

δ_{ti} stands for the thermal insulation thickness

ρ_m stands for the density of selected material

E_{em} stands for the embodied primary energy of selected material per kg of mass.

The annual embodied energy for the life cycle presents an embodied energy of thermal insulation divided by the number of the life cycle years, as shown in the following equation:

$$E_{aemtiy} = \frac{E_{emti}}{L_y} , \qquad \text{(Eq. 2)}$$

Where L_y stands for the number of the life cycle years.

The annual heat consumption of the house presents an annual heat consumption of the heaters in the house to sustain the desired air temperature, as shown in the following equation:

$$E_u = \sum_{d=1}^{365} \sum_{h=1}^{24} E_{uhd} , \qquad \text{(Eq. 3)}$$

Where E_{uhd} stands for the heat consumption in hour h on day d.

The annual primary energy consumption for heating the house presents the annual heat consumption of the house multiplied by a conversion factor from the primary energy to electricity. In Serbia, this factor is 3.04 [12]. Therefore, the primary energy consumption is calculated using the following equation:

$$E_{up} = E_u \cdot 3.04\,. \qquad \text{(Eq. 4)}$$

The objective function is the annual total primary energy consumption. It is the sum of the primary energy consumption for heating and the annual embodied energy, as shown in the following equation:

$$E_{sauy} = E_{up} + E_{aemtiy}\,, \qquad \text{(Eq. 5)}$$

The total primary energy consumption is sum of the primary energy consumption and the embodied energy for the life cycle period, as shown in the following equation:

$$E_{tupy} = (E_{up} + E_{aemtiy}) \cdot L_y\,, \qquad \text{(Eq. 6)}$$

To evaluate energy saving, the energy payback ratios are used. They present how many times the used primary energy for refurbishment is saved during the life cycle. Let us the refurbishment application to be the thermal insulation of the optimum width to the non-insulated house. The energy payback ratio X_{savedeyn} represents the amount of the saved primary energy per unit of the used embodied energy of the applied thermal insulation. The energy payback ratio is given by the following equation:

$$X_{savedeyn} = (E_{tupyn} - E_{tupyo}) / E_{emtio}\,. \qquad \text{(Eq. 7)}$$

Where E_{tupyo} stands for the used energy when using optimized thickness of the thermal insulation layer

E_{tupyn} stands for the used energy in the house without thermal insulation

E_{emtio} stands for the embodied energy in optimal thermal insulation layer.

The energy payback ratio X_{savedeys} gives the primary energy saving per unit of the embodied energy for the second case. Then, the primary energy is saved when the customary previously thermally insulated house is additionally thermally insulated by the new thermal insulation material of the optimum width. The energy payback ratio is shown in the following equation:

$$X_{savedeys} = (E_{tupys} - E_{tupyo}) / (E_{emtio} - E_{emtis}) \qquad \text{(Eq. 8)}$$

Where E_{tupys} stands for the used energy when using customary thickness of the thermal insulation layer

E_{emtis} stands for the embodied energy in the new thermal insulation layer.

3.2. GenOpt and optimization constraints

GenOpt is an optimization program used for the minimization of a function that is evaluated by an external simulation program, such as EnergyPlus, TRNSYS, SPARK, IDA-ICE or DOE-2. It has been developed for the optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. The independent variables can be continuous variables (possibly with lower and upper bounds), discrete variables, or both. Constraints on dependent variables can be implemented using penalty or barrier functions [13].

In this investigation using GenOpt, a thickness of a thermal insulation layer is optimized. A minimum thickness of the layer is taken to be 0.02m. A maximum thickness of the layer is set to 2m. The optimization method is that of Hooke-Jeeves [14]. The initial thickness for all simulations is set to 0.05m and the optimization step is 0.01. The number of step reduction is set to 4. The maximum number of iterations is set to 2000, but it is not reached (the maximum number of iterations is lower than 150 in all cases).

GenOpt reads results of simulation by EnergyPlus (the heat consumption), calculates the embodied energy, and calculates the total primary energy consumption. Then, it compares the obtained results with the results of previous calculation of the total primary energy consumption. The program checks if there is a decrease in the total primary energy consumption. After that it may automatically change the input values for the insulation thickness.

The advantage of using GenOpt instead of brute force search is in smaller time used for the optimization and in an elimination of human errors. The brute force search requires that user wait in front of computer for each simulation, compare the obtained values, and then change the value of the thickness of the insulation layer. Instead, by using GenOpt, about 50-150 simulations are automatically performed. There are 42 combinations of material type and lifecycle values. By using GenOpt, the user assistance is needed only 42 times, and in case of brute force search, the user assistance is needed about 4200 times (42 x 100) in average.

4. Thermal insulation materials

Thermal insulation materials used in the simulations represent the most common materials used in nowadays. Those materials are mineral wool, rock wool, polystyrene, polyurethane, cork, and fiberglass. Although their characteristics are discussed in literature for different regions, including New Zealand [15], the United States [16, 17], and the United Kingdom (hereafter, UK) [18, 19], the research results from Hammond and Jones [20] are taken and are representative as they are product of many years of research and the results are constantly updated and recalculated. These results are from the UK and they are taken in cooperation with their industry. Their work on the project, Inventory of Carbon & Energy (ICE) gives the embodied energy for each type of material [20]. There are no experimental and official data for embodied energy in materials in Serbia. In this study, the data from UK are taken because they can be found in the report of EU [21] from 2010. In Table 2, these values are given for each material analyzed in this investigation.

Table 2. The characteristics of the used insulation material

Material	Embodied energy, E_{em} (MJ/kg)	Density, ρ_m (kg/m^3)	Thermal conductivity,k (W/mK)	Relative/qualitative ranking ($E_{em}\rho_m k$)
Mineral wool	16.6	16	0.038	10.1
Rock wool	16.8	23	0.037	14.3
Cork	4	110	0.040	17.6
Fiberglass	28	24	0.036	24.2
Polystyrene	86.4	16	0.037	51.1
Polyurethane	101.5	24	0.028	68.2

The wall and roof types are taken from the URSA site [22]. They are given in Figure 2. In Figure 2, the wall thermal insulation layer is defined as Number 4 (left), and the roof thermal insulation layer is defined as Number 3 (right).

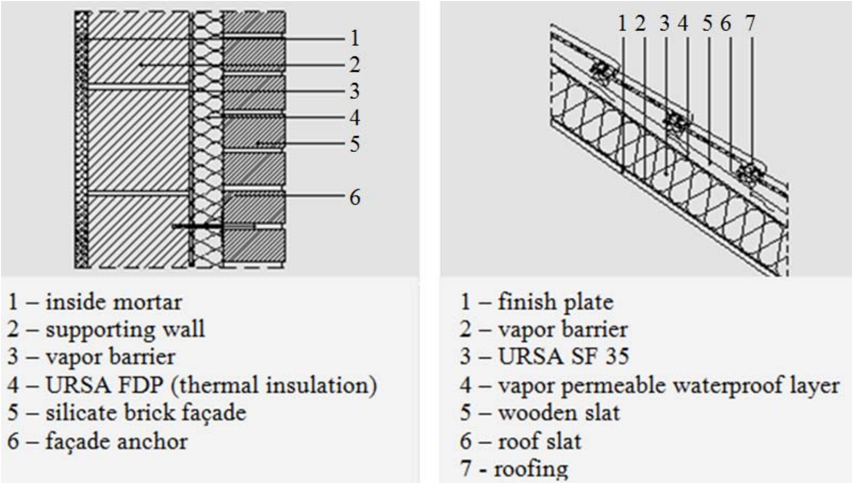

Figure 2. Wall (left) and roof (right) type by URSA

5. Results and Discussion

Figure 3 shows the optimum width of the thermal insulation layers as a function of their type and life cycle. The investigation is preformed for polyurethane, polystyrene, fibreglass, rock wool, mineral wool, and cork and the life cycles from 5 to 50 years. The optimization yields that the mineral wool layer would be the thickest and the polyurethane layer the thinnest (Figure 3). Namely, the width of the mineral wool layer is 2.5-3.5 times thicker than that of polystyrene and polyurethane.

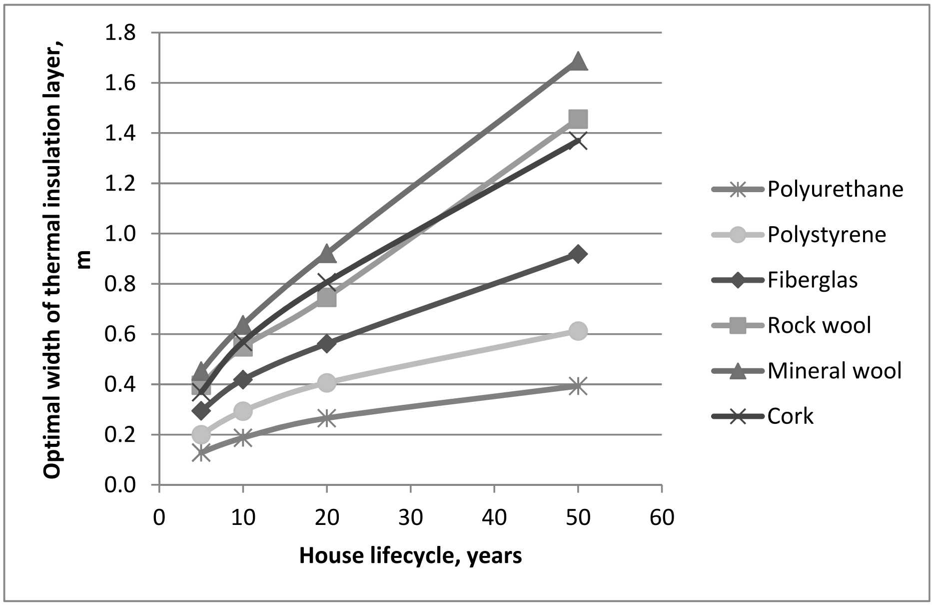

Figure 3. Optimum width of the thermal insulation layers as a function of their type and building lifecycle time

For the same thermal insulation types and life cycle range, Figure 4 shows the annual total energy consumption. It is clear that the annual total primary energy consumption is the lowest when the mineral wool is used as thermal insulation and the highest when the polyurethane is used as thermal insulation.

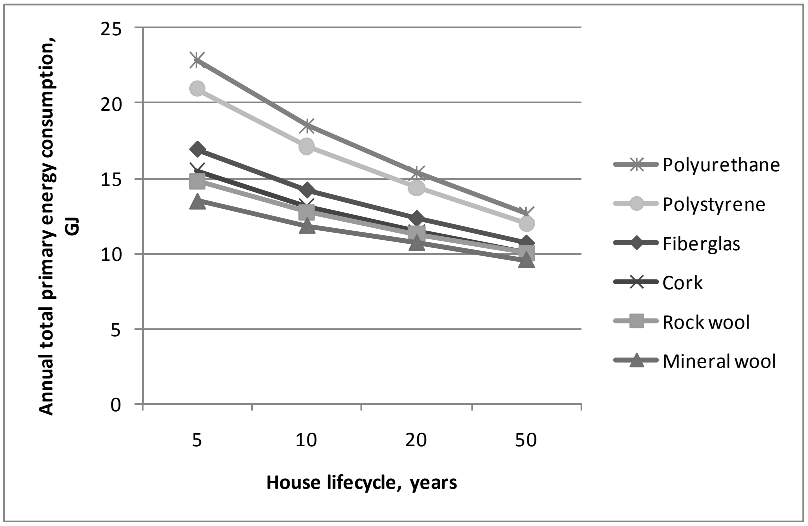

Figure 4. Annual total energy consumption vs. life cycle years and thermal insulation type

Figure 5 shows the annual total primary energy, the annual embodied energy, and the primary energy used for heating at the 50-year life cycle level for different types of thermal insulation. This figure demonstrates that the mineral wool has the smallest embodied energy and the smallest annual total primary energy used for the heating compared to that of other thermal insulation types. It is the fact that many studies have shown that building materials only contribute around 15% of the life cycle energy of a typical building. This study refers to the masonry constructions where there is the following situation. For the application of thermal insulation, the embodied energy contribution of the building materials to the total primary energy consumption will be around 27% for its lifecycle of 50 years, and around 56% for the lifecycle of 10 years. For wood constructions, it may be assumed that there is negligible amount of the used embodied energy in wood material, while the similar amount of the saved energy with thermal insulation would as that in the masonry construction. Then, the embodied energy contribution of the building materials to the total primary energy consumption would be lower and would have value of 13% for 50 years and 19% for 10 years of the life cycle. This analysis refers to the application of the optimal thickness of mineral wool for the thermal insulation.

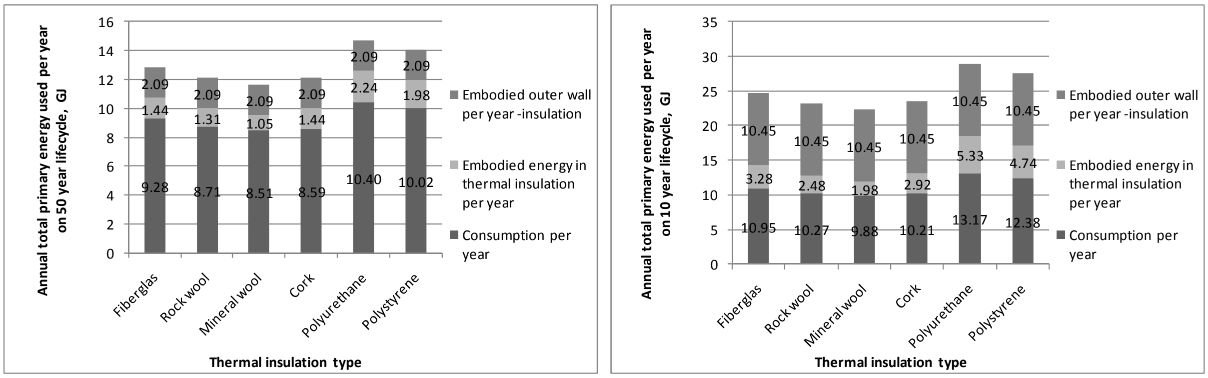

Figure 5. Annual total primary energy, annual embodied energy, and primary energy used for heating at 50-year life cycle level and at 10-year life cycle level

Figure 6 shows the total primary energy consumption for the house without, and those houses with custom and optimal thermal insulation. The thermal insulation is mineral wool. The house with the custom thermal insulation has the width for this region of 20cm of thermal insulation. All values rise in time.

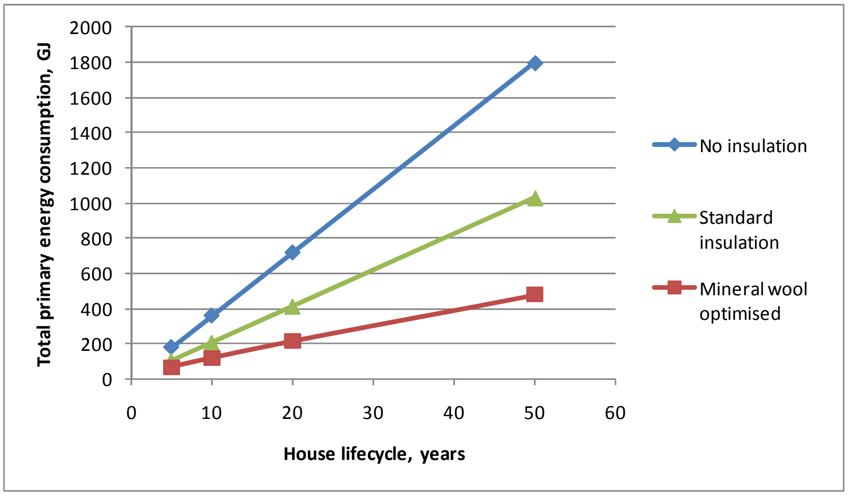

Figure 6. Total primary energy consumption for the house without, and with custom and optimal thermal insulation. The thermal insulation is mineral wool.

To evaluate energy saving on 50-year life cycle, Figure 7 shows the energy payback ratios for two refurbishment options: (1) the house with optimized thermal insulation atop the customary thermal insulation; and (2) the house with the optimized thermal insulation only. It is found that the introduction of 1 J of embodied energy to the house with the optimized thermal insulation saves 25.23 J of the primary energy ($X_{savedyn}$), whereas the introduction of 1 J of embodied energy to the house the optimized thermal insulation atop of the customary thermal insulation saves 11.96 J of the primary energy ($X_{savedys}$).

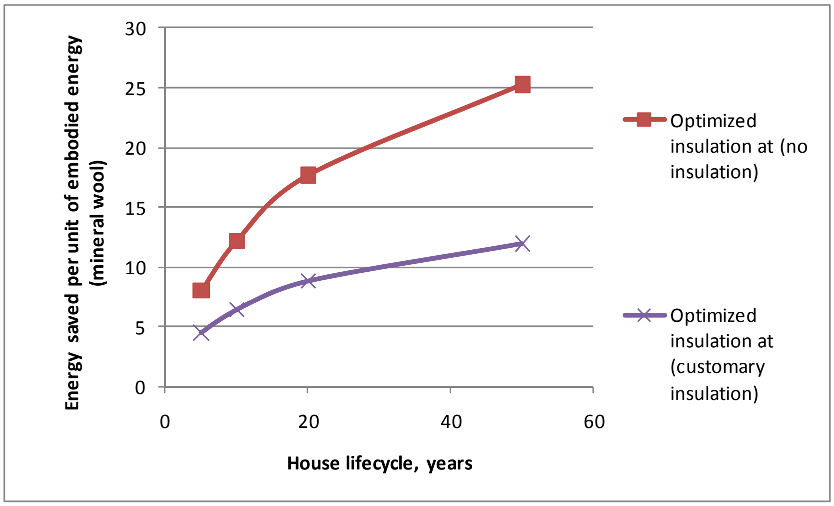

Figure 7. Energy saved per unit of the embodied energy

6. Conclusions

This paper shows that energy efficiency of the house can easily be improved by choosing proper thermal insulation width. The optimizations take into account the embodied energy in the thermal insulation. The results show that the lowest primary energy consumption is obtained by using mineral wool; however its width is the thickest when compared to all thermal insulation types. The highest primary energy consumption is obtained by using polystyrene; however its width is the thinnest. Two refurbishment options are discussed where the optimized thermal insulation of mineral wool is put to the building without any insulation and to the building with the customary width of thermal insulation, respectively. The saved energy per unit of embodied energy is as high as 10 to 25 times.

These results are obtained by using official data for embodied energy in materials in UK. However, in the future, it is important to organize research on the embodied energy in the used materials in Serbia that will take into account local conditions.

In future research, the cost and greenhouse gas emission optimization/minimization will be performed.

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Nomenclature

A	area, m^2
C	amount of carbon embodied, kg/kg
E	amount of energy, J
L	life cycle, years
X	number of times saved

Greek symbols

δ	thickness of thermal insulation, m
ρ	density of material, kg/m^3

Subscripts and superscripts

a	annual
d	number of days
em	embodied
h	number of hours
m	selected material
n	no insulation
p	primary energy
o	optimized
s	standard
ti	thermal insulation
u	used
y	years

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