Is Passive or Active House Needed In Face of Global Warming?

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Abstract. The article aims to determine how effective the stricter current requirements for the building envelope insolation are from the economic energy savings perspective. The article deals with a mathematical method for economic assessment of optimal building thermal insulation. The mathematical methods used in this article are based on evaluating the break-even point between the construction expenditures and the economic profit. Recent research shows that energy savings achieved solely through stricter standards applied to the building envelopes are limited in their ability to achieve maximum results. As the ratio of building volume to building envelope increases, further energy saving measures applied to the building envelope produce lower energy saving effects. Energy savings achieved using renewable energy resources, recuperation systems are much more effective. Research shows that much greater effect can be achieved by combining optimal building envelope energy efficiency measures with new requirements related to renewable energy sources and recuperating systems, such as solar batteries, wind turbines or heat pumps.

1. Introduction

Global warming concerns in various countries around the world have resulted in multiple energy saving measures. Among these measures are building related energy saving initiatives, such as stricter requirements for the building envelope, which constitutes building thermal insulation [1]. Lithuania is among the countries with such measures [2]. As of 2017, Lithuania plans to implement minimum energy level A requirement for all new buildings (Table 1). Such requirement is equivalent to the requirement applied to passive houses. As of 2018, this requirement is planned to be increased to the energy level A+. As of 2021, this requirement is foreseen to grow to energy efficiency level A++. Up until 2017, energy saving requirements for building envelopes were the only mandatory energy saving measures in new building construction. As of 2017, further measures will be implemented, including mandatory energy recuperates and renewable energy resources [3].

Not all European states have chosen heat saving route by making the only requirements for building envelopes stricter. The majority of the European states have adopted a mix of requirements for making the envelope requirements stricter and for the implementation of renewing energy as well as for the improvement of ventilation systems. Such requirements allow the building owner to select what measures to apply for heat saving. Recent research shows that energy savings achieved solely through stricter standards applied to the building envelopes are limited in their ability to achieve maximum results.

The practice of building modernization in Lithuania shows that by implementing only wall insulation works has led to shortage of specialists in this field, increased price of materials used for insulation and
price of construction works. The state was forced to reduce the support for people who started the renovation due to shortage of funds. Building modernization rate decreased.

On the other side, energy savings achieved through recuperation systems and renewable energy resources are much more effective. As the ratio of building volume to building envelope increases, further energy saving measures applied to the building envelope produce lower energy saving effects. Research shows that much greater effect can be achieved by combining existing energy efficiency measures for building envelopes with new requirements related to renewable energy sources and recuperating systems, such as solar batteries, wind turbines or heat pumps.

The article aims determine how effective the stricter current requirements for the building envelope insolation are from the economic energy savings perspective. To achieve this aim, the article uses an example with one of most popular currently non-ventilated wall insulation technology (plastered facade with rock wool thermal insulation).

Table 1. Heat transfer coefficient of residential buildings in m²K/W.

| Classes of energy performance of Buildings | Roofs | Ground floor | Walls | Windows Doors |
|------------------------------------------|-------|--------------|-------|---------------|
| D                                        | 0,24  | 0,31         | 0,35  | 1,85          |
| C or B                                   | 0,16  | 0,25         | 0,20  | 1,6           |
| A                                        | 0,10  | 0,14         | 0,12  | 1,0           |
| A+                                       | 0,09  | 0,12         | 0,11  | 0,85          |
| A++                                      | 0,08  | 0,10         | 0,10  | 0,70          |

2. Background
When talking about heat saving technology buildings it is important to mention zero energy buildings. The first building of this kind was built in 1975 in Denmark under the initiative of the Danish Technical university [4]. The emergence of this building is closely related to the rapidly cheapening and spreading installation of solar batteries. This house conception was very simple: to use as much energy as possible from the installed equipment, the basis of which was solar batteries. The solar power accumulated during summer was converted to electricity and transmitted to the city power grids. In winter time the accumulated solar energy was used for premise heating.

Passive house conception was created and implemented in 1991 under the initiative of Dr. Wolfgang Feist [5]. The idea of this concept was to achieve maximum heat saving in a building so that active building heating would become unnecessary. To achieve such result, building envelope parameters were strictly regulated. Additionally, recuperates were rapidly installed to allow for reduction the heat loss due to building ventilation. The emergence of such buildings could be related to the second-generation thermal insulation materials such as Styrofoam, rock wool and rapidly cheapening and spreading recuperation equipment. A lot of countries worldwide, including Lithuania, were impressed by the passive house idea.

The next heat saving stage could be related to massive installation of complex renewable energy equipment (such as heat pumps and solar batteries) in buildings. One of such successful renewable energy application cases is the emergence of the active house conception [6]. The main idea behind this concept is that an active house can generate so much energy one its own that it can meet its own energy needs and also provide energy to other buildings.

The first active house was built in the same Denmark, Orhus suburbs of Lustrup in 2009. It was planned to produce 5500 kWh of electricity power per year, of which residents would consume 4000 kWh. More houses around the world have been built since then based on the active house construction principles. One of the most impressive active house examples was a house built in Norway – Powerhouse Kjorbo. The energy that this building is predicted to generate over its 60 years of
exploitation is estimated to be equivalent to the energy that was required for this building's construction materials, construction, exploitation and utilization.

In period of rising concerns about global warming the interaction of energy consumption, ecological energy production, indoor climate conditions and impact on the external environment have particularly important.

3. Cost-benefit analysis in decisions about the thermo-isolation of building walls

Cost-benefit point analysis can be successfully applied in building thermo-isolation decisions [7]. In this case, knowing changes in heating costs $S_i$ and the costs associated with thermo-isolation of walls $S_r$ allows determine the optimal amount of thermo-isolation materials.

\[
S_i = \left( \frac{1}{R_1} - \frac{1}{R_1 + R_2} \right) \cdot (\theta_i - \theta_e) \cdot k \cdot T \cdot \frac{g \cdot c}{1000} \cdot m \cdot i
\]

\[
S_r = S_i \cdot x + S_2
\]

where: $R_1$ – wall resistant before thermal insulation in m²·K/W, $R_2$– thermal resistant of insolation in m²·K/W, $(R_2 = x \cdot 0.7548 / \lambda)$ expressed by thickness of layer of insolation $x$ in meters and thermal conductivity $\lambda$ in W/(m·K), $(\theta_i - \theta_e)$ – difference between the projected inside and outside temperatures during the heating season in °C, $k$ – coefficient used to assess the orientation of a building, wind direction and other factors that influence the calculations, $T$– heating period in hours per year; $g$ – price of heating fuel unit in euro, $c$– need of heating fuel in units per W of energy, $m$ – heating period in years, $i$– fuel price reduction coefficient to assess the inflation, $S_i$ and $S_2$ - insolation layer variable and steady expenses in euro.

While it is generally hard to predict future fuel prices, it is known that fuel prices are closely linked to the oil price fluctuations. World Bank oil price forecast is shown in Figure 1. Therefore, referring to the world bank forecast for oil price, we can make an assumption that fuel price will rise by 1.8 times over the thermal insulation materials exploitation period of 30 years ($n=1.8$).

Future fuel cost can be estimated by indexing current fuel costs to the price index obtained in reference to the oil price forecast:

\[
i = \frac{\sum_{m}^{n} n^{(m-1)/m} + n}{m}
\]

![Figure 1. World Bank oil price ($/bbl$) forecast](image)
Based on the market prices of materials and pricelists for construction works in 2016 [8][9], building insulation prices dependence on insulation thickness was determined:

\[ S_r = 168.4 \cdot x + 58.07 \]  \hspace{1cm} (3)

Correlation coefficient \( R^2 = 0.703 \) and F statistic \( F = 493.26 \), null hypothesis is rejected (figure 2).

Finally, we can create graphical relationship between insulation prices and heat saving during a certain period \( m \) for optimal wall thickness evaluation.

Let's take an example of a new building shown in figure 3 that is located in Vilnius, Lithuania, where the average outside temperature during the heating season is -0.7 °C and the inside temperature is +20 °C. The length of a heating season is 204 days. Thermal resistance of walls before insulation \( R_i = 0.7 \) m²·K/W; thermal conductivity of insulation material \( \lambda = 0.034 \) W/(m·K).

For the purpose of the examples we took: the highest ever natural gas price observed in Lithuania, \( g = 0.46 \) euro per m³ of natural gas, \( c = 0.1073 \) m³/W, \( k = 1.02 \), lifetime of thermal insulation 30 years, gas price inflation coefficient \( i = 1.286 \) (obtained by formula 2).

Results of calculation (figure 3) show that biggest economical effect will be reached with 20 cm insulation layer. In such case, economical effect per 30 years’ period will be about 142 euro per square meter of wall. Near this result is result with 25 cm insulation layer which is in line with requirement for walls of passive house. Heat transfer coefficient for passive is \( U = 0.15 \) m²K /W. In such case, economical effect per 30 years’ period will be about 138 euro per square meter of wall. Current requirement for residential buildings in Lithuania is \( U = 0.12 \) m²K /W, with is in line with 35 cm insulation layer. In such case, economical effect per 30 years’ period will be about 125 euro per square meter of wall.
To determine the maximum economically justified thermal insulation limit, let's assume that the regular walls in this building can be replaced by a very thin layer of supporting material for the attachment of the thermal insulation materials, \( R = 0.21 \, \text{m}^2\cdot\text{K}/\text{W} \). Results of calculation (figure 4) shows that economically reasonable maximal thermal insulation is 22 cm.

Results of modernization building in Vilnius with thermal resistance of walls before modernization \( R = 1.5 \, \text{m}^2\cdot\text{K}/\text{W} \) and thermal conductivity of insolation material \( \lambda = 0.034 \, \text{W}/(\text{m} \cdot \text{K}) \) are shown in figure 5. Small economical effect (7 euro) per 30 years’ period will be reached with 15 cm layer of thermal insulation.

Calculations results indicate that economically profitable modernization of walls with current prices of gas, works and materials in Lithuania is not reasonable, when thermal resistance of wall before modernization is \( R \geq 1.6 \, \text{m}^2\cdot\text{K}/\text{W} \).
4. Physical thermal-insulation energy saving limit

Assessing energy savings from the customer’s point of view, only energy loss and savings in a building are analysed. This is because a customer often has no ability to assess the energy embodied in the stages of material production. However, such assessment of thermal-insulation materials impact is necessary for reducing pollution. Some thermal-insulation materials are manufactured for the purpose of heat saving and have quite large energy input embodied in the stages of manufacture, transportation and construction. According to some authors, embodied energy input into construction materials and works makes up to 30 percent of energy amount saved through the entire exploitation period. Therefore, any government or legislative attempts to assess energy savings with anti-global warming objectives in mind should take into account all energy inputs. Only this way it will be possible to compare different materials and different insulation technologies in order to reduce global energy consumption.

Thus, assessing energy savings, we should ignore energy input during material manufacture, transportation and construction stages.

\[
\Delta \phi_B = A \left( \frac{1}{R_1} - \frac{1}{R_1 + R_2} \right) \cdot (\theta_i - \theta_e) \cdot k \cdot T \cdot m \cdot i - \phi_r - \phi_m - \phi_c, \tag{4}
\]

where: A - external wall area in m², \( \Delta \phi_B \) - heat savings when assessing the embodied energy in Wh, \( \phi_r \) - energy loss in transportation stage in Wh, \( \phi_m \) - energy loss in the manufacture stage in Wh, \( \phi_c \) - energy loss in the construction stage in Wh.

There is point at which further thickening of the thermal-insulation layer results in exponentially decreasing heat savings, and gradual increased in the embedded energy. At this point a limit is reached where material embedded energy exceeds energy savings. This limit can be called material thermal-insulation efficiency limit. Thermal-insulation layer efficiency limit can be determined by solving the equation:
After determining physical thermal-insulation energy saving limit, percentage scheme of savings from physical limit can be made. Figure 6 shows that for above given example of building with thermal insulation $R_i = 0.7 \, \text{m}^2\cdot\text{K}/\text{W}$ using non-ventilated wall insulation technology with rock wool and gas for heating physical thermal-insulation energy saving limit is 0.45 m.

$$
\frac{d}{dx} \left( A \cdot \left( \frac{1}{R_i} - \frac{1}{R_i + 22.2x} \right) \cdot (\theta_i - \theta_{ce}) \cdot k \cdot T \cdot m \cdot i - \phi_r - \phi_m - \phi_c \right) = 0. \quad (5)
$$

It is important to note that there is a big difference between physical and economic limits for energy savings arising from the use of thermo-insulation materials. When the economic limit is exceeded, the building owner will appreciate that the energy saving measures are no longer money saving for him. When the physical limit is exceeded, the environment is impacted. Specifically, exceeding the physical limit means that the production, transportation and installation costs of thermo-insulation materials are more than the savings derived from the use of thermo-insulation materials. In fact, physical limits are often exceeded when buildings are being renovated.

Figure 7 shows for above given example of building where the same type of materials and insulation technologies are deployed, but thermal resistance of wall prior to the modernization are equal to 3. In this case, physical limit of energy savings will be already exceeded when the building thermo-insulation material layer exceeds 35 cm.
Calculations results shows that modernization using non-ventilated wall insulation technology with rock wool and gas for heating, in Lithuania is only economically reasonable, when thermal resistance of walls before modernization $R \leq 6.11$ m²·K/W. When thermal resistance of walls before modernization $R = 1.6$ m²·K/W (figure 8) economically rational insulation limit is only 15 cm, physical thermal-insulation energy saving limit is 40 cm of rock wool insolation layer. Modernized wall with 15 cm layer of thermal insulation allows to save 95% of heat and prise of energy loss per 30 years will be about 11 euro per $m^2$ of wall.

**Figure 7. Physical thermal-insulation energy saving limit, $R_i = 3$ m²·K/W**

**Figure 8. Physical thermal-insulation energy saving limit, $R_i = 1.6$ m²·K/W**

5. **Alternative heat saving methods in buildings**

In comparing various construction approaches it is often forgotten that there are other heat saving methods in buildings. Apart from the temperature acceptable for human lifestyle inside a building, the building has to be also provided with sufficient amount of fresh air. There is no solid agreement on how often the air must change in buildings, but according to the requirements adopted by most countries this
indoor air change must be at least 40 percent of the indoor volume per hour. Energy demand for covering heat loss due to compulsory indoor ventilation is calculated according to the formula:

\[ \Delta \phi_v = s \cdot V \cdot n \cdot (\theta_i - \theta_e) \cdot T / 24 \cdot 1000 \]  

(6)

where \( \Delta \phi_v \) – heat loss in kWh/year, \( s \) – air specific heat equal to 0.36 Wh/(m\(^3\)K), \( n \) – air change, times per hour, \( V \) – volume in m\(^3\), \( T \) – number of days of heating period, \( \theta_i \) – indoor air temperature in \(^\circ\)C, \( \theta_e \) – outdoor air temperature in \(^\circ\)C.

For a building with ideal proportions (in this case a building in a shape of a cube) it is possible to determine in percent how much the heat saving through envelopes is more important in comparison to heat saving for heating fresh air in order to create favourable living conditions in a building. From the provided figure 9 it can be seen that the loss due to ventilation in the cubic building whose side is more than 10 m and average building resistance \( R_i = 2.5 \) m\(^2\)K/W exceeds the loss due convection. This means that in all buildings of larger dimensions the biggest challenge is to resolve the issue of energy loss resulting from ventilation (rather than from convection).

Price and cost analysis carried out by author shows that investment in a recuperate would pay off in a period of a couple of years. Solar battery 10 kW power station would pay off in fifteen years. Biomass would pay off in ten years. Under current conditions, investment into wind energy projects pays off in about twelve years. All of this indicate that the longest pay off time and cost would be associated with energy saving measures dedicated to improving thermo-insulation properties of building envelope.

![Figure 9. Loss due to ventilation and convection in kWh/year, \( R_i = 2.5 \) m\(^2\)K/W](image)

6. Conclusions
The practice of building modernization in Lithuania up to 2017 shows that focus on wall insulation alone has resulted in shortage of this field's specialists, increased prices of materials used for insulation and increased cost of construction works. The state was forced to reduce the support for people who started the renovation due to shortage of funds. Building modernization rate decreased.
Calculations made in this article indicate that the requirements put forth by the Lithuanian government for the new building wall thermo-insulation properties do not exceed the physical energy saving limit but may not always give the best economic result.

In case of newly built buildings in Lithuania, under the scenario where non-ventilated wall insulation technology with rock wool is used in combination with gas as a basis for building heating, the physical insulation limit is 45 cm, and economically rational insulation limit is only 22 cm.

Results of calculations show that modernization in Lithuania, under the scenario where non-ventilated wall insulation technology with rock wool is used in combination with gas as a basis for building heating, is only economically reasonable when the thermal resistance of walls before modernization \( R_i \leq 1.6 \text{ m}^2\cdot\text{K}/\text{W} \). When thermal resistance of walls before modernization \( R_i = 1.6 \text{ m}^2\cdot\text{K}/\text{W} \) economically rational insulation limit is only 15 cm, physical thermal-insulation energy saving limit is 40 cm of rock wool insulation layer. Modernized wall with 15 cm layer of thermal insulation allows to save 95 % of heat and the price of energy loss per 30 years will be about 11 euro per \( \text{m}^2 \) of wall.

In modernising existing buildings one should always pay attention to the thickness of the thermal insulation layer. In situations of building modernisation one can exceed not just the economic but also physical energy savings limit.

Finally, it can be stated that investment into renewable energy sources in buildings pay off much faster and give greater economic effect than investment into building envelope upgrade.

References

[1] Directive 2010/31/EU On the energy performance of buildings, European Parliament and The Council, 2010.

[2] STR 2.01.09:2012 Energy Performance of Buildings. Certification. Vilnius, 2012.

[3] STR 2.01.02:2016 Energy Performance of Buildings. Classification and Certification. Vilnius, 2016.

[4] T.V. Esbensen, V.Korsgaard, Zero Energy house, MeddelelseE NR. 64, Copenhagen, 1976

[5] W. Feist Wolfgang, Passive Houses in Central Europe, Thesis, University of Kassel, 1993

[6] A. Purcell, Zero-carbon eco home is light years ahead, The Guardian, 2009. Access by Internet: https://www.theguardian.com/environment/2009/may/21/active-house-denmark-zero-carbon.

[7] R. Tamošaitis. Economic Assessment of Reconstruction Needs // Engineering Structures and Technologies. Vilnius: Technika, 2010, t. 2, Nr. 1, p. 38-44.

[8] Pricelist for building modernization, Vilnius, SISTELA, 2014.

[9] Pricelist for construction works. Vilnius, PROSAMA, Access by Internet: 2014. Access by Internet: http://www.dycode.net/lt/prosama.