Optimal insulation thickness in historic buildings with a heat pump as an energy source

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Abstract. Improvement in the thermal performance of the historic buildings can possibly lead to a reduction in the energy they need to operate. Thus, the negative impact of such buildings on the environment can be mitigated. Generally, any kind of works that would modify the looks of the façade of historic monuments is forbidden, that is why their thermal upgrading must be carried out inside. This process is usually more expensive because it requires individually selected materials and technologies. This study shows the analysis carried out to select the optimal insulation thickness with respect to the total costs of the electrical energy consumed to run the pump and the costs of thermal upgrading of the walls. Based on the example of natural cork panels with thermal conductivity of 0.04 W/mK and polyurethane foam boards with drywall finish at one side ($\lambda=0.022$ W/mK), the optimal insulation thickness was determined for five-year duration of the investment loan at 5% fixed interest rate. In the calculations, local climate conditions are taken into account.

1. Introduction

In household sector, one of the major energy consumers, energy is used mainly for space heating of buildings and providing domestic hot water. In the years 1993 and 2012, the mean domestic sector accounted for 70.9% and 14.8% of the total energy consumption, respectively. Meanwhile, according to the Energy Market Agency forecasts, the percentage reductions in final energy consumption in the residential sector should amount to 1.9%, 2.6%, 3.3% and 3.8% in the years 2016, 2020, 2025 and 2030, respectively. To achieve those levels, it is necessary to take decisive actions aimed at energy modernization of existing buildings. That requires proper selection of optimal solutions, especially in the case of old buildings, which being under supervision of conservation officers cannot be thermally upgraded using typical technologies that involve the external walls insulation retrofit by over-cladding. When thermal upgrades of such buildings are prepared, strict requirements concerning the energy performance are often relaxed. Detailed analyses are made to choose such renovation solutions that would ensure maximum environmental protection and preserve historic heritage [1]. As a result, technologies selected to fit specific buildings generate higher costs. Therefore, it is necessary to seek funds that would allow the conservation of the possible largest historic environment and, at the same time, be acceptable to the public [2]. One of the major factors which should be examined is the insulation of the walls, which significantly affects heating and cooling loads, and thus directly influences energy consumption.

In Poland, like in other countries, a large range of the building stock is found. The data that are available indicate that approx. 413.3 thousand buildings were constructed before 1918. The number of
buildings from the interwar period, i.e. the years 1918 - 1945, is 828.2 thousand. Regardless of their condition, they are treated as heritage buildings. In a vast majority of those buildings, the current standards on wall thermal performance are not met. Consequently, more energy is needed to heat those buildings, resulting in increased CO₂ emissions into the atmosphere. Large cities with densely built-up environment struggle with bad air quality, which has become a severe problem, and which is caused by the use of coal for space heating. The reason for users' preference for coal are lower prices when compared with other energy carriers [3].

For historic, heritage, and traditional buildings, significant energy consumption improvement can be achieved without changing their individual character. On the example of two buildings in Portugal from the early 20th century, the implementation of an integrated cost optimisation and environmental assessment are described in paper [4]. Optimal insulation thicknesses with respect to the lowest environmental impacts and cost were calculated. In historic buildings, specific retrofit solutions are needed that take into account renovation costs. One of the possible solutions are energy simulation models in which multiple factors should be considered. They include conservation, aesthetical requirements, structural and energy issues, as well as on economic factors [5]. In all cases, however, the simulation procedures should be selected on individual basis [6].

Historic buildings that are in various condition, were constructed using different technologies and materials used in the period when a given structure was built. Every time the building envelope upgrading is planned, it is necessary to check the chemical composition, or conduct an analysis of the materials that will be used [7-8]. In the case of large constructions, the analyses of the energy consumption and its reduction have to be carried out with respect to the building historic value and also various materials technology applied [9-10].

Historic buildings can be classified by the function they perform, namely they include residential buildings, religious buildings, museums, theatres, libraries, academic institutions and palaces [11]. Desirable climatic conditions inside each type of building should decide on the selection of the heating option [12]. This also applies to heat sources that are environmentally friendly, thus reducing greenhouse gas emissions. They include heat pumps [13], the proper selection of which depends on the local climate, settings and the building characteristics [14].

For building space heating, air conditioning and domestic hot water generation electric heat pumps are most frequently used. Heat pumps are considered as a possible solution to reduce primary energy consumption and they have often been proposed as a substitute for conventional systems [15]. Generally, heat pipes are classified into different types depending on the heat source and heat sink they are designed for. Usually, they operate as ground, or air source units. Their energy efficiency depends on the low-temperature source and the heat distribution system. Thermal parameters of the ground are more advantageous compared with atmospheric air, consequently the performance coefficient of heat pumps of water-to-water type is higher [16]. The drawback of such pumps involves the necessity of constructing horizontal or vertical ground exchangers. They occupy quite a lot of space adjacent to the heritage building, which is usually also subject to protection. Air-to-water heat pumps are much more convenient in this respect. The reason for this is the unlimited availability of energy that allows an uncomplicated and quick installation. In Poland, the temperature of ambient air changes significantly depending both on the time and season. That leads to a reduction in the heat pump output as the temperature of the heat source drops. The performance of an ambient air heat pump decreases as the heating demand grows [17], but even then, the device can be used for heating applications in cold regions [18]. When the temperature difference between the heat source and heat sink is too large for the heat pump to operate, the device has to be stopped. That increases the demand for an auxiliary heating system. The heat pump can operate in the mono-energy system, in which the pump is supported by an additional electrical power source. Another option is a bivalent parallel system, in which the lacking power is supplied by the other heat source that operates in parallel to the pump. Finally, in the bivalent alternative system, the heat pump is switched off when its heating performance drops considerably, and the whole amount of energy is generated by the alternative source.
The selection of all the system components is related to the system performance. That was described in paper [19] on the example of mono-compressor on-off, multi-compressor and inverter-driven heat pumps.

The thermal upgrading of the existing buildings allows significant reductions in energy consumption and global emissions of greenhouse gases. In study [20], a systematised approach to appropriate selection and identification of the best upgrading options for the existing buildings was discussed. Possible actions were classified into the following: supply and upgrading of the energy generation systems, management of the demand for heating and cooling, limited heat losses to the environment and management of the comfort of use. The study conclusions indicate it is also necessary to take into account the non-technical factors, e.g. while restoring historic buildings.

Taking into account all the constraints mentioned above, it is possible to make improvements in thermal properties by installing insulation on the internal side with simultaneous modernization of the heating system so that the costs of the thermo-insulation would be covered by savings in heating expenses. The aim of this study is to present simple methodology of calculations for the building heated with air-to-water heat pump. In the calculations, local climate conditions are taken into account.

2. Optimum insulation thickness with respect to heating and investment costs
The thermal performance of insulation in different structures is neither the same nor constant. The performance value can be specified by the total costs with respect to a defined cycle, e.g. investment payback period, building service life, or loan repayment period, and others. In particular, that refers to historic buildings, in which traditional methods of insulation installing, i.e. on the exterior of the building is often not allowed. Putting the insulation inside the building is usually costlier. That results from the demand on high quality of workmanship and that on the quality of the materials, especially with respect to their impact on hygrothermal behaviour of the wall [21]. That especially concerns large cities with high density of built-up environment. The property owners often do not have enough funds at their disposal to cover the costs of refurbishments and thermal upgrading of the heating system to make it more environmentally friendly. That is major issue in the localities in which revenues are generated through tourism, and in which air quality is decisive for maintaining or developing the tourism industry. Local governments in such areas launch programmes to support pro-environmental changes, e.g. by reimbursing the purchase of heating systems. In such a case, one of the viable options is to install air-to-water heat pump and, at the same time, improve the thermal performance of the building envelope components.

To seek the optimum solutions when balancing the thermal upgrading, it is necessary to balance the total costs $C_{A,N}$, which include the costs of heating and the costs of putting insulation, together with the costs of necessary materials. The following notation was used: $f_1$, $f_2$=1-$f_1$ the share of the opaque building part and the part (e.g. windows) that is not thermally upgraded, respectively, $U_1$, $U_2$ respective overall heat transfer coefficients, $R_w$ thermal resistances of the subsequent layers of the envelope, $d_{ins}$ and $\lambda_{ins}$ thickness and thermal conductivity of the insulation material. The total costs $C_{A,N}$ in reference to 1 m² can be calculated from the formula:

\[
C_{A,N} = \frac{f_1}{R_w + \frac{d_{ins}}{\lambda_{ins}} + U_2 f_2} NC_{Em} \sum_j \left( T_i - T_j \right) \frac{\tau_j}{COP_{bin} (T_j)} + NC_{np} (d_{ins} C_{ins} + C_d)
\]

where:
- $T_i$ – average temperature maintained inside the building
- $T_j$ – temperature at the time interval of concern,
- $\tau_j$ – cumulative time in which the same external temperature $T_j$ prevails during the heating season, e.g. in hours,
- $C_{Em}$ – average cost of electricity in $N$ years,
C_{np} – coefficient describing the cost of loan over the repayment period.

The coefficient of performance of the heat pump under partial load conditions \( \text{COP}_{\text{bin}} \) at temperature \( T_j \) may be calculated in accordance with [22):

\[
\text{COP}_{\text{bin}}(T_j) = \text{COP} \frac{P_h}{C_p C_c P_d} \tag{2}
\]

where

\( \text{COP} \) – coefficient of the performance of heat pump,
\( P_h = P_h(T_i) \) – heat load of the building at temperature \( T_i \),
\( P_d = P_d(T_i) \) – power output of the heat pump at temperature \( T_i \),
\( C_c \) – reduction factor due to on/off losses.

For temperatures that are lower than the bivalence temperature, it is not possible to maintain the preset thermal parameters with the heat pump output. In such a case, it is necessary to supply the energy that is lacking by the alternative source. If that is an electric heater, the value \( \text{COP}=1 \) is assumed.

If the thermo-modernisation investment is carried out with the funds obtained through the bank loan at fixed interest rate \( i_r \), the total repayment over \( N \) years is:

\[
C_{np} = i_r \left( 1 + \frac{i_r}{12} \right)^{12N} \left[ \left( 1 + \frac{i_r}{12} \right)^{12N} - 1 \right]^{-1} \tag{3}
\]

In formula (1), it was assumed that the building space heating starts when the external temperature \( T_e \) is lower than the base temperature \( T_b \).

If the external constraints or other requirements, e.g. those related to codes, are not found, the investment should be carried out in accordance with the criteria imposed to ensure the optimal realisation. The criteria include the condition of the minimal total costs. From eq. (1), the minimum costs with respect to insulation thickness \( d_{ins} \) is computed. The necessary condition for the occurrence of the extremum is the zero value of the total costs first derivative \( C_{A,N} \) with respect to insulation thickness \( d_{ins} \), which leads to the following expression:

\[
d_{\text{ins,Opt}} = \left( \lambda_{w} f_{1} C_{\text{En}} C_{\text{opt}}^{-1} \sum_{j} \left( T_{i} - T_{j} \right) \frac{\tau_{j}}{\text{COP}_{\text{bin}}(T_{j})} \right)^{1/2} - \lambda_{w} R_{w} \tag{4}
\]

The analysis of the electrical energy prices in the years 1999-2014 shows price linear dependence on time. A very high coefficient of determination for linear approximation \( R^2=0.97 \) shows the type of variation adopted for this energy carrier is sufficient for all analyses, including the price predictions for the next years. When electricity price in the year prior to the investment is denoted as \( C_{E1} \), based on Poland’s Central Statistical Office data, an index of the yearly increase in the price of electrical energy \( r_{E} \) can be determined. Using the extrapolation of the electricity price to \( N \) successive years, the expected costs of energy consumption \( C_{E} \) can be calculated acc. formula:

\[
C_{E} = \frac{(1 + r_{E})^{N} - 1}{r_{E}} C_{E1} \tag{5}
\]

\( C_{E1} \) is a unit price of electrical energy in the first year.

3. Results
To calculate the total costs of the thermal upgrading investment, it is necessary to know weather conditions for the period of loan repayment, or the amortisation of the investment. Unfortunately, all
climatic forecasts for periods that are longer than a month are not reliable. The safest option is to employ multi-year averaged series. The weather data for the city of Kielce, according to the reports by Poland’s Ministry of Infrastructure and Development [23], are presented in Figure 1.

![Figure 1. Counts of hourly temperatures in Kielce for the duration of the heating season.](image)

To compute thermal load on building, a division into climatic zones was introduced. The zones were assigned the lowest external temperatures, for the city of Kielce this value is -20°C. As can be seen in Fig 1, temperatures that low hardly ever occur. The temperatures below -10°C are recorded for approx. 3% of the heating season. Additionally, temperature measurements taken at high sampling frequency indicate that such cold conditions do not last all the day long. Temperature grows during daylight hours, consequently the demand for space heating of the building is correspondingly lower. The information of that kind should be taken into account while seeking the optimal heat pump for a given building. It is usually assumed the heat pump is capable of supplying the energy for the building space heating until the ambient temperature drops to -7°C, below that value an additional energy source is usually required. The reason for that situation is the pump output $P_d$ decrease with the temperature of the bottom source. That can be seen in Figure 2, in which exemplary graphs show power demand for building space heating and domestic hot water production.

![Figure 2. Characteristic curves of air-to-water heat pump ($P_h$, COP) and heat load of the building $P_d$.](image)

To achieve improvement in the energy performance of historic buildings, it is necessary to carefully select the materials and fabrication technology. That is intended to avoid disadvantageous physical phenomena related to a change in thermal-humidity conditions inside the envelope components [24]. A wide range of various technologies for interior thermal upgrading are available on the market. The materials used include: foamed polystyrene, mineral wool, polyurethane foam, cork and different heat-saving coating mortars. Their heat conductivity coefficient ranges from 0.02 W/mK for phenolic foam to 0.043 W/mK for foamed concrete boards. It is obvious that products from such a wide range come at different price.
In this study, exemplary computations for the selection of the optimum insulation thickness were made on the example of cork panels ($\lambda=0.04$ W/mK) and polyurethane foam boards with drywall finish at one side ($\lambda=0.022$ W/mK). Those materials are relatively easy to install, also on self-basis. They are recommended by manufacturers as insulation of the inside of the building. When balancing the thermal upgrading project, to seek optimal solutions, it is necessary to achieve balance of total costs $C_{AN}$, which contain heating costs and insulation placing costs, and the costs of necessary materials.

![Figure 3. Costs of insulation: a) natural cork and b) polyurethane foam for five-year loan repayment period and 5% fixed interest rate.](image)

![Figure 4. Change in the optimum insulation thickness depending on loan repayment period for insulation upgrading with cork and polyurethane foam.](image)

4. Conclusions

Improvement in the thermal performance of the historic buildings can possibly lead to a reduction in the energy they need to operate. Thus, the negative impact of such buildings on the environment can be mitigated. Generally, any kind of works that would modify the looks of the façade of historic monuments is forbidden, that is why their thermal upgrading must be carried out inside. This process is usually more expensive because it requires individually selected materials and technologies. The decision on the choice of thermo-modernisation technology taken by the owner of a historic building is most often influenced by the investment costs. The investment should be realised at the minimum costs and for the assumed return period. The results of analysis performed for historic buildings are influenced by the choice of the heat source. The use of an air-to-water heat pump is a good option. Due to lower emissions of greenhouse gases, it is environmentally friendly.

This study shows the analysis carried out to select the optimal insulation thickness with respect to the total costs of the electrical energy consumed to run the pump and the costs of thermal upgrading of
the walls. Based on the example of natural cork panels with thermal conductivity of 0.04 W/mK and polyurethane foam boards with drywall finish at one side (\(\lambda = 0.022 \text{ W/mK}\)), the optimal insulation thickness was determined for five-year duration of the investment loan at 5% fixed interest rate. As can be seen in Figure 3, the optimal thickness is approx. 2 cm for cork and 2.4 cm for the polyurethane foam board. Both values were determined with the assumption of a constant annual increase in electrical energy prices of 7% [25],[26]. The value of price growth was estimated on the basis of the data published by Poland’s Central Statistical Office [25]. The advantageous effect of the length of the loan repayment period on the investment should be noted. At 5% fixed interest rate and 10-year repayment period, the optimal thickness of cork insulation is approx. 3.6 cm. For the same terms of loan and polyurethane foam insulation, which 25% less expensive, the optimum thickness is similar and amounts to approx. 3.75 cm. Additionally, foam thermal properties are about 45% more advantageous. That is directly related to the final outcome, i.e. lower emissions of greenhouse gases, and also helps getting cheap bank loans.

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