Climate-Responsive Building Envelope Retrofit: Insulation Strategies in a Changing Environment

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Abstract. This study delves into retrofitting buildings for energy efficiency in Polish cities, focusing on thermal insulation in mid-rise residential buildings. Through simulations, it explores strategies to reduce energy usage and environmental impact amid climate change uncertainties. Utilizing statistical downscaling, it assesses insulation methods under evolving climates. Initial findings suggest potential insulation thickness reduction over time, emphasizing the need for adaptable strategies. The research stresses continual adaptation in construction practices to confront future climate variations, aiming for sustainable building development. It advocates proactive retrofitting to combat climate change, highlighting the importance of flexible approaches to environmental shifts.

Keywords: Thermal Insulation · Building Envelope · Residential buildings · Mitigation Climate Change

1 Introduction

Buildings significantly influence global energy use, accounting for about 32% worldwide, which can increase to 40% in developed areas like the U.S. and Europe [1]. This has placed them at the forefront of sustainability discussions, leading to new energy-saving policies and designs, especially as urbanization grows. The energy demands of buildings, from homes to commercial spaces, underscore their importance in economic and environmental sustainability, highlighted by their role in Poland's energy consumption [2]. EU building energy use has declined since 2008, with 2013 averages at 180 kWh/m^2, though rates vary by country [3]. Poland, reliant on coal, is shifting under EU policy pressures, aiming to close coal mines by 2049 [4] and its construction sector is booming, expected to grow by 5.4% from 2020 to 2021 [5]. This study emphasizes the need for ongoing adaptation in building practices to create resilient structures for climate change. By advocating for proactive envelope retrofits, it highlights that future reductions in material thickness are crucial, offering valuable insights for sustainable construction. Below are the research questions outlined:

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1. What would be the optimal type of envelope retrofit strategy, to be effective for current and potential future climatic conditions under the impacts of climate change?
2. How much total energy consumption and occupant's comfort may change by using the new building envelope retrofit strategy?

2 Methodology

The study employs simulations to assess a common thermal strategy's effect on energy use and thermal comfort in a mid-sized residential building under present and future scenarios (Fig. 1). It begins with analyzing two key areas: the characteristics of various insulation materials (from two different insulation cluster based on their thermal conductivity; mid-range (mineral wool) and low-range (VIP)), leading to the selection of Mineral wool as a standard choice based on prior research and Vacuum Insulated Panel (VIP) as an effective yet expensive option in Poland (Table 1).

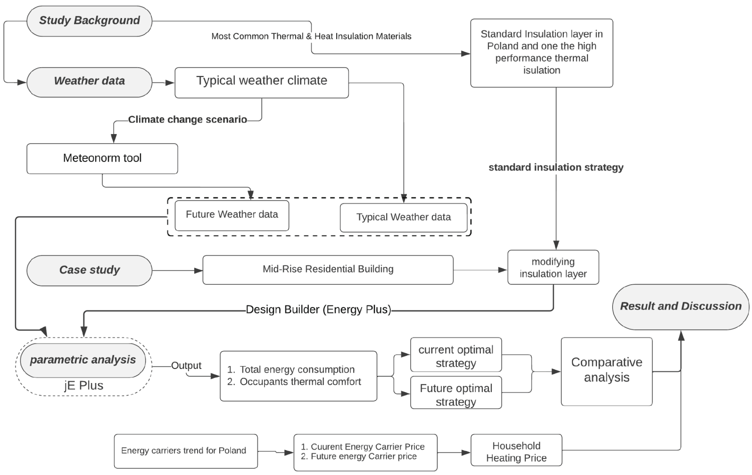

Fig. 1. Flowchart of the process of the research, Sources: authors

Table 1. Physical feature and cost of selected thermal insulation [6, 7]

Insulation material	Density (kg/m3)	λ (W/m.K)	Specific heat (kJ/kg.K)	execution cost per m^2	Material cost per m^3
Mineral wool	100	0.044	0.85	40	522
Vacuum Insulated Panel	220	0.004	1	300	30000

In step three, the studied residential building is modeled in Design Builder software to test insulation thickness variations of 1 to 5 cm. There are several studies focusing on the thickness of insulation layer [7, 8] and some studies focusing on the performance study of the building in the future [9, 10] and combining these two attitudes are not a standard practice in the literature. After that, through JEplus, an automated process of energyplus run for different insulation thicknesses is performed. After the energy simulation run, a comparative analysis is conducted to compare the performance of different thicknesses under different climate change scenarios (simulated using future weather data through statistical downscaling in Meteonorm tool). Finally, variations that perform best under varying climate conditions are identified.

2.1 Prototype Building

A medium-size residential building built in 1920 is chosen as a representative of the historic multi-family housing in Poznan for the test (Fig. 2).

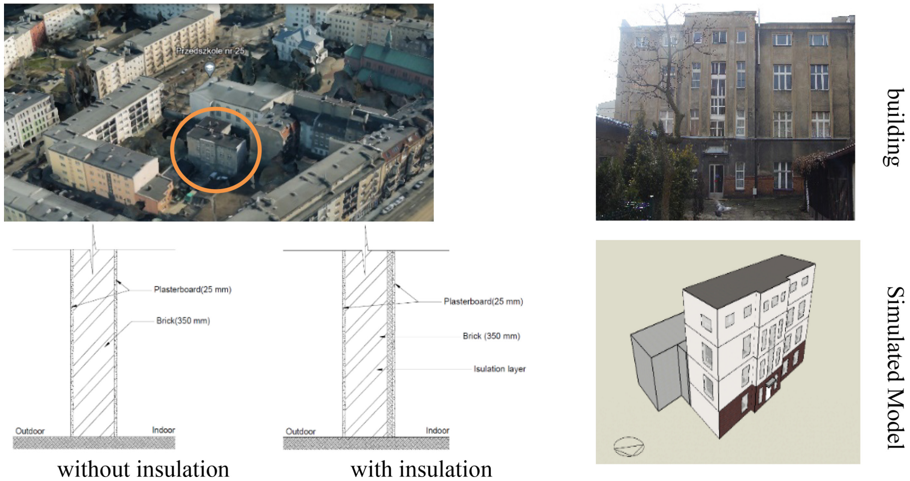

Fig. 2. Case study characteristics

3 Result and Discussion

Based on the assumption of annual increase rates of 0.5% for coal and 4% for natural gas, and assuming no change in district heating costs, the projected weighted average costs for residential heating in Euro/kWh for the years 2040, 2060, 2080, and 2100 are calculated (Table 2).

Results of the analysis is in the form of energy saving (kWh) of insulation materials at various thicknesses (Fig. 3) and Category III Acceptability Limits in the context of the EN15251-2007 adaptive comfort model (Fig. 4). As visible, the increasing thickness both materials shows better saving, VIP with a huge drop for 1 cm and mineral wool in almost a steady way. Similarly, applying both materials shows improvement in the comfort level and the thicker the insulation the higher the comfort level. Additionally, it

Table 2. Households' Energy Consumption by Energy Commodity

Households' heating cost in Poland	percent	Price per kWh				
		2024	2040	2060	2080	2100
District Heating (Euro/kWh)	50%	0.1265	0.1265	0.1265	0.1265	0.1265
Hard Coal (Euro/kWh)	40%	0.0375	0.0406	0.0449	0.0496	0.0548
Natural Gas (Euro/kWh)	10%	0.055	0.103	0.2257	0.4955	1.0846
Weighted Average Total (Euro/kWh)	100%	0.0837	0.0898	0.1038	0.1325	0.1935

can be seen that the level of energy saving will be reduced in the future while the comfort level will be increased (Fig. 5).

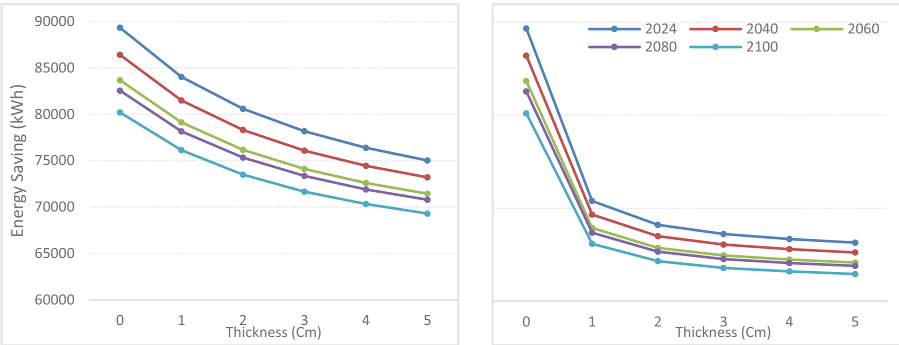

Fig. 3. Energy Saving of mineral wool (left), and VIP (right) in different thicknesses.

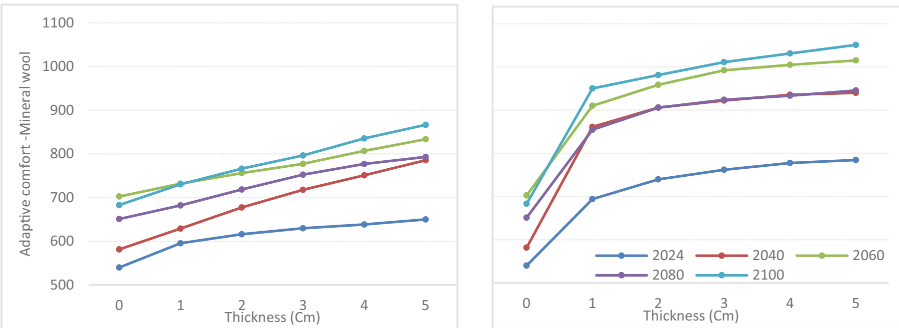

Fig. 4. Adaptive comfort of mineral wool (left), and VIP (right) in different thicknesses

The economic study of insulation materials revealed that mineral wool's savings grow with thickness, peaking at PLN 439,618 for 5 cm.

In contrast, VIP have diminishing returns beyond 1cm, eventually leading to losses. Mineral Wool offers lower upfront costs than VIP, making it more accessible. While

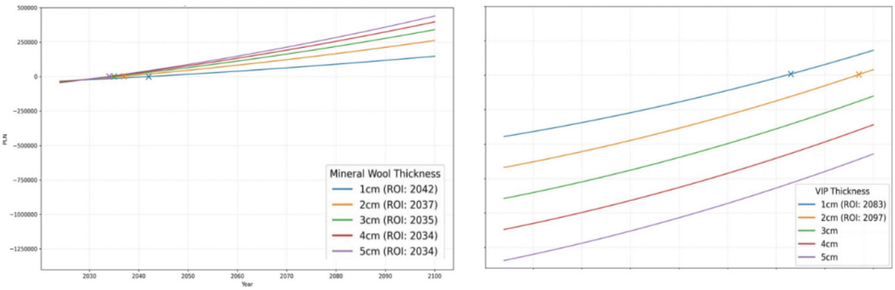

Fig. 5. Energy Saving of mineral wool (left), and VIP (right) in different thicknesses

Mineral Wool achieves a return on investment by 2034 for thicknesses of 4 cm and 5 cm, VIP's return extends far beyond, with no ROI for thicknesses over 3 cm within the foreseeable future. The comparative analysis suggests that mineral wool is often the better choice for general use due to its affordability lower investment requirement, steady savings, and reasonable ROI period, while VIP, at a 1 cm thickness, suits specialized needs where efficiency per thickness is critical regardless of budget, it becomes economically unfeasible above 2 cm due to its high cost and diminishing returns (Fig. 6).

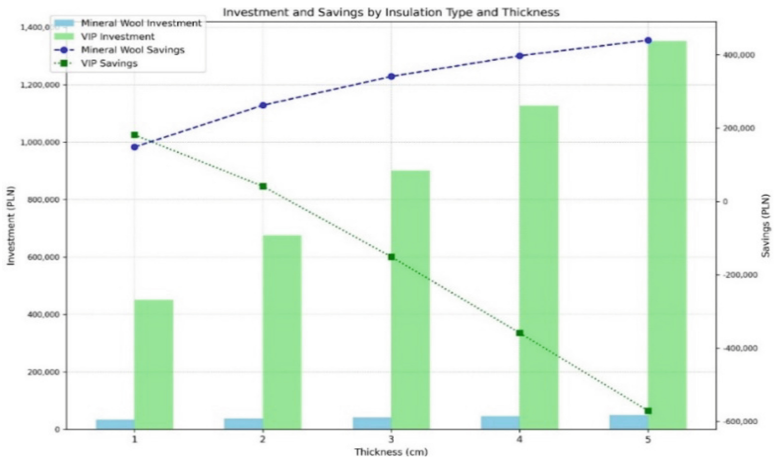

Fig. 6. Investment and Savings by insulation type and thickness

4 Conclusions

Results of this insulation optimization in this study reveals that mineral wool stands out for its affordability and increasing savings with added thickness, making it a solid choice for diverse insulation needs with its financial advantages including lower upfront costs and a quicker return on investment. VIP, on the other hand, offers superior savings at a

1cm thickness, ideal for specialized situations where efficiency per thickness is crucial. However, its economic viability decreases with thickness, as initial expenses rise sharply and savings turn negative beyond 2 cm, making it less suitable for broader applications as global warming will reduce the need for insulation material to a great extent. Given these findings, the recommendations are as follows:

- Standard Insulation Projects: opt for Mineral Wool across varying thicknesses to capitalize on its cost-effective nature and reliable savings potential. Its swift ROI timeline further reinforces its suitability for a wide array of insulation requirements.
  Space-Sensitive Installations: For situations where the insulation space is at a premium and the efficiency per unit thickness is of utmost importance, consider employing 1cm VIP despite its higher upfront cost. This option should be reserved for specialized applications where the benefits justify the investment.
- Long-Term Investment Scenarios: For projects where the focus is on long-term savings and sustainable investment, thicker Mineral Wool (4 cm to 5 cm) is advisable. It promises increased savings over time and a swift return on investment, aligning with strategic financial planning and energy efficiency goals.
- Poznań's data (climate consultant 6.0) shows a consistent upward trend in temperature and solar radiation over several decades. The average annual temperature rises from 9.6 °C in 2024 to 12.2 °C 2100, indicating a significant warming trend. The hottest temperatures decrease towards the end of the century, while the coldest temperatures increase. The requirement for heating decreases with time as a result of shifts in the heating trend. As a result, using materials with extremely high performance becomes less important, and mineral wool is recommended.

In conclusion, while VIP offers specific advantages under particular conditions, Mineral Wool is the recommended insulation for its consistent financial benefits and broad applicability. This recommendation aligns with both the immediate and long-term financial considerations of typical insulation projects.

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