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# The relationship between thermal insulation and heat source in shaping the energy efficiency of residential buildings: a case study of Poland

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**Abstract:** The energy efficiency of residential buildings results from the complex interplay of thermal insulation parameters of building envelopes, ventilation systems, and heat sources. This article examines these interdependencies in the context of reducing the EP (primary energy) index, considering the standards effective from 2021. The study highlights that improving the thermal insulation of external walls plays a pivotal role in lowering the EP index, surpassing the effects of roof or ground floor insulation. The findings reveal that the benefits of reducing the U-value vary depending on the heat source. The greatest savings were observed in buildings with electric heating, while buildings equipped with heat pumps showed limited benefits due to their high efficiency (COP). Furthermore, the application of mechanical ventilation improves a building's energy performance, particularly when combined with traditional heat sources. In contrast, its impact is minimal in buildings with heat pumps. The results emphasise the importance of an integrated approach to building design, accounting for the interactions between envelope insulation, ventilation systems, and heat sources. It is recommended to optimise thermal parameters and invest in modern heating and ventilation technologies to achieve significant energy savings and meet stringent climate requirements.

**Keywords:** thermal insulation, energy efficiency, U-value

## 1. Introduction

The thermal insulation of external partitions, measured by the thermal transmittance coefficient (U-value), plays a crucial role in the energy balance of a building. The U-value expresses the heat flux passing through a partition (e.g. walls, roofs, windows, or doors) per unit area and per unit temperature difference across the partition, in units of $W/(m^2 \cdot K)$ [1,2]. Reducing the U-value directly translates into a decrease in heat losses within the building, thereby improving energy efficiency, lowering operational costs, and reducing greenhouse gas emissions [3,4,5,6,7,8,9]. At the same time, technical requirements related to building design and thermal protection are defined, among others, by the EP indicator [10]. This indicator specifies the annual demand of a building for non-renewable primary energy required for heating, ventilation, domestic hot water preparation, and cooling. Both the U-value and the EP indicator are key parameters for assessing the energy performance of buildings and constitute essential elements in energy balance analyses [11].

The U-value depends on the materials used for the construction of partitions and their thickness. The minimum U-values that building partitions must meet are regulated by the Technical Conditions Ordinance, effective since 1 January 2014 [12]. Over the decades, there has been a systematic trend of lowering the maximum allowable U-values, resulting from technological advancements and increasingly stringent requirements for energy savings and environmental protection. For example, for external walls, the U-value, which was approximately 1.64 W/(m²·K) in 1954, was reduced to 0.30 W/(m²·K) by 1997, and since 2021, the maximum allowable value is 0.20 W/(m²·K). Similar changes apply to other partitions, such as roofs or ground floors. In the context of passive and energy-efficient buildings, the U-value should be even lower – for passive house walls, it is 0.15 W/(m²·K), and for energy-efficient houses, 0.20 W/(m²·K), as shown in Table 1. Thus, buildings designed in accordance with regulations in force after 2021 must meet requirements similar to those of energy-efficient houses.

The reduction of the U-value in construction results not only from technological development and the availability of modern materials but also from increasing demands for energy efficiency [13]. The construction sector, in particular, plays a pivotal role in implementing climate policy, which aims for a gradual reduction in energy consumption and greenhouse gas emissions [7,13]. Since 2014, the Technical Conditions have also regulated the U-value for window and door joinery, as presented in Table 1 and Fig. 1 [14]. These values have been significantly lowered – for windows and balcony doors, the U-value decreased from 1.8 W/(m²·K) in 2014 to 0.9 W/(m²·K) since 2021. Similar reductions apply to other glazed partitions, reflecting the ongoing effort to minimise heat loss and improve the energy efficiency of buildings. Consequently, there is a growing need to implement architectural and construction solutions that meet increasingly stringent energy efficiency standards. Optimising the U-value has become a key factor in designing sustainable buildings, contributing to global efforts to reduce energy consumption and protect the environment.

Table 1. Requirements for the thermal insulation of walls, flat roofs, and glazed surfaces in Poland [own study]

| Year | Legal regulations | $U_{max}$ [W/(m²K)] External wall | $U_{max}$ [W/(m²K)] Roof | $U_{max}$ [W/(m²K)] Windows |
|---|---|---|---|---|
| to 1954 | None | None | None | |
| 1955 – 1965 | PN/B-02405:53<br>PN/B-02405:57 [15] | U≤1.35 and U≤1.64 | U≤1.01 | |
| 1966 – 1975 | PN-64/B-03404 [16] | U≤1.35 | U≤1.01 | |
| 1976 – 1982 | PN-74/B-03404 [17] | U≤1.35 | U≤0.81 | |
| 1983 – 1991 | PN-82/B-02020 [18] | U≤0.75 | U≤0.45 | |
| 1992 – 1997 | PN-91/B-02020 [19] | U≤0.55 | U≤0.30 | |

| Year | Legal regulations | $U_{max}$ [W/(m$^2$K)] External wall | $U_{max}$ [W/(m$^2$K)] Roof | $U_{max}$ [W/(m$^2$K)] Windows |
|---|---|---|---|---|
| 1997 – 2002 | Regulation of the Minister of Internal Affairs and Administration of 30 September 1997 [20] | $U_{k(max)} \leq 0.30$ material with insulation coefficient $\lambda \leq 0.05$ W/(mK), $U_{k(max)} \leq 0.50$ | $U_{k(max)} \leq 0.30$ | |
| 2002 – 2008 | Regulation of the Minister of Infrastructure of 12 April 2002 [21] | $U_{k(max)} \leq 0.30$ material with insulation coefficient $\lambda \leq 0.05$ W/(mK), $U_{k(max)} \leq 0.50$ | $U_{k(max)} \leq 0.30$ | |
| 2008 – 2013 | Regulation of the Minister of Infrastructure of 6 November 2008 [22] | $U_{(max)} \leq 0.30$ | $U_{(max)} \leq 0.25$ | $U_{(max)} \leq 1.8$ |
| 2013 – 2016 | Regulation of the Minister for Construction of 5 July 2013 [23] | $U_{C(max)} \leq 0.25$ | $U_{C(max)} \leq 0.20$ | $U_{(max)} \leq 1.3$ |
| 2017 – 2020 | Notice of the Minister of Infrastructure and Development of 17 July 2015 [12] | $U_{C(max)} \leq 0.23$ | $U_{C(max)} \leq 0.18$ | $U_{(max)} \leq 1.1$ |
| 2021 | Notice of the Minister of Infrastructure and Development of 17 July 2015 [12] | $U_{C(max)} \leq 0.20$ | $U_{C(max)} \leq 0.15$ | $U_{(max)} \leq 0.9$ |

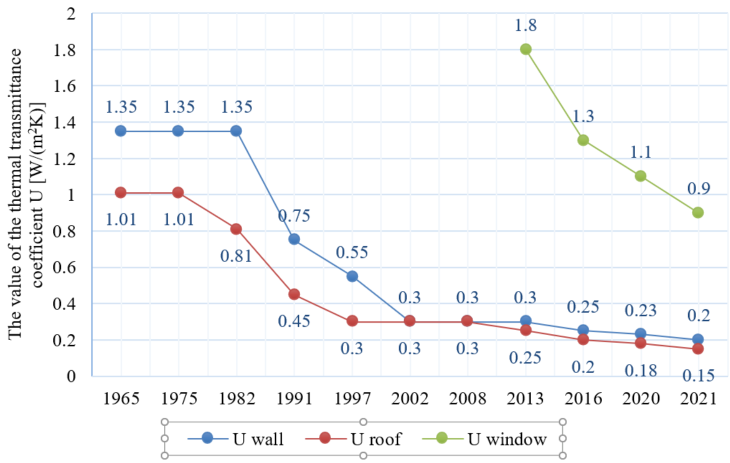


Fig. 1. Permissible U-values \[W/(m$^2$·K)] for external walls and roofs over the years 1965–2021 [Own study based on Table 1].

In practice, a lower U-value means reduced heat loss through building partitions, which consequently decreases the energy required for heating the building [9,24]. However, although the U-value has a significant impact on the EP indicator, the type of heat source plays a key role in shaping its value. The heat source determines the EP value through its efficiency and the emission factors associated with thermal energy production. For example, systems based on renewable energy sources (RES), such as heat pumps or biomass installations, are characterised by significantly lower EP values compared to traditional systems based on fossil fuels, such as gas or coal boilers [25].

Nevertheless, Polish building regulations do not specify minimum levels of renewable energy use, nor do they require the installation of such systems in newly constructed or modernised buildings [26]. There are also no defined indicators for the share of RES in the energy balance of buildings. This means that investors and designers are free to choose either conventional or alternative energy sources, provided that the general requirements for the maximum EP value are met. Such a situation allows for a diversity of design solutions but also requires particular attention during the design analysis stage. The choice of an appropriate heat source can bring significant benefits in terms of both energy efficiency and operational costs. Thus, while the U-value remains an important element in the energy assessment of a building, the selected heat source is the primary determinant of the final EP value.

Studies by Życzyńska [27,28,29] have shown that the impact of improved partition insulation on the EP index is highly dependent on the efficiency of the heating system. Highly efficient heat pumps result in diminishing returns from further improvements of the U-value in terms of EP reduction, whereas in buildings with gas boilers or electric heating, this effect is much more pronounced. Similar conclusions can be drawn from the works of Kwiatkowski and Firląg [28,30,31,32,33,34,35], who emphasise that the synergy between partition insulation and RES systems, as well as the use of mechanical ventilation with heat recovery, can significantly enhance energy efficiency, although this effect is limited in buildings that are already very well insulated or equipped with heat pumps with a high COP.

The presented research extends existing findings by simultaneously evaluating the impact of the thermal transmittance coefficient (U), the type of heat source, and the ventilation system on the primary energy indicator (EP) for a residential building. This article focuses on a direct comparison of the effects of partition insulation in the context of various heating systems. The influence of mechanical ventilation on thermal insulation efficiency is also taken into account, considering the specific conditions of the Polish energy mix and the current WT 2021 requirements. Additionally, for the first time in the literature, a cost-effectiveness threshold for further reduction of the U-value depending on the applied heat source has been identified. The contribution to the development of the discipline also includes the hierarchy of partitions in terms of their impact on EP under Polish climatic conditions.

## 2. Methodology

The aim of this study was to precisely determine the impact of the thermal transmittance coefficient (U-value) for various building partitions on the primary energy demand (EP) in residential buildings, taking into account the type of heat source and the ventilation system used. The analysis considered five heat sources (Table 2), including both conventional sources – electricity, natural gas, and coal – and alternative sources – heat pumps and biomass.

Table 2. List of selected heat sources [own study]

| Fuel | Heat Source |
|---|---|
| Natural gas | Condensing boiler with a capacity of up to 50 kW |
| Lignite (brown coal) | Dual-function constant-temperature boiler (manufactured after 2000) |
| Biomass | Dual-function constant-temperature boiler (for biomass—wood, pellets, wood chips; automatic, up to 100 kW) |
| Heat pump | Glycol/water heat pump, compressor type, electrically driven |
| Electricity | Electric storage water heater |

In the context of ventilation, the study focused on two approaches: natural ventilation and mechanical ventilation with heat recovery (75% efficiency), aiming to investigate how different ventilation systems affect the overall energy efficiency of the building. The analysis adopted varying U-values for three key external partitions: exterior walls, roofs, and ground floors. Calculations were based on the maximum permissible U-values effective since 2021, compliant with technical regulations for modernised buildings.

For each computational variant (U1–U8), different U-values were assigned depending on the partition type, as shown in Table 3:

1. Exterior walls: The U-value for exterior walls was reduced first, decreasing it by 0.04 W/(m²·K). Three values were ultimately analysed: 0.20, 0.16, and 0.12 W/(m²·K).
2. Ground floor: Subsequent steps examined the impact of lowering the U-value for the ground floor, reducing it from 0.30 to 0.20 W/(m²·K), and then to 0.12 W/(m²·K). The flexibility in adjusting these values stemmed from the technical feasibility of modifying insulation thickness.
3. Roof: The final two variants (U7–U8) involved lowering the roof U-value from 0.15 to 0.12 W/(m²·K), with U8 adopting parameters required for passive house standards.

Table 3. Adopted computational variants of thermal insulation for walls, flat roofs, and ground floors

| variant U1 | | |
|---|---|---|
| envelope | Value of the U coefficient | unit |
| External wall | 0.20 | W/(m$^2$·K) |
| Roof | 0.15 | W/(m$^2$·K) |
| Ground floor | 0.30 | W/(m$^2$·K) |
| variant U2 | | |
| envelope | Value of the U coefficient | unit |
| External wall | 0.16 | W/(m$^2$·K) |
| Roof | 0.15 | W/(m$^2$·K) |
| Ground floor | 0.30 | W/(m$^2$·K) |
| variant U3 | | |
| envelope | Value of the U coefficient | unit |
| External wall | 0.12 | W/(m$^2$·K) |
| Roof | 0.15 | W/(m$^2$·K) |
| Ground floor | 0.30 | W/(m$^2$·K) |
| variant U4 | | |
| envelope | Value of the U coefficient | unit |
| External wall | 0.20 | W/(m$^2$·K) |
| Roof | 0.15 | W/(m$^2$·K) |
| Ground floor | 0.20 | W/(m$^2$·K) |
| variant U5 | | |
| envelope | Value of the U coefficient | unit |
| External wall | 0.16 | W/(m$^2$·K) |
| Roof | 0.15 | W/(m$^2$·K) |
| Ground floor | 0.20 | W/(m$^2$·K) |

| variant U6 | | |
|---|---|---|
| envelope | Value of the U coefficient | unit |
| External wall | 0.12 | W/(m$^2$ ·K) |
| Roof | 0.15 | W/(m$^2$ ·K) |
| Ground floor | 0.20 | W/(m$^2$ ·K) |
| variant U7 | | |
| envelope | Value of the U coefficient | unit |
| External wall | 0.16 | W/(m$^2$ ·K) |
| Roof | 0.12 | W/(m$^2$ ·K) |
| Ground floor | 0.12 | W/(m$^2$ ·K) |
| variant U8 | | |
| envelope | Value of the U coefficient | unit |
| External wall | 0.12 | W/(m$^2$ ·K) |
| Roof | 0.12 | W/(m$^2$ ·K) |
| Ground floor | 0.12 | W/(m$^2$ ·K) |

For the remaining partitions, such as external joinery, the maximum permissible U-values in accordance with the Technical Conditions effective since 2021 were adopted. These values, presented in Table 4, included, among others, a U-value of 0.9 W/(m$^2$·K) for windows, 1.1 W/(m$^2$·K) for roof windows, and 1.3 W/(m$^2$·K) for external doors. Additionally, Table 4 included data on U-values for other building elements, such as internal walls (2.40 W/(m$^2$·K)) and internal floors (1.30 W/(m$^2$·K)).

Table 4. Summary of adopted U-value parameters for selected building envelopes and joinery

| Envelope name | Value of the U coefficient | unit |
|---|---|---|
| Internal walls | 2.40 | W/(m$^2$ ·K) |
| Slab | 1.30 | W/(m$^2$ ·K) |
| Windows | 0.9 | W/(m$^2$ ·K) |
| Coefficient g | 0.7 | - |
| Roof window | 1.1 | W/(m$^2$ ·K) |
| Doors | 1.3 | W/(m$^2$ ·K) |

To investigate the impact of varying U-values on primary energy consumption (EP), an annual simulation model was employed, accounting for different thermal insulation scenarios of building partitions. The analysis was conducted using computer-based calculations in the *ArCADia-Termo* software, which enabled the evaluation of U-value changes on the building's energy balance.

The study adopted a single-family residential building model as the basis for analysing energy demand for heating and ventilation purposes (Fig. 2).

Due to the high degree of individuality in spatial solutions in residential construction, the characteristic parameters were based on the most common or recommended practices. It was assumed that the building is a detached house, located in the second climatic zone of Poland, with a traditional masonry structure and a rectangular floor plan. The calculations took into account various ventilation systems and heat sources, allowing for a comprehensive assessment of their impact on the building's energy efficiency. The main entrance was assumed to be on the north side, while the living area, with the largest amount of glazing, was oriented to the south, in accordance with energy-efficient building guidelines.

The basic data of the analysed building are presented in Table 5 and Table 6.

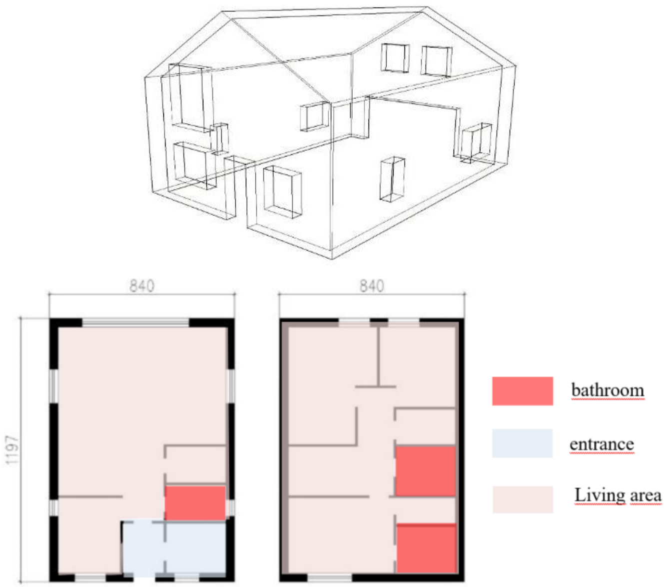


Fig. 2. Perspective view and schematic floor plans of the building [own study]

Table 5. Adopted assumptions common to the calculation of primary energy demand for heating and ventilation purposes

| Assumptions | value | unit |
| --- | --- | --- |
| Design outdoor air temperature | -18 | ˚C |
| Average annual outdoor air temperature | 7.8 | ˚C |
| Design indoor air temperature in rooms | 20 | ˚C |
| Design hot water temperature | 55 | ˚C |
| Design hot water consumption | 180 | l/ day |

Table 6. Characteristic parameters of the building model adopted for the calculations

| Symbol | Name | Value |
| --- | --- | --- |
| $A_g$ | Building footprint area | 101.36 $m^2$ |
| $A_f$ | Heated floor area | 161.38 $m^2$ |
| $V_e$ | Volume | 542.2$m^3$ |
| $V_f$ | Volume of the heated space | 373.10 $m^3$ |
|  | External dimensions | 12.05 x 8.4 m |
| $A_{w,e}$ | External wall area | 136 $m^2$ |
| $A_p$ | Transparent surface area | 31.54 $m^2$ (17%) |
| A | Area of partitions separating the building from the external environment and unheated parts | 359$m^2$ |
| $A/V_e$ | Shape factor | 0.66 |

## 4. Results and discussion

The conducted research indicates that reducing the thermal transmittance coefficient (U-value) of external partitions, particularly external walls, has a crucial impact on lowering the EP (primary energy) index of a residential building, as shown in Figs 3 and 4. The greatest energy benefits were achieved by decreasing the U-value of external walls from 0.16 W/(m²·K) to 0.12 W/(m²·K), while maintaining moderate insulation parameters for the roof (U = 0.15 W/(m²·K)) and the ground floor (U = 0.20 W/(m²·K)).

Figs 3 and 4 below present a comprehensive summary of the impact of the U-value on the EP index for a residential building, depending on the heat source and type of ventilation. Based on the results, it was observed that reducing the U-value of the walls by 0.04 W/(m²·K) yields better results than reducing the U-value of the ground floor by 0.10 W/(m²·K). It was demonstrated that a U-value of 0.12 W/(m²·K) for external walls, 0.15 W/(m²·K) for the roof, and 0.20 W/(m²·K) for the ground floor provides better results than variant U7, which is characterised by low U-values for the ground floor and roof (0.12 W/(m²·K)) but a higher U-value for external walls (0.16 W/(m²·K)) (see Figs 4 and 5). Variant U3 also performs more favourably compared to variant U7. These results indicate that, in the context of optimising energy efficiency, external walls are the most sensitive building element, and their improvement brings greater benefits than reducing the U-value of the ground floor from 0.30 W/(m²·K) to 0.20 W/(m²·K), which reduces the EP index by only about 0.5% (Fig. 6).

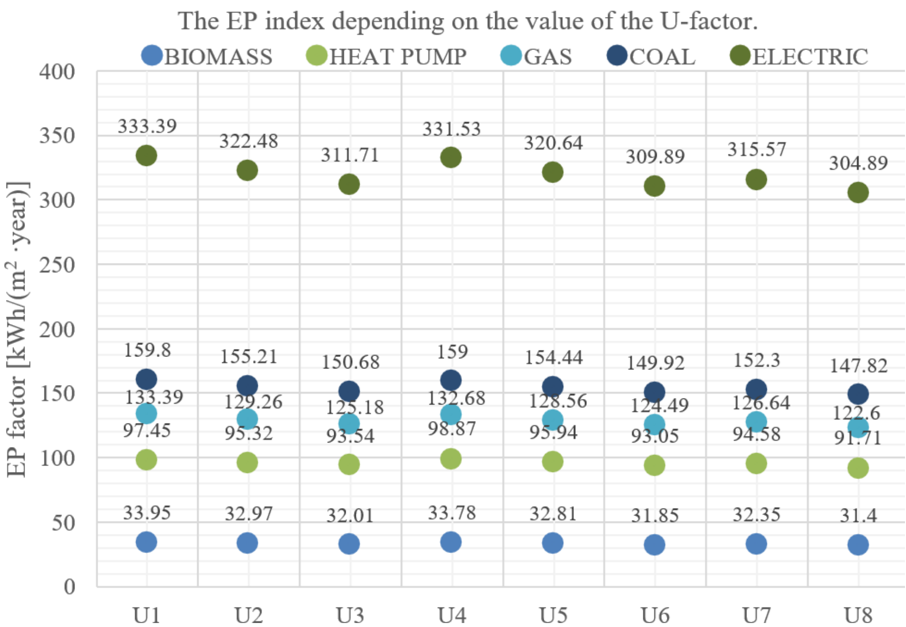


Fig. 3. A comparison of the EP index values depending on the U-value variant for a building equipped with natural ventilation [own study]

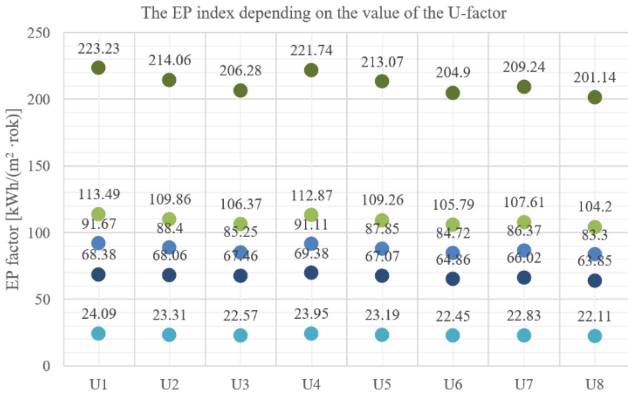


Fig. 4. A comparison of the EP index values depending on the U-value variant for a building equipped with mechanical ventilation [own study]

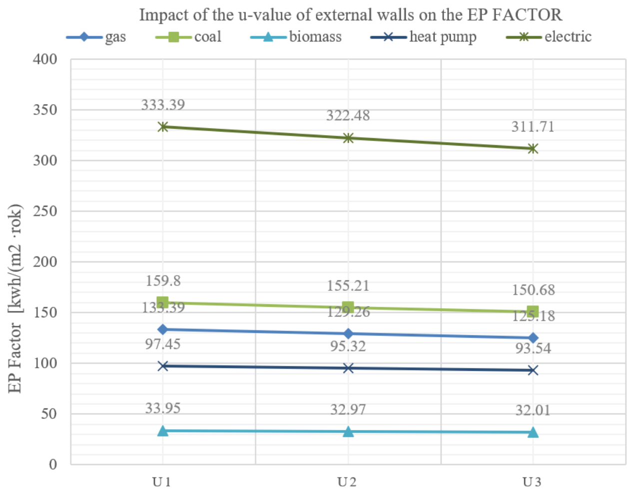


Fig. 5. EP index value with the reduction of the U-value of external walls [own study]

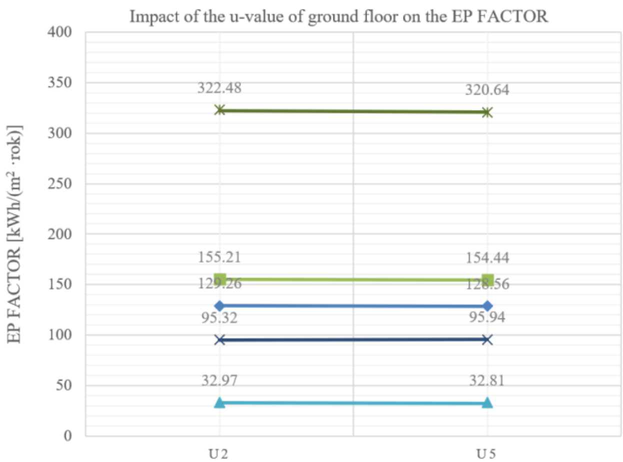


Fig. 6. EP index value with the reduction of the U-value of the ground floor [own study]

The results presented in Tables 7 and 8 clearly indicate that the significance of improving the thermal insulation of external partitions varies depending on the type of heat source used. The greatest impact was observed in buildings with electric heating, where reducing the U-value between variants U1 and U3 decreased energy demand by 6.5%. These findings highlight the importance of optimising insulation in the context of rising energy costs and the necessity to reduce primary energy demand. In buildings equipped with heat pumps, the effect of reducing the U-value on the EP index was significantly smaller. The difference in energy consumption was only 4%, which is attributable to the high coefficient of performance (COP) characteristic of heat pumps. The limited energy-saving effect of insulation in this case suggests that heat pumps are approaching a technological maximum in efficiency, which diminishes the importance of further improving the thermal parameters of building partitions.

The use of mechanical ventilation, compared to natural ventilation, contributed to a further reduction in the EP index, especially in buildings utilising electric heating. In this case, the decrease in primary energy demand reached as much as 7.6%. Mechanical ventilation provides more precise control of air exchange and stabilisation of thermal conditions, which, when combined with good partition insulation, results in significant energy savings. The smallest impact of mechanical ventilation was observed in buildings with heat pumps. Here, the reduction in primary energy demand was only 1.3%, and when combined with a lower U-value, the total reduction was 2.7%. These results indicate that in buildings with heat pumps, the potential for energy savings related to mechanical ventilation is limited.

Table 7. The impact of reducing the U-value of building envelopes on the primary energy index (EP) of a building with natural ventilation, depending on the heat source [own study]

| Gas – Z1 | | | |
|---|---|---|---|
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 133.39 | 100% | - |
| U2 | 129.26 | 96.9% | - 3.1% |
| U3 | 125.18 | 93.85% | - 6.15 (3.05%_) |
| Coal – Z2 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 159.8 | 100% | - |
| U2 | 155.21 | 97.1% | - 2.9% |
| U3 | 150.68 | 94.30% | - 5.70 (2.80%) |
| Biomass – Z3 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 33.95 | 100% | - |
| U2 | 32.97 | 97.1% | - 2.9% |
| U3 | 32.01 | 94.30% | - 5.7 (2.80%) |
| Heat pump- Z4 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 97.45 | 100% | - |
| U2 | 95.32 | 97.8% | - 2.20% |
| U3 | 93.54 | 96.0% | - 4.0 (1.8%) |

| electric – Z5 | | | |
|---|---|---|---|
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 333.39 | 100% | - |
| U2 | 322.48 | 96.7% | - 3.3% |
| U3 | 311.71 | 93.50% | - 6.5 (3.2%) |

Table 8. The impact of reducing the U-value of building envelopes on the primary energy index (EP) of a building with mechanical ventilation, depending on the heat source [own study]

| Gas – Z1 | | | |
|---|---|---|---|
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 91.67 | 100% | - |
| U2 | 88.4 | 96.4% | - 3.6% |
| U3 | 85.25 | 93.00% | - 7.0 (-3.4%_) |
| Coal – Z2 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 113.49 | 100% | - |
| U2 | 109.86 | 96.8% | - 3.2% |
| U3 | 106.37 | 93.7% | - 6.30 (3.10%) |
| Biomass – Z3 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 24.09 | 100% | - |
| U2 | 23.31 | 96.8% | -3.2 % |
| U3 | 22.57 | 93.7% | - 6.3 (3.10%) |
| Heat punp- Z4 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 68.38 | 100% | - |
| U2 | 68.06 | 99.5% | - 0.50% |
| U3 | 67.46 | 98.7% | - 1.30 (0.8%) |
| electric – Z5 | | | |
| U-value Version [W/m²K] | EP Index Value [kWh/m² year] | Share [%] | Decrease [%] |
| U1 | 223.23 | 100% | - |
| U2 | 214.6 | 95.70% | - 4.3% |
| U3 | 206.28 | 92.40% | - 7.6 (3.3%) |

The conducted research confirms that the greatest energy savings can be achieved in buildings where electricity is used as the primary heat source. Optimisation of the U-value of external partitions, particularly walls, is crucial for improving the energy efficiency of such buildings. In the case of heat pumps, the benefits resulting from improved insulation and the use of mechanical ventilation are relatively smaller, which suggests the need for alternative strategies to optimise energy efficiency in these heating systems. According to the study, the most favourable variant, U8, reduces the EP index compared to the least favourable variant, U1, by 5.9–8.55% in the case of natural ventilation and by 5.6–9.9% with mechanical ventilation, as shown in Fig. 7.

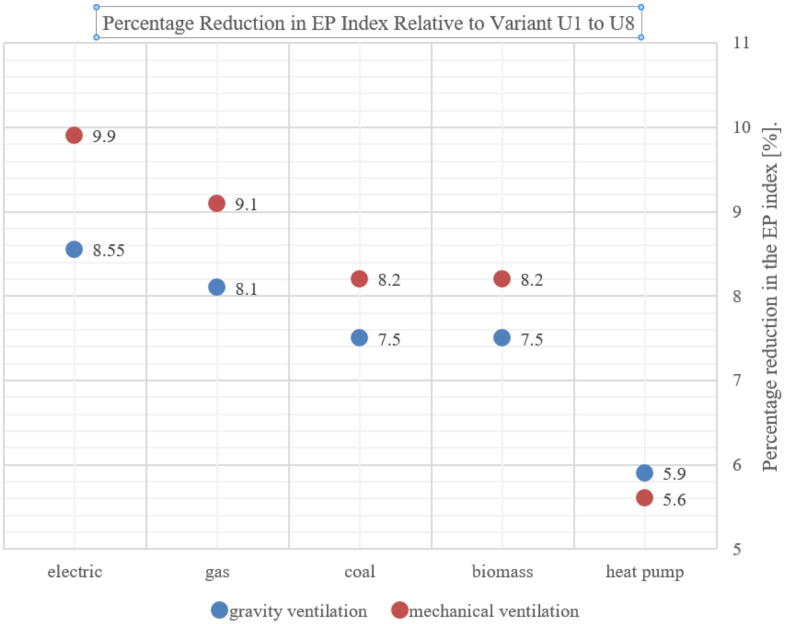


Fig. 7. Percentage reduction in EP index from variant U1 to U8 [own study]

## 5. Conclusions

Building energy efficiency is the result of the interplay of many factors—from the thermal insulation of partitions, through ventilation systems, to energy sources. The key to reducing the EP index is understanding these relationships and consciously utilising them in the design process. Analysing the impact of the U-value and the type of heat source on the EP index clearly demonstrates the need for an integrated approach to building design. Interdependencies between building partitions, ventilation systems, and energy sources must be considered. This means that a building's energy efficiency should be assessed holistically, not solely from the perspective of partition insulation or heat source type. Research shows that reducing the U-value does not yield equal benefits for every type of heat source. In buildings with modern, highly efficient heating systems such as heat pumps, decreasing the U-value has a relatively smaller impact on the EP value compared to buildings with traditional gas or coal boilers.

Based on the conducted research, several key conclusions can be drawn regarding the impact of the insulation parameters of external partitions on primary energy consumption in residential buildings:

1. Significance of external partition insulation: The results clearly indicate that improving the insulation parameters of external partitions has the greatest effect on primary energy demand in the case of electric heating. The difference in energy consumption between variants U1 and U3, amounting to 6.5%, highlights the important role of insulation materials in the building's energy balance. In particular, reducing the U-value of external walls contributes to lowering electricity demand, which is crucial in the context of rising energy costs and the need to improve building energy efficiency.

2. Limited impact in the case of heat pumps: The smallest impact of improved insulation parameters was observed in buildings equipped with heat pumps, where the difference in primary energy demand was 4%. This result can be explained by the specific operation of heat pumps, which are characterised by a higher coefficient of performance (COP). This means that changes in building insulation do not significantly translate into energy savings, which may suggest that the technical maximum efficiency of heat pumps has already been reached.
3. Benefits of mechanical ventilation: The use of mechanical ventilation showed a positive impact on the energy performance of buildings compared to natural ventilation. Depending on the heat source, the difference in energy consumption related to mechanical ventilation ranged from 0.3 to 1.1 percentage points. The greatest savings were achieved in the case of electricity, where the reduction in consumption was 7.6%. Mechanical ventilation enables more effective control of air exchange and the maintenance of stable thermal conditions in the building, which, combined with improved insulation, leads to greater energy savings.
4. Challenges for heat pump technology: Despite the use of modern mechanical ventilation and reduced U-values, buildings with heat pumps showed the smallest benefits, with only a 1.3% reduction in energy consumption. This may indicate limited possibilities for improving energy efficiency in buildings with this heat source, which should be taken into account in future construction and modernisation projects.
5. Recommendations for building design: The results suggest that optimising the U-value of external partitions is crucial for energy efficiency, especially for buildings using electricity as the main heat source. Therefore, investments in insulation materials and ventilation systems can bring tangible economic and environmental benefits in the long term.

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