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The embodied primary energy and optimisation of energy-efficient houses

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Subject review

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The embodied primary energy and optimisation of energy-efficient houses

The main requirement for the design of modern family houses is a high energy performance. With the properly selected heat generation system, the primary energy consumption and CO_2 emissions can be reduced over decades of building use. In addition to the service life of the building, the construction stage also constitutes a burden with regard to energy and environment. Houses have an embodied primary energy and CO_2 emissions, which is why efforts are currently made to improve the thermal envelope, ventilation, and the heat generation system. An additional requirement for energy-efficient buildings involves a minimum embodied energy.

Key words:
thermal insulation, heat generation, passive house, low-energy house, primary energy, embodied energy, operational energy

Pregledni rad

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Ugrađena primarna energija i optimizacija energetski učinkovitih kuća

Glavni zahtjev pri projektiranju moderne obiteljske kuće jest visoka energetska učinkovitost. Pravilnim odabirom sustava grijanja može se smanjiti potrošnja primarne energije i emisija stakleničkih plinova tijekom više desetljeća boravljenja u kući. Osim uporabnog vijeka građevine, faza gradnje također predstavlja energetsko i okolišno opterećenje. Kuće imaju ugrađenu primarnu energiju i emisiju CO_2, zbog čega se danas teži poboljšanju ovojnice, ventilacije i sustava grijanja. Između ostalog, dodatni zahtjev za energetski učinkovite zgrade jest minimalni udio ugrađene energije.

Ključne riječi:
toplinska izolacija, sustav grijanja, pasivna kuća, niskoenergetska kuća, primarna energija, ugrađena energija, operativna energija

Übersichtsarbeit

Miha Praznik, Martina Zbašnik-Senegačnik

Eingebaute Primärenergie und Optimierung energieeffizienter Häuser

Die Hauptanforderung beim Entwurf moderner Familienhäuser ist eine hohe Energieeffizienz. Durch die richtige Auswahl des Heizungssystems können der Verbrauch an Primärenergie, sowie die Emission von Treibhausgasen während jahrzehntelanger Hausnutzung vermindert werden. Außer der Lebensdauer des Bauwerkes, stellt auch die Erbauungsphase eine Belastung für Energieverbrauch und Umwelt dar. Bei Häusern bestehen eingebaute Werte von Primärenergie und CO_2 Emission, daher wird heutzutage versucht, Gebäudehüllen sowie Ventilations- und Heizungssysteme zu verbessern. Unter anderem stellen minimale Werte der eingebauten Energie eine zusätzliche Anforderung an energieeffiziente Gebäude.

Schlüsselwörter:
Wärmeisolierung, Heizungssystem, Passivhaus, Niedrigenergiehaus, Primärenergie, eingebaute Energie, Betriebsenergie

1. Introduction

Buildings need energy throughout their life cycle in both direct and indirect ways: directly at the construction stage, operational stage (operational energy), rehabilitation stage and removal stage, and indirectly in the production of raw materials and materials for the building and technical equipment required for its operation (embodied energy). The share of energy required at the stages of integration, removal and transport of materials is negligible, estimated to be approximately 1 % of the total life cycle energy use. In most studies, the recycling stage of the building is not considered to be part of the life cycle [1].

Research shows [2] that operational energy is still the dominant parameter, especially in cold and temperate climates [3]. Sartori notes that operational energy constitutes a major part of the total energy in low-energy and conventional buildings [1]. The total operational energy of a building encompasses appliances, hot water, heating, cooling and lighting. However, in the context of building design, it can be argued that only the operational energy of the heating and cooling equipment should be considered, since it is strongly affected by the building. All other operational energy is generally independent [2].

To reduce the total life cycle energy use, the use of the building (operational energy) has been identified in recent decades as the key stage. This goal is achieved by improving the thermal envelope of the building (a thicker thermal insulation layer, windows with enhanced thermal insulation, thermal envelope free of thermal bridges and with improved air-tightness), and by installing energy-efficient ventilation and heat generation equipment. Most of the measures reduce the operational energy but also cause an increase in the embodied primary energy content and CO_2 emissions. Several studies have been published dealing with the shares of primary energy use in total life cycle energy use. Some of them concluded that the operational stage of the building remains the most important [4, 5], while others showed that 40 % – 60 % of the total life cycle energy is used during the manufacturing and construction stages of low-energy buildings. [6]. However, there have also been studies that found that energy demand decreases during the operational stage of the building, while other stages are becoming increasingly important for optimising the total life cycle energy use [7].

More than 90 % of energy and carbon emissions emanate from the upstream boundary of the supply chain in product manufacturing [8]. In order to reduce the total energy use in buildings, it is of great importance in the design phase of a new building not only to reduce operational energy demand but also to pay attention to the choice of building materials [9]. On the other hand, it has been noted that the choice of supply system has a significant impact on operational primary energy use [5], possibly even larger than the measures applied to the building envelope [3].

Optimising improvements in the thermal envelope and selecting appropriate heating and ventilation systems are becoming the key concepts that determine the energy performance of buildings [10]. The results of analyzes [11] of new residential buildings with heat demand for space heating Q_{NH}/A_u between 10 and 50 kWh/(m^{2}a) indicate significantly changed relationships between energy needs and emission loads of the various stages of the life cycle. The ratio of primary energy used for heat generation in building's 60 years operation and the primary energy used for the construction and subsequent renovation can range from 0.75 to 2.2. These results indicate that the operational and embodied primary energy in energy-efficient buildings can even be equal.

This article focuses on new single-family buildings. Its key contribution is to present answers to various questions about the justifiability of the added embodied primary energy and CO_2 emissions, which make residential buildings highly energy-efficient. The results of the analysis may serve for sustainable design of modern new buildings that will have an acceptably rapid payback period for the added embodied primary energy and CO_2 emissions compared to the life cycle of improved components.

2. Methodology

The embodied primary energy content and CO_2 emissions required for the construction of energy-efficient single-family houses were compared by calculating values using a single building model. The calculated values assess the primary energy and relevant emissions embodied in structural components and elements until the completion of production. For the purpose of analysis, the building was designed and executed as a passive house (PH) or low-energy house (LEH) in terms of energy efficiency. In addition to the energy efficiency impact, the comparative analysis included the impact of various thermal envelope building systems and various heat generation systems. Input data used for the analysis of the building material, joinery components and installations were taken from available web applications [12]. Key energy and environmental indicators were calculated. The obtained calculated values were used to compare various typical structural components of the thermal envelope. Based on these comparisons, guidelines for sustainable thermal envelope concepts of energy-efficient solid masonry or wooden buildings that would require the minimum embodied primary energy content and CO_2 emissions were prepared. The impact of a central ventilation system on achieving higher energy efficiency of buildings and on the required embodied primary energy content and CO_2 emissions was also studied. The importance of selecting a proper heat generation system was also analyzed. This selection has an important impact in the construction phase and plays the key role in the subsequent operation of the building and related primary energy use and generation of CO_2 emissions.

2.1. Presentation of the building model

A single architectural model of a two-storey, compact designed single-family house was used for comparative calculations. The main parameters of the building were: heated area of the building A_u = 137 m^2, thermal envelope surface A = 454 m^2, window area A_w = 30 m^2 and shape factor f_o = 0.68 m^2 m^{-3}.

The impact of technological solutions of various efficiency for a passive (PH) and low-energy house (LEH) was tested on the specified architectural model. In order to achieve different target energy classes for the building, the key parameters of the building concept were modified (Table 1), such as the heat transfer coefficient or U-value of the thermal envelope elements and external joinery components, thermal envelope air-tightness and heat recovery efficiency of the central ventilation system. Other key parameters were identical for both passive and low-energy houses. The mean air exchange per hour in the building was n = 0.4 h^{-1}. The building location has the reference climate for Slovenia with a temperature deficit HDD = 3200 K d a^{-1}. The building is used by four persons.

The calculations of thermal characteristics and energy flows were made using the PHPP method [13], which is based on the methodologies of international standards [14, 15]. The results of heat demand calculations for heating the space were different for the low-energy and passive houses (Table 1). However, in both houses, the calculated heat demand value for providing hot sanitary water was equal, due to the same number of residents, and amounted to approx. 3 MWh/a and 22 kWh/(m^2a), respectively.

Table 1. Characteristic values for the PH and LEH models

Observed parameters	PH	LEH
Mean heat transfer coefficient of the building envelope U_m [W/m^2K]	0,15	0,20
Airtightness of the thermal building envelope n_{50} [h^{-1}]	0,6	0,8
Heat recovery efficiency of the ventilation system η_{rek} [%]	90	85
Heat demand for heating the building Q_{NH}/A_u [kWh/m^2a]	15	31
Demand for thermal power during the peak heating season P_H/A_u [W/m^2]	14	21

2.2. Presentation of thermal envelope variants

The analysis compared various technological solutions of thermal envelope building for passive and low-energy houses. Five variants taken from practice were considered:

- Variant V1: In practice this is the most commonly used variant of building wooden houses, since it is most affordable Mineral wool is used in the thermal envelope wooden structure. Façades and ground floor are insulated by expanded polystyrene (EPS). Windows with PVC frames are fitted.
- Variant V2: Wooden I-beams are used in place of solid wood elements. Cellulose flakes and wood fibre boards are used for thermal insulation. Windows with wooden frames are fitted. The ground floor is insulated by mineral wool.
- Variant V3: A solid masonry brick house, which is the most common because of its low price. Façades and the ground floor are insulated by EPS and only the roof is insulated by mineral wool. The windows have PVC frames.
- Variant V4: A selection of sustainable solutions for a brick house, since only mineral wool is used in the thermal envelope and the windows have wooden frames.
- Variant V5: A house made of aerated concrete. Mineral wool is used for thermal insulation. In this variant, the windows also have wooden frames.

The configuration of thermal envelope elements for Variants V1 to V5 is shown in Table 2. Descriptions of thermal envelope structural components are given in the tables below (Tables 3-5).

Table 2. Thermal envelope structural components for the five analysed variants of the building

Thermal envelope structural component	Analyzed variance				
	V1	V2	V3	V4	V5
Ground floor	GF1	GF2	GF1	GF2	GF2
Façade	LW1	LW2	SB2	SB1	AC
Roof	PR1	PR4	PR2	PR2	PR3
Windows	PVC/AL	W/AL	PVC/AL	W/AL	W/AL

2.2.1. Descriptions of structural components

Descriptions of structural components for walls, roofs and ground floor are given in the tables below (Tables 3-5).

Table 3. Structural components for the exterior walls [12]

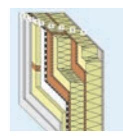
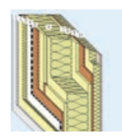
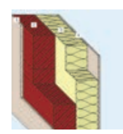
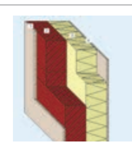
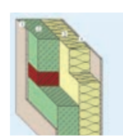
Designation	Description	Drawing
LW1	Light wooden wall 1 Mineral wool between load-bearing wooden elements, an extra layer of EPS on the exterior surface. The impact of using thermal insulation of synthetic origin is tested by this method.	
LW2	Light wooden wall 2 Wooden I-beams are used in place of solid wood elements. Natural thermal insulation materials are used: cellulose flakes and wood fibre boards on the interior and exterior surfaces.	
SB1	Solid brick wall 1 A brick wall: mineral wool is used for thermal insulation on the exterior surface.	
SB2	Solid brick wall 2 Based on structural component SB1: EPS is used in place of mineral wool for thermal insulation.	
AC	Aerated concrete wall A wall made of aerated concrete blocks: mineral wool is used for thermal insulation on the exterior surface. The impact of modified loadbearing material of a solid wall is tested by this method.	

Table 4. Structural components for pitched roofs [12]

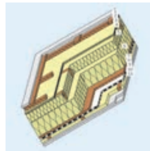
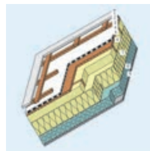
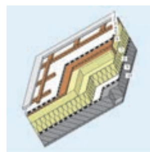
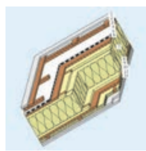
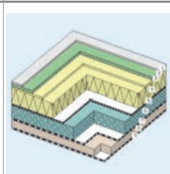
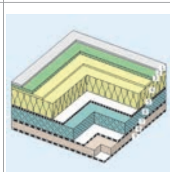
Designation	Description	Drawing
PR1	Pitched roof 1 Main structural component for a pitched roof: mineral wool between rafters. Extra mineral wool thermal insulation under the rafters	
PR2	Pitched roof 2 Rafters over a reinforced concrete slab. Mineral wool thermal insulation between the rafters and over the slab. The impact of the added concrete is tested by this method.	
PR3	Pitched roof 3 The structural component is based on PR2. Aerated concrete panels are fitted instead of a reinforced concrete slab. Mineral wool thermal insulation between the rafters and over the panels.	
PR4	Pitched roof 4 Wooden I-beams are used instead of solid wood elements, with cellulose flakes filled in-between. Better thermal insulation is attained by raising the height of the I-beams and thus increasing the thermal insulation thickness.	

Table 5. Structural components for the ground floor [12]

Designation	Description	Drawing
GF1	Ground floor 1 Reinforced concrete foundation slab, with EPS over it. Insulation thickness varies depending on the required thermal protection.	
GF2	Ground floor 2 Reinforced concrete foundation slab, with mineral wool over it. The impact of selecting a different thermal insulation material is tested by this method.	

2.3. Heat generation systems for buildings

An analysis of embodied primary energy content and CO_2 emissions was also performed for mechanical installations. Both passive and low-energy houses must be fitted with a heat generation system and central ventilation system.

Table 6. The commonest heat generation systems for energy-efficient buildings

Type of system	Designation
Air to water heat pump	HP1
Heat pump capturing heat from a horizontal ground heat exchanger	HP2
Heat pump capturing heat from a vertical ground heat exchanger or borehole	HP3
Gas boiler fitted with solar energy panels for providing hot sanitary water	GS
A boiler apparatus with pellets and solar energy panels for central heating	BS

Different technologies generate useful heat, with various efficiency rates, by converting fuel or consuming electricity, while also using renewable energy sources to different extents. An array of technologies is available to provide heat for family houses (Table 6). The most commonly used in energy-efficient buildings are air to water heat pumps (HP1), because they are the cheapest. Ground source heat pumps (earth to water heat pumps) are used in heat generation systems with the best energy performance or when passive cooling of premises in the summer is required. In both variants, the heat from the surrounding area is captured using a horizontal (HP2) or vertical ground heat exchanger (HP3). In urban areas, buildings can be connected to a gas pipeline system. In this case, the use of a gas condensing boiler is complemented by small-size solar thermal energy panels (GS), in order also to meet expectations for the use of renewable energy sources in the heat supply of the building. The construction of new buildings outside cities is characterised by a functional combination of devices, with a pellet-fired fireplace complemented by small size solar thermal energy panels (BS) in order to provide central heating to the building.

2.4. Controlled central ventilation systems for buildings

The controlled central ventilation system (design. CV) with exhaust air heat recovery was designed in two variants in order to obtain the calculated values. The energy performance of the system in operation was identical in the two variants but the materials used for air distribution through the building and the air preheating system using the geothermal source, including the related materials, were different:

- Variant CV1: distribution of air through plastic pipes. A liquid collector with indirect preheating capturing earth heat is used to preheat the fresh air.
- Variant CV2: distribution of air through sheet metal ducts. A buried duct is used to preheat the fresh air directly using earth heat. This system has been used more frequently in recent years.

3. Energy and environmental indicators of the thermal building envelope elements

Key indicators were identified for a comprehensive assessment of the energy required for constructing the thermal envelope and a subsequent assessment of environmental impacts. This environmental analysis was limited to the period extending until the completed production of building materials and structural components. The analysis examined four indicators for the thermal envelope structural components and joinery components used that are affected by the U-values of the structural components:

- $PEC_{n.r.}$ – the energy indicator, assessing the amount of primary non-renewable energy resource used per unit area of the structural component (indicator unit kWh/m²).
- GWP_{100} – the environmental indicator, assessing the global warming potential, per unit area of the structural component (indicator unit kg CO_2equ/m²).
- AP – the environmental indicator, assessing the environment acidification potential, per unit area of the structural component (indicator unit kg SO_2equ /m²).
- The OI3 indicator [16] – the combined indicator, providing more comprehensive information about the combined effect of the three preceding indicators through a dimensionless score system. The three indicators were equally weighted (in thirds) according to the following equation (Eq.1):

$$\Delta OI3 = \frac{1}{3} \times \left[\frac{1}{3} \times PEC_{n.r.} + \frac{1}{2} \times GWP_{100} + \frac{100}{0,25} \times AP \right] \text{ [points]} \quad (1)$$

3.1. Assessment of the thermal envelope structural components

For further analysis, the values of the four indicators for structural components were calculated within a broad spectrum of the U-values: for passive houses U = 0.10 W/(m²K) and for low-energy houses U = 0.15 W/(m²K) (Figure 1.a - 1.d).

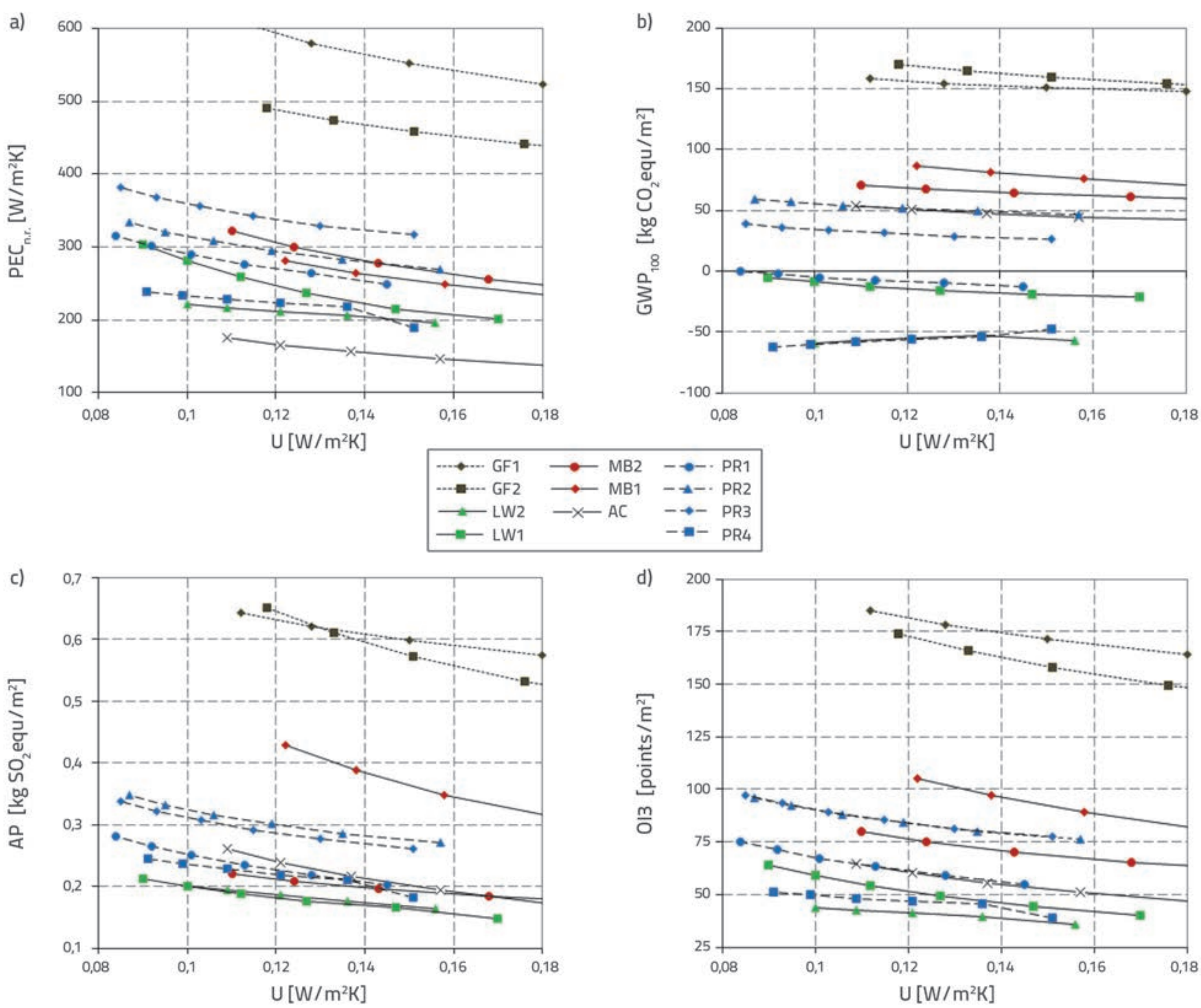


Figure 1. Continuous values for the $PEC_{n.r.}$, GWP_{100}, AP and OI3 indicators, depending on the U-value of opaque components of the thermal envelope, values per unit area of the structural component

With the decreasing U-value in individual structural components, the value of the used primary energy indicator $PEC_{n.r.}$ (Figure 1, A), the values of the environmental indicators AP (Figure 1, C) and GWP_{100} (Figure 1, B) and the value of the OI3 combined environmental indicator (Figure 1, D) were increasing. Increased values of these indicators result from higher levels of thermal insulation, which is reflected in the form of continuous curves in the diagrams. However, the continuous values may deviate in structural components whose composition is also being modified in order to enhance energy efficiency, e.g. in wooden components. For most of the structural components considered, the $PEC_{n.r.}$ values ranged between 150 (LEH) and 350 kWh/m² (PH), the GWP_{100} values between -50 (LEH) and 100 kg CO_2equ/m² (PH), and the AP values between 0.15 (LEH) and 0.35 kg SO_2equ/m² (PH).

An exception in the otherwise typical continuous values occurred in the environmental indicator GWP_{100} in the wooden components of prefabricated wall LW2 and pitched roof PR4, which were insulated by cellulose insulation. In fact, the GWP_{100} value even decreased by increasing the quantity of wood and wooden products used (Figure 1, B). Since the AP indicator values were also low for both of the specified structural components, they had the best overall assessment, i.e., the lowest value of OI3 combined environmental indicator.

The highest values in all four indicators were obtained by the two ground floor components, GF1 and GF2. Due to the higher embodied primary energy in the reinforced concrete foundation slab, the impact of the subsequently fitted thermal insulation was considerably lower than in the remaining structural components. The difference between the values of the OI3 combined environmental indicator for the U-value of the ground floor component in a passive house and low-energy house was approximately 15 %. In the remaining analysed structural components, on which the impact of the structure is considerably lower, the difference was between 25 % and 35 %. In terms of OI3 indicator, the use of mineral wool in the ground floor component is more desirable because it has better characteristics than EPS and, consequently, more favourable $PEC_{n.r.}$ and AP indicators.

The best values of the OI3 combined indicator were obtained by the wooden structural component insulated by cellulose. Slightly less favourable OI3 values were indicated by the wooden prefabricated wall LW1 with EPS insulation, since the three indicators had relatively low values. The next best results were produced by the aerated concrete wall insulated by

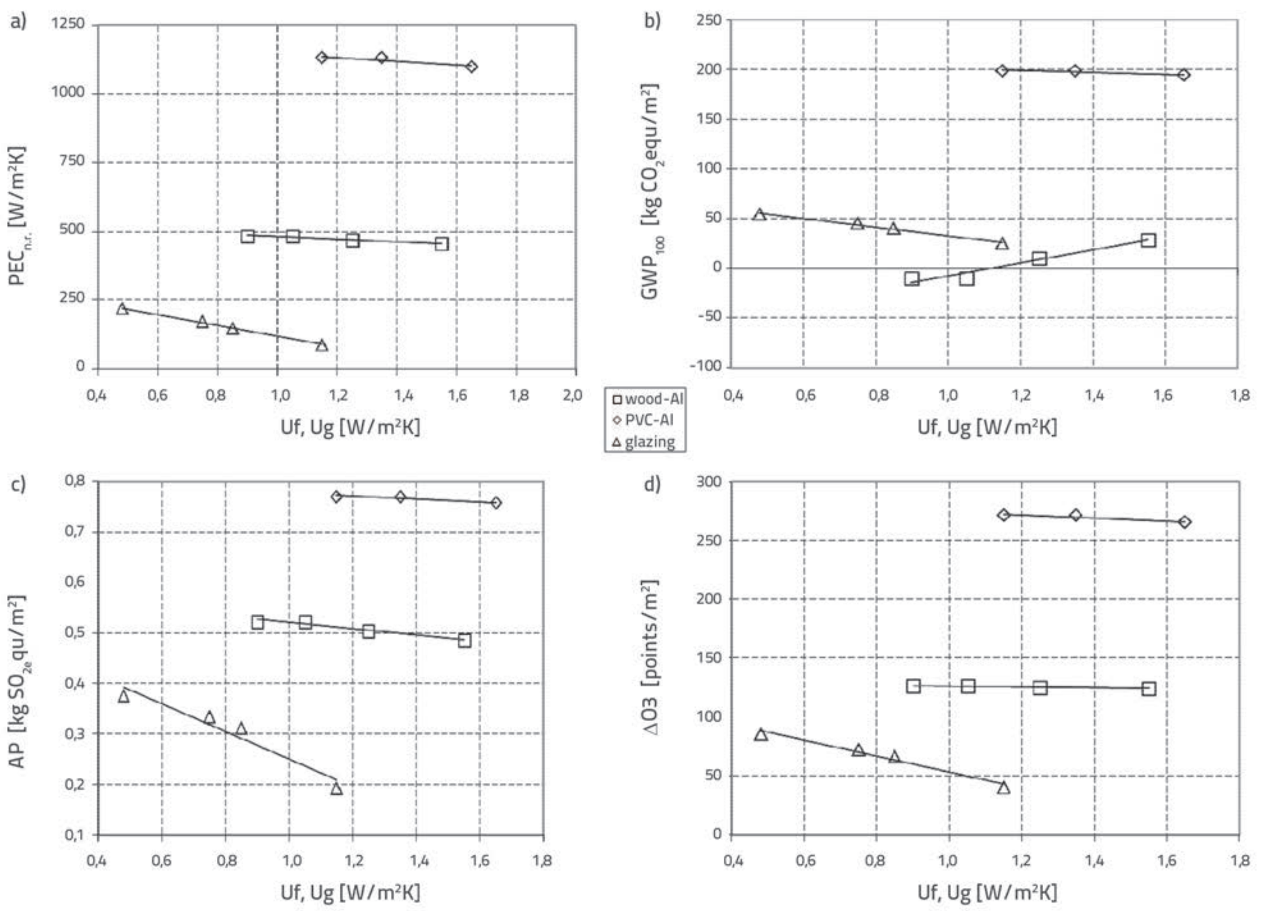


Figure 2. Continuous values of indicators $PEC_{n.r.}$, GWP_{100}, AP and OI3 depending on the heat transfer coefficients of window frames U_f and glazing U_g, values per unit area of the structural component

mineral wool (AC), but they were largely due to a low embodied primary energy content in the aerated concrete. The same curve of OI3 values was also recorded with the wooden pitched roof PR1, insulated by mineral wool.

Slightly higher, but virtually identical values of the OI3 indicator, were also obtained by the structural components of solid pitched roofs made of concrete and aerated concrete, i.e., PR2 and PR3, which were insulated by mineral wool. The thickness of the concrete inclination was inferior to that of the aerated concrete roof elements, which brought the two OI3 indicators to the same level.

The exterior brick wall again showed the advantage of using thermal insulation of mineral origin rather than EPS, because the OI3 values for SB2 were lower than those for SB1. The OI3 indicator result for the SB2 wall in a passive house remained lower than that for the SB1 wall in a low-energy house.

3.2. Assessment of joinery components

The overall U-values of the windows were U_w = 0.8 W/(m²K) for the passive house and U_w = 1.0 W/(m²K) for the low-energy house. The above values were mostly determined by the heat transfer coefficients of the glazing U_g and of the window frame U_f, taking into account the corresponding surface area of the two elements. In the family house model considered, the window frame surface area accounted for approx. 25 % of the total window surface area.

The calculated values for the glazing indicate that the values of the four indicators were within the range that is characteristic of the opaque structural components of the thermal envelope (Figure 2.a - 2.d). However, aluminium window frames had higher values. The values of all four indicators were better (i.e., lower) in wooden window frames than in PVC frames.

3.3. Assessment of the selected thermal envelope variants

The five thermal envelope variants were assessed on the basis of the previously calculated values. The values of the embodied primary energy content and embodied CO_2 emissions for the two key indicators, $PEC_{n.r.}$ and GWP_{100}, were calculated for the whole building and specific to heated floor area of the building (A_u = 137 m²), forming the basis for the analysis presented below.

The embodied primary energy content for the five building variants and their different energy performances was between 137 MWh/building and 223 MWh/building (Figure 3). The specific value $PEC_{n.r.}$ calculated per heated floor area of the building ranged between 980 kWh/m²a and 1,590 kWh/m²a (Figure 3). Comparison of the results shows that two of the variants had comparable low embodied primary energy contents: the wooden house insulated by cellulose (variant V2) and the house made of aerated concrete insulated by mineral wool (variant V5). The same applied to the wooden house with a higher embodied primary energy content (variant V1), which had the same values as the brick built house insulated by mineral wool (variant V4). Comparison of the five variants with different energy performance indicated that the brick low-energy house insulated by EPS and fitted with PVC windows (variant V4), for example, was equivalent to the passive brick house insulated by mineral wool and fitted with wooden windows (varijant 5).

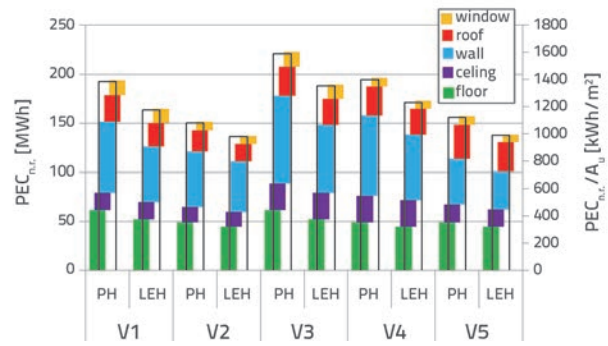


Figure 3. The $PEC_{n.r.}$ indicator in various thermal envelope variants for PH and LEH, values per buillding and per unit area of the heated surface

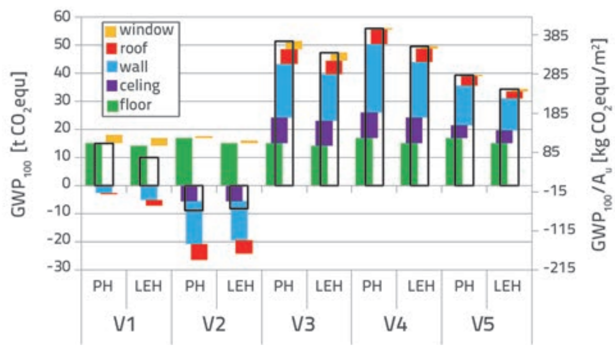


Figure 4. The GWP_{100} indicator in various thermal envelope variants for PH and LEH, values per buillding and per unit area of the heated surface

CO_2 emissions were also calculated for the whole building and specific to heated floor area of the building A_u. The presented results (Figure 4) show that CO_2 emissions in the wooden and solid construction house variants are different. In terms of construction technology, the minimum values were obtained by the light prefabricated construction of variant V2 and amounted to -8 tons kg CO_2equ or -60 kg CO_2equ/m²; the result was identical for both PH and LEH. The maximum value of embodied emissions was obtained by the brick house (PH) insulated by mineral wool (variant V4), i.e., 56 ton kg CO_2equ or 400 kg CO_2equ/m². Among solid construction structures, the house made of aerated concrete (variant V5) had the lowest CO_2 emissions.

Compared to the low-energy house, the passive house had higher embodied primary energy content and CO_2 emissions, because its thermal envelope had higher levels of insulation (Figures 5 and 6). The embodied primary energy increase in the five variants differed, ranging between 10 % and 18 %, with the minimum increase recorded in V2 and the maximum increase in V1 and V3. The embodied CO_2 emissions were higher in the thermal envelope executed in the passive standard and typically ranged between 8 % and 15 %, whereas the minimum embodied CO_2 emissions were recorded in variant V2. However, a deviation in the form of a 50 % increase was detected in variant V1.

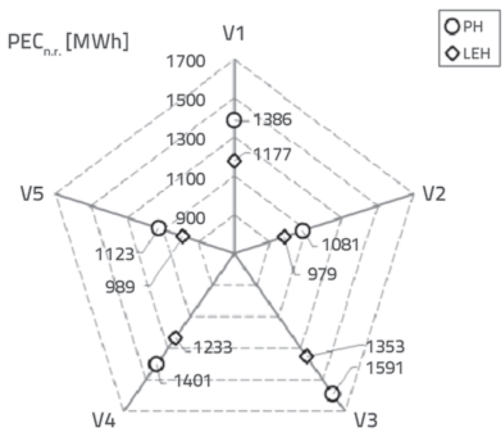


Figure 5. The difference recorded in the energy indicator of thermal envelope variants between passive and low-energy houses, values per unit area of the heated surface

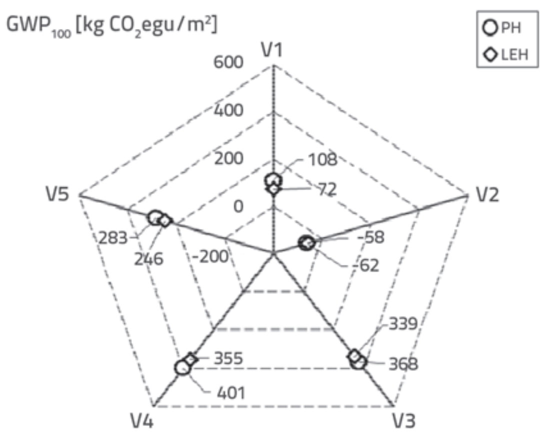


Figure 6. The difference recorded in the CO_2 emissions indicator of thermal envelope variants between passive and low-energy houses, values per unit area of the heated surface

4. Energy and environmental indicators of energy systems for buildings

For the purpose of comparison with the results presented for the thermal envelope, the embodied primary energy indicator ($PEC_{n.r.}$) and the environmental indicator of embodied CO_2 emissions (GWP_{100}) are also calculated for the central ventilation systems and heat generation systems.

4.1. Assessment of the central ventilation system

For the previously designed central ventilation system variants CV1 and CV2 and subject to the application of input data for the components [12], the calculated value of the $PEC_{n.r.}$ indicator was between 11 and 26 MWh/building, and the calculated value of the GWP_{100} indicator was between 0.6 and 1.4 ton CO_2equ/building. The structure of the above values indicates a similar impact of all three main parts of the ventilation system: the ventilation device, air distribution within the building and air preheating system. The ventilation systems for the low-energy and passive houses had the same capacity and comparable elements, so the results apply to both of them.

Comparing the indicator values for the ventilation system in variant CV1 and the previously specified variants of the thermal envelope building, it can be concluded that the type of ventilation system only accounts for 5 % to 8 % of the primary energy used for thermal envelope construction under variants V2 and V3. However, in the case of CO_2 emissions, this share was only 1 %, compared to the solid masonry building under variant V3. Due to the heat recovery in the central ventilation system, the annual demand for heat in the model building was reduced by 20 kWh/(m²a). A reduced amount of embodied primary energy and CO_2 emissions in installing a ventilation system provides greater energy savings than could be achieved by improvements in the thermal building envelope!

4.2. Assessment of heat generation systems

For a similar comparison, the $PEC_{n.r.}$ and GWP_{100} indicators for the five typical heat generation systems were assessed (Table 2). The values were calculated for the specified types of heat generation system, subject to the application of input data for each component and/or component parts of the systems [12]. The difference in the installed calorific power of the heat generator generating heat for space heating and heat for providing hot sanitary water between the low-energy and passive house was approx. 1 kW. In consequence, the same solution was chosen to assess the heat generation system in the low-energy and passive houses, which subsequently yielded the same results.

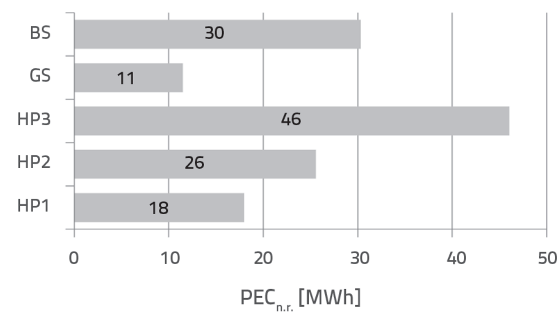


Figure 7. Primary energy use for selected heat generation systems

The installation of the specified heat generation systems in the building required between 11 MWh and 46 MWh of primary energy (Figure 7). The corresponding CO_2 emissions ranged between 0.8 and 2.9 ton CO_2equ (Figure 8). The least complex heat generation system GS had values that were comparable to central ventilation system CV1. In terms of primary energy use and embodied CO_2 emissions, the most complex heat generation systems had about four times higher values. Due to the higher embodied primary energy content, more complex heat generation systems should be included in the concepts of new buildings as appropriate with the aim of improving the environmental impact in their subsequent operation.

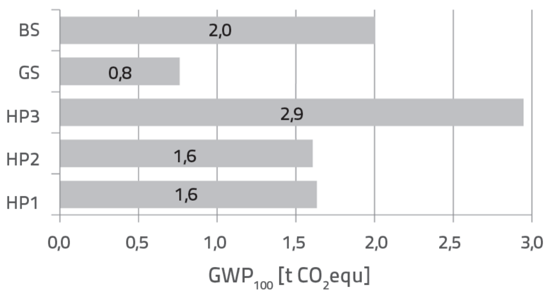


Figure 8. CO_2 emissions generated with selected heat generation systems

5. Analysis of results

An adjusted selection of thermal envelope building materials and structural components may have a significant impact on the embodied primary energy content and CO_2 emissions of a building. In a further process of thermal envelope optimisation when the thermal characteristics of a low-energy house are improved until they meet the level of passive house requirements, an adjusted selection of thermal insulation systems may influence the minimum added embodied primary energy content and CO_2 emissions. The results obtained indicate that this difference is from 10 % to 15 %, whereas the heating demand of the building may be reduced by up to 50 %.
The selection of an appropriate heat generation system for a building is an integral part of sustainable planning because it is associated with the embodied primary energy demand, whereas in the following decades during use of the building, the operational energy demand is the most important. A properly selected heat generation system may even reduce the building's primary energy demand and CO_2 emissions in the case of less environmentally friendly structural components of the thermal envelope. However, if the heat generation system is not selected properly, an otherwise properly designed building with the best results for embodied energy and CO_2 emissions may be overburdened during its use and, consequently, its final results may be downgraded. The planning process should take into account that the heat generation system has a considerably shorter life cycle than the thermal envelope, i.e., from 15 to 20 years compared to a 50- or even more-year life cycle of the external joinery and structural components. The embodied energy and operational energy must therefore be taken into account in designing the thermal envelope and energy systems. Monitoring key indicators such as $PEC_{n.r.}$ and GWP_{100} should therefore be performed in a cumulative manner over an extended period of time.

5.1. Payback of added embodied primary energy use and CO_2 emissions in an improved thermal envelope

A thermal building envelope with improved thermal insulation has a lower transmission heat loss, so the building's heat demand for space heating is lower. The heat generated for heating the premises is also defined by the primary energy use and CO_2 emissions. In assessing the payback periods of the primary energy and CO_2 emissions embodied in structural components, the following assumptions were used:

- Since most buildings with high energy performance are supplied with heat by heat pumps, electrical energy with a specific emission of 0.53 kg CO_2/kWh and a primary energy conversion factor of 2.5 were used in the calculation. Both values were determined [17] in cases in which the type of fuel was not exactly defined, or not known. Heat pump annual efficiency COP = 3.5 was also used in the calculation. Such value is considered as the minimum permissible value for the heat generation with air-water type heat pumps.
- In order to determine the transmission heat loss, the reference temperature deficit HDD determined as the most frequent and/or significant value in the territory of Slovenia [18] was taken into account.
- Reference values for thermal insulation of buildings were taken from Slovenia's legislative requirements [17], which determine the maximum permitted U-values of external joinery U = 1.3 W/(m²K), ground floor U = 0.30 W/(m²K), roof or ceiling U = 0.20 W/(m²K) and exterior walls of the building U = 0.28 W/(m²K). The reference value for exterior walls was used for solid masonry structural components, since the façade insulation thickness may be modified continuously. It is practically impossible to achieve such a high reference U-value in wooden exterior walls. Their defined reference U-value was 0.18 W/(m²K), which may already be achieved in these structural components with minimum thermal insulation.
- Simple payback period is calculated as the ratio of additional built-in primary energy and CO_2 emissions and thereby achieved reduction in annual transmission heat losses of the building components.

The payback of embodied primary energy and CO_2 emissions added in order to improve the thermal protection of structural components refers to the ratio between the described reference U-value and the target U-value of structural components for a low-energy house (U = 0.15 W/(m²K)) and a passive house (U = 0.10 W/(m²K)).
The added embodied primary energy in the analysed structural components is paid back in the form of savings as a result of reduced energy demand for space heating. The payback period is between 10 and 20 years (Figure 9). An exception is an exterior wall structural component made of aerated concrete

(AC), whose payback period is shorter than 10 years due to the previously described properties of the material (Figure 1, A). In the ground floor structural component, the payback period can be longer than 20 years. All the above payback periods are much shorter than the life cycles of the thermal envelope structural components! Comparative results also indicate that the added embodied primary energy in the structural components of a passive house is paid back in less than 5 years. CO_2 emissions embodied in structural components have different payback periods (Figure 10) at the operational stage of buildings, due to improved heat insulation. The most frequent values achieved were between 10 and 20 years. Upward deviation was recorded in the ground floor structural component. Due to the wood and cellulose insulation properties (Figure 1, B), structural components with higher levels of thermal insulation have shorter payback periods.

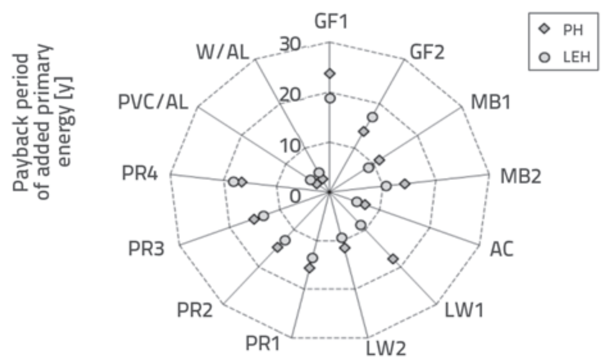


Figure 9. Payback period of added embodied primary energy in the thermal envelope elements of LEH and PH

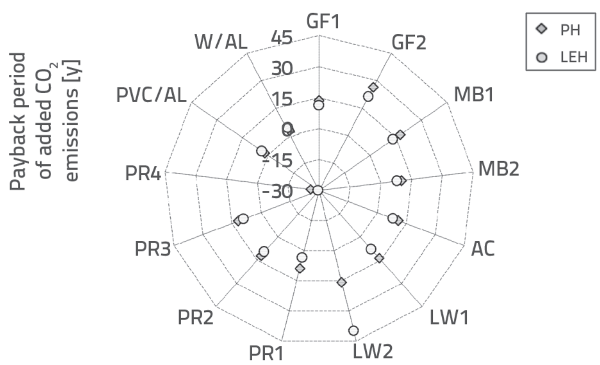


Figure 10. Payback period of added embodied CO_2 emissions in the thermal envelope elements of LEH and PH

It is characteristic of external joinery that the U-value of elements decreases with the minimum added primary energy (Figure 2, A), so the payback period is very short and is identical for windows with both wooden and PVC frames. During the subsequent use of the building, more primary energy is saved by higher energy-efficient windows because of a greater difference between the reference U-value and target U-value. The payback period for low-energy components is therefore from 4 to 5 years, whereas the payback period for passive components is shorter, amounting to 3 years (Figure 9).

The payback period of added embodied CO_2 emissions for PVC frame windows is between 2 years (PH) and 3 years (LEH). This payback period is between 1 year (PH) and 3.5 years (LEH) for wooden-frame windows. Comparing the results of opaque structural components of the thermal envelope, a reverse trend is recorded in the payback periods for external joinery. External joinery with better energy performance always has shorter payback periods of added embodied primary energy and CO_2 emissions (Figure 10)!

5.2. The impact of key parameters on the payback of added embodied primary energy and CO_2 emissions for the higher energy-efficient thermal envelope

The cumulative results of the primary energy and CO_2 emissions used for the construction and subsequent use of structural components are also influenced by certain key parameters not directly associated with the type of thermal envelope and heat generation system. The relationship may only be indirect and should be taken into consideration as appropriate in designing sustainable energy efficient buildings.

5.2.1. The impact of temperature deficit

The impact of temperature deficit deviations at the site of new construction was analysed. It had a major influence on modified transmission heat losses of the building and thus a modified demand for the primary energy used for space heating. Such influence was analysed for the exterior brick wall of SB1. In the temperature deficit reference conditions, the payback period of added embodied primary energy was 11 years and 9 years, respectively, for thermal protection executed in low-energy and passive standards (Figure 9). The payback periods of added embodied CO_2 emissions were 18 years and 13 years (Figure 10). To assess the impact, two typical temperature deficit threshold values, HDD 2,000 and 4,000 K to-1, were selected. Slovenian coastal towns (e.g., Koper, Izola), with a value of 2,100 K d a^{-1}, were ranged above the selected temperature deficit bottom threshold value, while towns in the Alpine region (e.g., Jesenice), with a value of 4.100 K d a^{-1}, were ranged above the temperature deficit top threshold value.

In a thermal envelope of a new construction located in an environment with a more distinct temperature deficit, positive effects are recorded in the form of increased annual energy savings and are reflected in shorter payback periods, specifically from 20 % to 25 %. In milder environments, the values tend to move in the opposite direction, extending the payback periods by 40 % to 50 %. The findings were the following:

- In colder climatic conditions, the highest level of thermal insulation of the thermal envelope structural components is always justified, also from the environment point of view, and must therefore always have a priority role in decision-making.

- In milder climatic conditions, the energy and environmental results characteristic for the exterior walls of low-energy and passive houses are virtually equivalent at the end of the thermal protection life cycle. In milder climates, the highest level of thermal protection is not necessarily justified from the environmental point of view.

5.2.2. The impact of heat generation mode

Given that the embodied primary energy and CO_2 emissions may be influenced by the composition of the structural components in the building envelope, the subsequent operation of the building may similarly be influenced by the choice of energy source and heat generator. In the preceding part of the analysis, the most common energy source (electricity) and the most common heat generation technology (heat pump) were used for calculating reference values. The least and most burdensome modes of heat generation for space heating in terms of energy and environment were used for calculating the threshold values of the analysed heat generation impact. They are represented by the use of wood biomass in modern combustion plants and electricity consumption for direct conversion into heat. In the case of choosing the least favourable heat generation mode (electricity), the payback periods for the thermal envelope structural component of the SB1 were reduced by 60 % to 70 %, i.e., to a period of less than 10 years, as a result of the extremely wasteful and environmentally burdensome operation. By selecting the heat generation mode with the minimum impact (wood biomass) on primary energy and CO_2 emissions, the payback periods may exceed the end of the thermal envelope life cycle. The findings may be summarised as pointing in two directions during the decision-making process:

- In heat generation systems representing a low environmental burden (e.g., wood biomass), only highly efficient thermal protection systems with a minimum initial energy and environmental input (e.g., structural components made of wood and natural materials) should be used. Heat generation with a lower environmental impact also requires such thermal envelope composition as will present the minimum possible environmental burden.
- In heat generation systems representing a higher environmental burden, a thermal envelope structural component with higher energy performance should be used. When deciding on a structural component, its energy efficiency should play the main role. In this case, the environmental aspect of construction technology is not of decisive importance, since the impact of the construction stage is practically minimal.

6. Conclusion

Proper configuration of technical solutions is of major importance for the design of sustainable buildings. The decisions of designers not only influence lower primary energy use and, consequently, lower CO_2, emissions generated during the construction stage of buildings; a proper design should also maintain the lowest possible cumulative values of this energy and environmental indicator during the many decades of the building's use. A high energy efficient building can be designed with minimum additional investment, which is rapidly repaid at the operational stage of the building due to reduced energy use.
The analysis results show that the added embodied primary energy and CO_2 emissions required for the construction of a passive house thermal envelope are justified, regardless of the location of new buildings, i.e., irrespective of the temperature deficit. The payback periods are short in comparison to the life cycle of structural components, even at the temperature deficit reference values. When designing buildings, the following findings should also be considered: higher energy-efficient external joinery has shorter payback periods and is therefore always preferable to less efficient solutions. Improving thermal insulation in structural components with a greater impact of load bearing material has limited effect, so sustainable solutions should focus on higher efficiency insulation. In order to reduce the use of primary energy used for thermal envelope building, a wooden or solid masonry construction may be equally chosen. In terms of CO_2 emissions, wooden structures or thermal insulation of wooden origin, are always the preferred choice.
Central ventilation has low energy demand at the construction stage and, at the same time, provides high savings in the energy used for space heating at the operational stage. Such savings cannot be obtained by making additional improvements in the thermal envelope, subject to the same embodied primary energy content and CO_2 emissions. The choice of heat generation systems with higher demand at the construction stage should be coupled with appropriate decisions on the thermal envelope building system or aimed at sustainable building design. A wooden passive house using a modern combustion plant fired by wood biomass has the minimum long-term environmental impact, whereas heat generation systems using fossil fuels should be combined with thermal protection systems which are typical of passive and low-energy houses.

Nomenclature

A_k	- building treated floor area [m²]
A	- heat loss surface of the building thermal envelope [m²]
A_w	- window surface [m²]
f_0	- surface area-to-shape ratio [m⁻¹]
U	- thermal transmittance coefficient [W/m²K]
U_m	- mean thermal transmittance coefficient of the building envelope [W/m²K]
U_f	- thermal transmittance coefficient of window frames [W/m²K]
U_g	- thermal transmittance coefficient of window glazing [W/m²K]
U_w	- thermal transmittance coefficient of whole window [W/m²K]
n	- total air exchange per hour in the building [h⁻¹]
n_{50}	- airtightness of the thermal building envelope, measured at 50 Pa pressure difference [h⁻¹]
HDD	- heating degree days [Kd/a]
η_G	- energy efficiency of heat recovery in ventilation system [%]
Q_{NH}	- annual heat demand for space heating [kWh/a]
P_H	- demand for thermal power during the peak heating season [W]
$PEC_{n.r.}$	- amount of primary non-renewable energy resource used per unit area of the structural component [kWh/m²]
GWP_{100}	- global warming potential in 100 years in equivalent CO_2 emissions per unit area of the structural component [kg CO_2equ/m²]
AP	- environment acidification potential in equivalent SO_2 emissions per unit area of the structural component [kg SO_2equ/m²]
OI3	- combined dimension less environmental indicator (point)

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