Embodied and Operational Primary Energy Content and CO_2 Emissions_

Optimising the Efficiency of the Building Envelope

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ABSTRACT **Buildings are major energy consumers. The embodied energy and operational energy account for the largest share of the total energy use. Increased energy efficiency of the buildings, which results in reduced operational energy, entails an increase in embodied energy. For this reason, when improving the energy efficiency of buildings, the decisions and measures to be taken need to be properly balanced.**
Embodied and operational energy and their environmental impact are evaluated with the environmental parameters $PEC_{n.r.}$ (non-renewable primary energy content), GWP_{100} (global warming potential in 100 years), and *AP* (acidification potential). The energy-environmental impact of the built-in energy is shown. The values of the above three environmental parameters, according to their thermal conductance coefficient λ, are presented for specific structural sections of the building envelope (walls, roof, floor to ground, windows). The most common construction sets for building envelope, composed of different materials - brick, wood, and aerated concrete, with added thermal insulation of synthetic, mineral, and natural origin, were analysed. The analysis of the building envelope structure also includes windows with different frames.
The advisability of thermal insulation improvement depends on the payback period. For the energy efficiency improvement measures of each individual construction set, the expected payback period is presented. The improvement of thermal insulation is achieved by additional thermal insulation, resulting in increased cost of investment.

KEYWORDS primary energy content, embodied energy, operational energy, passive house, low-energy house

1 Introduction

The built environment largely depends on energy. 30 - 40% of all primary energy is used for buildings, which are held responsible for 40 - 50% of greenhouse gas emissions (Asif, Muneer, & Kelley, 2007). The data on the primary energy use also present useful indicators on greenhouse gas emissions and the resulting impacts on the environment.

Buildings demand energy throughout their life cycle, which consists of the following phases: the production of raw materials, production of building materials and components, integration of materials and components and, finally, demolition of the building. The results show that 80 – 90% of energy is required in the operational phase (operational energy), and 10 – 20% of energy in the construction phase (embodied energy) of a building. At the end of a building's service life, energy is required to demolish the building and transport the waste material to landfill sites or recycling plants. Data indicate that the share of energy required for the demolition of a building accounts for approx. 1% of the total energy use (Adalberth, 1997). Energy savings from recycling or reusing the demolished building materials are not considered in the above calculation.

The analysis of life cycle energy savings identifies and mostly targets the phases that have the largest primary energy use, i.e. the operational and embodied energy.

Embodied energy is the energy used during the manufacturing phase of the building. It is associated with the production of raw materials, production and transport of materials and technical equipment, and the construction and renovation of the building. In the analyses, the operational phase of a building is limited to 60 years, with intermittent rehabilitation of technical installations and those materials that have a shorter life span than other materials. In addition to this, buildings require regular annual maintenance, which also demands energy.

Operational energy is the energy required for maintaining the optimal comfort conditions and day-to-day maintenance of the buildings. It is the energy for HVAC (heating, ventilation, and air conditioning), domestic hot water, lighting, and powering appliances.

Activities to achieve reduction in primary energy use over the building's life cycle are focused mainly on reducing the operational energy demand of the buildings. This is implemented by applying passive and active technologies, such as the provision of a thicker layer of thermal insulation on the shell of the building, using gas filled triple pane windows with low emissivity coatings, ventilation air heat recovery from exhaust air, heat pumps coupled with air or ground/water heat sources, solar thermal collectors, and building integrated solar photovoltaic panels. However, reduced demand for operational energy results in an increased share of embodied energy of the building due to the use of energy intensive materials, installations, and equipment. Although the embodied energy constitutes only a 10 – 20% share in comparison to

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life cycle energy, the use of low energy materials should be encouraged. Venkatarama and Jagadish (2003) state that, in this way, the embodied energy may be reduced by 30 – 40%. Thormark (2000) also notes that the reuse of materials and components in a building may save 55% of embodied energy.

Increasing the energy efficiency of a building is an important measure to reduce the demand for operational energy. A number of energy efficient building types based on different concepts have been developed, such as very low-energy houses, passive houses, zero-energy houses, self-sufficient houses, etc. The analyses show that passive houses are the optimal energy-efficient houses in terms of the energy used over the building's entire life cycle (Feist, 1996). However, measures may also be counterproductive if the increase in embodied energy is excessive. Currently, self-sufficient houses that are entirely independent from external energy sources (zero operating energy) have a higher energy demand in the life cycle context than low energy houses (Ramesh, Prakash, & Shukla, 2010). For this reason, when improving the energy efficiency of buildings, the decisions and measures to be taken need to be balanced properly.

A building's negative impact on the environment is defined by the energy and environmental indicators, which serve to assess these impacts. The $PEC_{n.r.}$ energy indicator refers to the non-renewable primary energy content required for the production of building materials, elements, and components. The environmental indicators GWP_{100} (global warming potential, 100 years) and *AP* (acidification potential) are used to assess the burdening of the environment during the phase of production of building materials and components with substances causing a greenhouse effect. The *OI*3 indicator provides combined assessment of all three indicators and comprehensive information about the combined effect of building materials, elements, or components on the environment. The study presents different variants of building envelope structural components made of different building materials and using different construction technologies through the perspective of energy and environmental indicators, and the expected payback period of different measures applied to improve their energy efficiency.

2 Energy and Environmental Indicators of Thermal Envelope Structural Elements

When deciding on energy efficient building, it is therefore essential to study the negative potential over the total life cycle of the building, which consists of the following four phases:

- production of raw materials, building materials and components for the building;
- sale and integration of building materials and components;
- use of the building as the longest phase of its life cycle;
- demolition of the building and its components.

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In the environmental analysis, which is limited to the period extending to the completed production of structural elements, four indicators that apply to thermal envelope structural components are comparatively examined:

- the first is the $PEC_{n.r.}$ energy indicator, assessing the primary non-renewable energy content, used per unit area of the structural component (indicator unit kWh/m^2);
- the next two indicators are the environmental indicators GWP_{100}, assessing the global warming potential of the product (in 100 years), and *AP*, assessing the environment acidification potential of the product, measured per unit area of the structural component (indicator units kg_{CO2equ}/m^2 and kg_{SO2equ}/m^2);
- the last environmental indicator is the *OI3* indicator (IBO, 2017), providing more comprehensive information about the combined effect of the three preceding indicators through a dimensionless score system. The three indicators are equally weighted (in thirds) according to the following equation (Eq. 2.1):

$$\Delta OI3 = \frac{1}{3} \times \left[\frac{1}{10} \times PEC_{n.r.} + \frac{1}{2} \times GWP_{100} + \frac{100}{0{,}25} \times AP\right] \quad [points]$$

2.1 Building Materials and Their Impact on the Environment

The energy efficiency of a building depends on the thermal envelope composition, i.e. on the wall and roof structure, the structure of floors in contact with the ground or floors exposed to unheated parts of the building, and joinery. The impact of the materials incorporated in the thermal envelope on the environment varies over the life cycle of a building. A proper selection of materials improves the heat insulating properties and the values of environmental parameters. The study focuses on the comparison of environmental impacts of different building envelope structures. For the evaluation of environmental parameters, the most frequently used load-bearing building materials and thermal insulation have been selected:

- materials used for solid masonry structure
- materials used for light timber structure
- synthetic thermal insulation materials
- mineral thermal insulation materials
- natural (biological) thermal insulation materials.

Materials utilised for load-bearing structure and thermal protection vary in terms of their thermal conductance coefficient, which, according to the manufacturers (Baubook, 2017), falls in the range of $\lambda \leq 0.05$ W/(m • K) for thermal insulation materials. The impacts of materials on the environment (also depending on their thermal conductance) are assessed using the environmental parameters $PEC_{n.r.}$, GWP_{100}

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and *AP*, with the data obtained from different databases, including from Baubook (2017).

No significant trends are observed in the non-renewable *primary energy* ($PEC_{n.r.}$) content, required for the production of all five selected groups of materials (Fig. 2.1), which means that the use of materials in a thermal envelope should be considered on a case-by-case basis for each separate structure. Materials utilised for solid masonry structure have values between e.g. 250 – 500 kWh/m^3. Thermal insulation materials of natural origin have the lowest values in the group, materials of mineral origin record higher values, and materials of synthetic origin have the highest values. The differences between the values are in the range of 0 – 1,200 kWh/m^3.

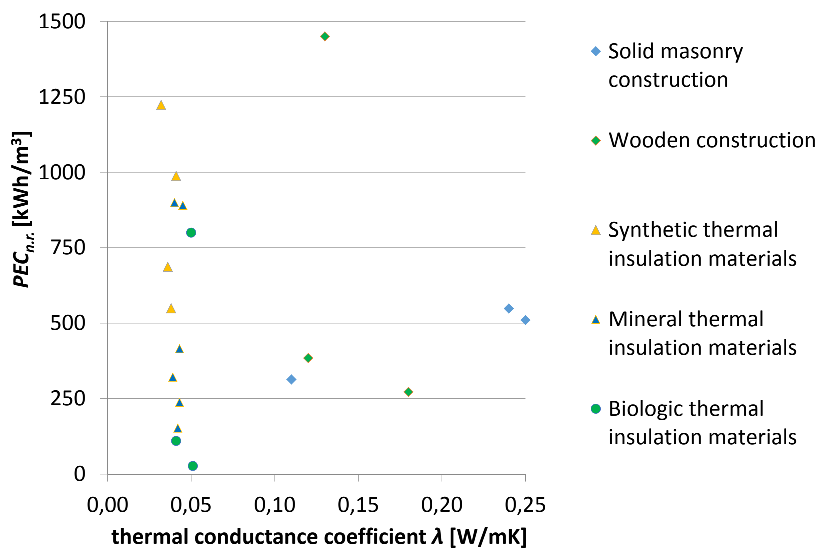


FIG. 2.1 Primary energy ($PEC_{n.r.}$) content required for the production of different groups of building materials depending on their thermal conductance

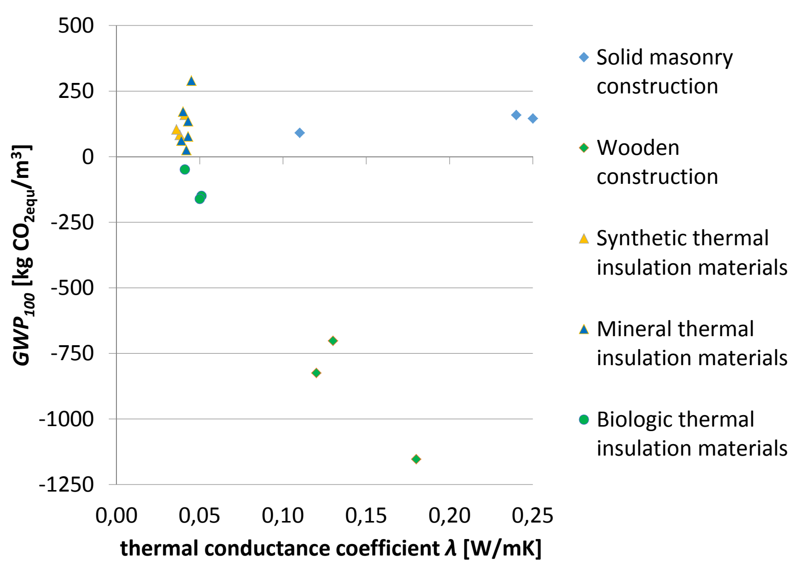


FIG. 2.2 Global warming potential (GWP_{100}) depending on thermal conductance of building materials

The values of *global warming potential* (GWP_{100}) indicate positive aspects of using load-bearing construction and thermal insulation materials of natural origin, such as, for example, wood and wood products (Fig. 2.2).

These materials, due to the CO_2 accumulated or tied in at the growth stage, have negative GWP_{100} values, which range up to -200 kg CO_{2equ}/m^3 for thermal insulation materials, and from -700 – -1,200 kg CO_{2equ}/m^3 for load-bearing construction materials. The GWP_{100} values of all other materials fall within the positive range from 0 – 300 kg CO_{2equ}/m^3.

The values of *environment acidification potential* (*AP*) do not depend on the structure in which the material is incorporated. The results fluctuate between the values of 0.1 – 1.1 kg SO_{2equ}/m^3 (Fig. 2.3).

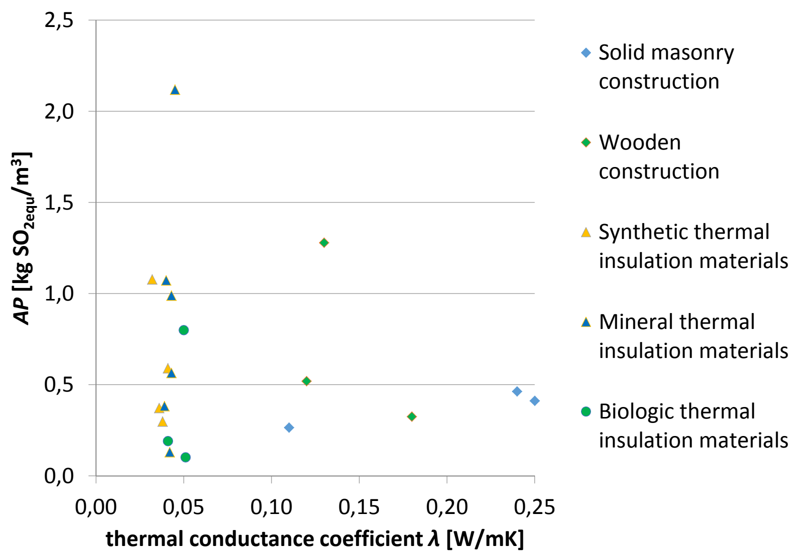


FIG. 2.3 Environment acidification potential (*AP*) depending on thermal conductance of building materials

2.2 Variants of Building Envelope Structural Components

For further analysis, descriptions of the structural components of the building envelope that are most frequently used in new construction are given for:

- **solid masonry walls** (SW) and **lightweight timber walls** (LW);
- **pitched roofs** (PR) and **flat roofs** (FR), and
- **ground floor** (GF) and **floor to unhea;ed parts** of the building (FU).

The components are identified by codes for the purpose of analysis presentation. They are presented below, together with the objectives and decisions that influenced their selection.

2.2.1 Solid Wall

Nine structural components have been selected for the exterior solid walls, and are described in Table 2.1:

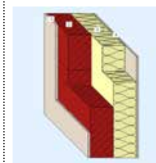
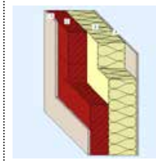
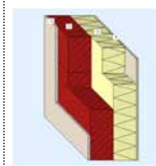
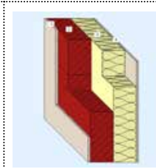
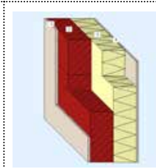
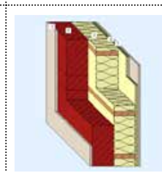
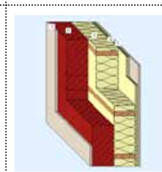
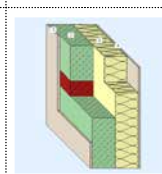
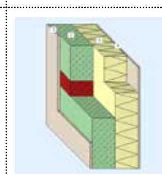
SW1	30 cm brick wall, mineral wool thermal insulation	
SW2	Derived from SW1, 20 cm brick wall, mineral wool thermal insulation	
SW3	Derived from SW1, 30 cm brick wall, thermal insulation made of expanded polystyrene (EPS)	
SW4	Derived from SW1, 30 cm brick wall**,** mineral wool thermal insulation of lesser density (for ventilated façade)	
SW5	Derived from SW1, 30 cm brick wall, thermal insulation from extruded polystyrene (XPS) (for brick walls below ground level)	
SW6	Derived from SW1, 30 cm brick wall, mineral wool of lesser density installed in a timber substructure, finished on the exterior with a wood fibreboard (assessing the impact of wood in the solid wall component)	
SW7	Derived from SW6, 30 cm brick wall, thermal insulation from cellulose flakes blown into the timber substructure, finished on the exterior with a wood fibreboard (assessing the impact of materials of biological origin)	
SW8	Derived from SW1, 30 cm wall made of aerated concrete blocks (instead of reinforced concrete), thermal insulation from mineral wool (assessing the impact of the load-bearing building material)	
SW9	Derived from SW8, 30 cm wall made of aerated concrete blocks, thermal insulation from EPS (instead of mineral wool).	

TABLE 2.1 Structural components for the exterior solid walls *(Baubook, 2017)*

2.2.2 Light Timber Wall

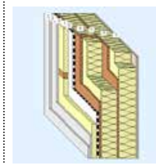
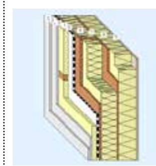
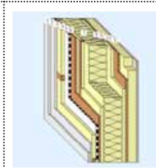
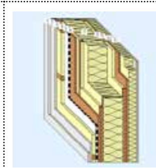
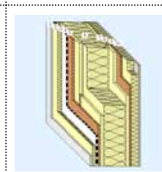
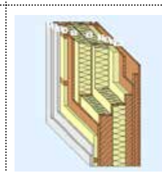
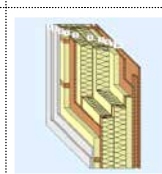
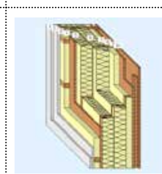
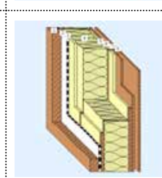
LW1	16 cm thick timber structure filled with mineral wool insulation; a layer of mineral wool insulation on the exterior surface (with plaster); installation frame filled with mineral wool on the interior surface	
LW2	Derived from LW1, thermal insulation from EPS on the exterior surface (assessing the effect of synthetic insulation)	
LW3	Structure from timber I-beams, with mineral wool of lesser density filled in-between; mineral wool of lesser thickness and a thin-layer of plaster on the exterior surface; installation frame filled with mineral wool on the interior surface	
LW4	Derived from LW3, EPS on the exterior surface (assessing the effect of synthetic façade insulation)	
LW5	Derived from LW3, natural thermal insulation is used – cellulose flakes filled between I-beams, wood fibre boards on the exterior and interior surfaces	
LW6	Framework structure (built in-situ): mineral wool insulation filled in-between; wood fibre thermal insulation on the exterior surface, ventilated façade.	
LW7	Derived from LW6; cellulose flakes are blown into the timber structure spaces.	
LW8	Derived from LW6; straw bales are fitted in-between the timber load-bearing structure	
LW9	Wall from solid glued wood; substructure made of I-beams on the exterior surface, thermal insulation from cellulose flakes blown in-between; wood fibre board on the exterior surface.	

TABLE 2.2 Structural components for the exterior lightweight timber walls *(Baubook, 2017)*

A lightweight timber structure is the preferred structural component of energy-efficient buildings. There are two main implementation methods: the building envelope structure can be prefabricated, or put together at the construction site. Nine structural components for the exterior lightweight timber walls were selected for the analysis, and are described in Table 2.2:

2.2.3 Flat and Pitched Roofs

Different structural components for pitched roofs and flat roofs, with wood and reinforced concrete structures, have been selected for analysis. Pitched roofs are described in Tab. 2.3, and flat roofs in Tab. 2.4.

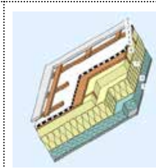
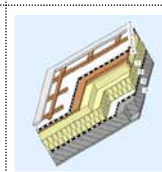
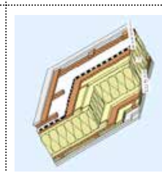
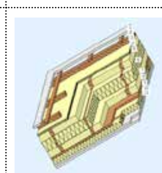
PR1	Mineral wool of lesser density between rafters; mineral wool of lesser density under the rafters between the spaces of the timber substructure	
PR2	Rafters over a reinforced concrete slab, mineral wool between and under the rafters (assessing the impact of the concrete)	
PR3	Derived from PR2, aerated concrete slab instead of a reinforced concrete slab	
PR4	Structure from timber I-beams, thermal insulation made of cellulose flakes	
PR5	Derived from PR4, straw bales instead of cellulose flakes	

TABLE 2.3 Structural components for pitched roofs *(Baubook, 2017)*

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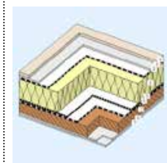
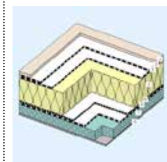
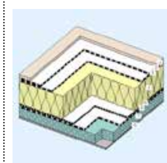
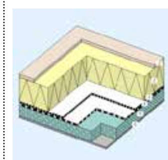
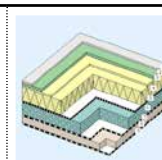
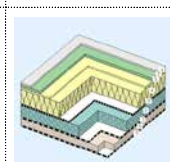
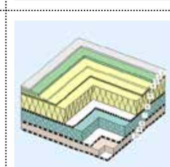
FR1	Glued wood slab, mineral wool on the exterior surface	
FR2	Reinforced concrete slab; EPS on the exterior surface	
FR3	Derived from FR2; reinforced concrete slab; mineral wool on the exterior surface	
FR4	Reinforced concrete slab; XPS on the exterior surface	

TABLE 2.4 Structural components for flat roofs *(Baubook, 2017)*

2.2.4 Ground Floor and Floor to Unheated Basements

Structural components for solid floors in contact with the ground, and structural components for solid and lightweight timber floor structures that are exposed to unheated parts of the building, have been selected for the analysis, and are described in Tab. 2.5 and Tab.2.6:

GF1	Reinforced concrete slab; EPS on the exterior surface	
GF2	Derived from GF1; mineral wool on the exterior surface (assessing the impact of selecting different thermal insulation)	
GF3	Derived from GF1; perlite on the exterior surface (assessing the impact of thermal insulation with different environmental parameters)	

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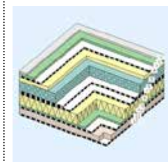
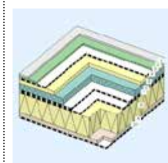
GF4	Reinforced concrete slab; mineral wool on the exterior surface and XPS on the interior surface	
GF5	Derived from GF4, foamed glass insulation on the interior surface (assessing the effect of exclusively mineral thermal insulation materials)	

TABLE 2.5 Structural components for ground floors *(Baubook, 2017)*

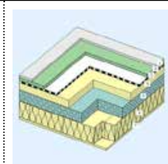
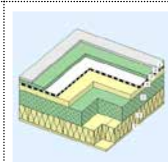
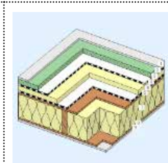
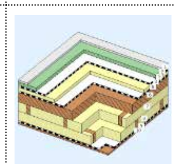
FU1	Reinforced concrete slab; mineral wool on the exterior surface; suspended ceiling with mineral wool on the interior surface	
FU2	Derived from FU1; aerated concrete slab	
FU3	Ceiling made of timber joists with mineral wool in-between; mineral wool on the exterior surface	
FU4	Glued wood slab; mineral wool on the exterior surface; mineral wool fitted in-between timber beams on the interior surface	

TABLE 2.6 Structural components for floors exposed to unheated parts of buildings *(Baubook, 2017)*

2.2.5 Windows

Windows have a major impact on the energy balance. On the one hand, they impact the reduction of heat losses, and on the other hand, they provide for solar gain. However, energy efficiency and impact on the environment are not measured only in terms of the effects that the windows have on the building's thermal balance during the building use phase, but throughout its life cycle. Selection of the most appropriate windows is based on various criteria, e.g. the window frame material, protection against external influences, the glass used, and the construction and physical characteristics such as thermal transmittance of the window frame and glass, and solar energy transmittance of the glass.

For the purpose of further analysis of energy and environmental parameter trends, six groups of window frames with different composition and thermal transmittance U_f have been selected:

- a frame made of larch, external layer made of aluminium (wood-alu, larch)
- a frame made of spruce, external layer made of aluminium (wood-alu, spruce)
- a frame made of spruce (wood, spruce)
- a frame made of larch (wood, larch)
- a frame made of PVC
- a frame made of PVC, external layer made of aluminium (PVC-alu).

Glazing also has an impact on the thermal transmittance of windows. Triple glazing with different thermal transmittance (U_g) has been selected for analysis. Double glazing has only been used in the comparative part of the analysis.

3 Analysis of Energy and Environmental Indicators in the Structural Components of the Selected Building Envelope

For the aforementioned structural components of the building envelope, the analysis of energy and environmental indicators associated with their production has been carried out.

The first part of the analysis compares the trends in key parameters in terms of the target, i.e. operational energy efficiency, reflected through the achieved thermal transmittance, for different structural components.

The second part of the analysis shows the trends in environmental indicators according to the different primary energy inputs required for achieving a better thermal insulation performance of a structural component. At the same time, the payback period of such primary energy inputs in terms of subsequent operational savings is analysed. The overall payback time of primary energy input for different thermal protection levels achieved in the components is compared with that obtained under the reference thermal transmittance U, e.g. the maximum permitted thermal transmittance.

The third part of the analysis examines the cumulative environmental indicators over the life cycle of a building through a comparison between the reference and energy-efficient solutions for buildings.

3.1 Primary Energy Content, Global Warming Potential, and Environment Acidification Potential, and *OI3* Indicator for Building Envelope Structural Components

The values of the four targeted indicators for previously described structural components have been obtained by using online tools (Baubook, 2017).

3.1.1 Solid Walls

The trends in solid wall indicators are shown in Fig. 3.1 – 3.4. Since thermal protection of masonry components is modified by varying the thickness of thermal insulation, the trends in the observed indicators are continuous as expected. The monitoring of parameters is focused on thermal insulation and the recorded values range between the low thermal transmittance of structural components adhering to the passive house standard (U = 0.10 - 0.15 W/(m^2 • K)) and the reference values, i.e. the maximum values (U = 0.28 W/(m^2 • K)) permitted by the Slovenian legislation for the exterior walls during the study period (Uradni list RS, No. 52/2010).

***PEC**$_{n.r.}$*

The findings in terms of the $PEC_{n.r.}$ indicator trend are as follows (Fig. 3.1):

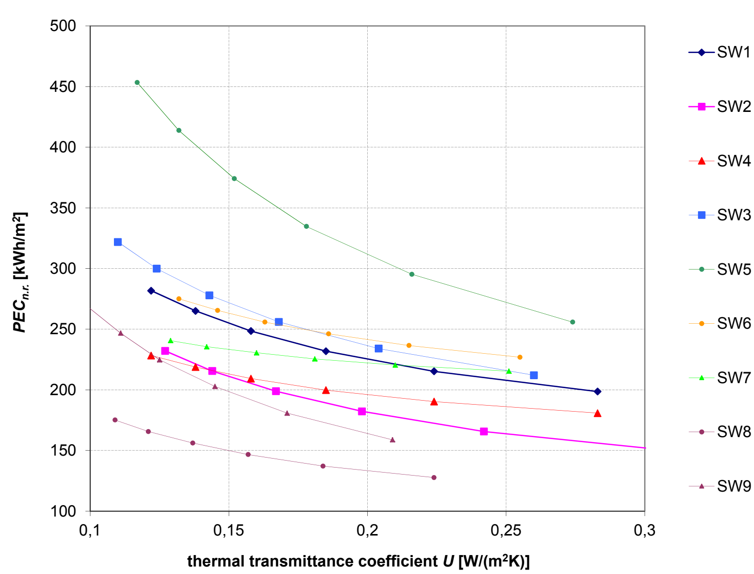


FIG. 3.1 The $PEC_{n.r.}$ indicator of primary energy content for exterior solid walls

– The primary energy used for the execution of the basic masonry component SW1 ranges from 200 – 300 kWh/m^2, and the relevant U-values of the component range from 0.28 – 0.10 W/(m^2 • K). The execution of a SW1 structural component with high thermal insulation performance requires 50% more primary energy content due to a thicker mineral wool layer.

- The primary energy content required for the execution of the SW2 solid wall component is reduced due to a lower proportion of bricks used, as follows: in the variant with thermal transmittance U = 0.28 W/(m^2 • K), it is reduced by approximately one quarter, and in the passive house variant by only one sixth. Due to a lower proportion of brick material, the same embodied energy content is used to produce a structural component with thermal transmittance U_{SW2} = 0.10 W/(m^2 • K) or U_{SW1} = 0.15 W/(m^2 • K).

- If EPS thermal insulation is used, the embodied energy content in the SW3 structural component is slightly increased, e.g. by 10% compared to the basic SW1, at thermal transmittance U = 0.15 W/(m^2 • K). Thus, a change in the façade system, which consists of replacing the mineral wool thermal insulation with a cheaper synthetic one, does not have a significant effect on the analysed parameter.

- By replacing mineral wool of a higher density with that of a lower density (the SW4 variant), the primary energy savings are 20% lower than those associated with the SW1 variant, at thermal transmittance U = 0.15 W/(m^2 • K). This difference indicates that the replacement of thermal insulation (change in the façade system) in solid masonry walls already has a more significant effect on the energy indicator.

- XPS is usually used when other materials cannot be applied. Compared to the analysed variants, the embodied primary energy content is highest in the SW5 variant (250 – 500 kWh/m^2). In terms of embodied primary energy content, the variant with the maximum permitted thermal transmittance exceeds the SW1 by one quarter, and the passive house variant by two thirds, due to an increased use of insulation material.

- The SW6 structural component with mineral wool insulation in a timber substructure is not significantly at variance with the SW1 variant. By increasing the thickness of thermal insulation, the embodied primary energy content in this component has turned out to be equal or lower at U_{SW6} = 0.12 W/(m^2 • K), due to a larger quantity of wood and mineral wool of lesser density used.

- The difference in the embodied primary energy content grows even more significant when only natural materials are used for insulation. In the SW7 variant, the embodied primary energy content becomes equal to that of the SW1 variant at U = 0.20 W/(m^2 • K), whereas at U = 0.10 W/(m^2 • K), the embodied primary energy content is lower by as much as one sixth. Opting for wooden façade cladding on solid walls is thus preferable in terms of primary energy use only when combined with natural thermal insulation.

- The variant involving solid walls made of aerated concrete blocks and insulated with mineral wool has yielded the best results among the variants. The SW8 structural component has 45% less embodied primary energy content compared to the SW1 variant, which highlights the great advantage of constructing the buildings with aerated concrete blocks.

- The SW9 variant with EPS thermal insulation applied to walls made of aerated concrete blocks still reflects the positive effects of aerated concrete use. Compared to the SW1 variant, the primary energy use is lower by 20% to 30%, according to reduced *U*-values.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for exterior walls are as follows (Fig.3.2):

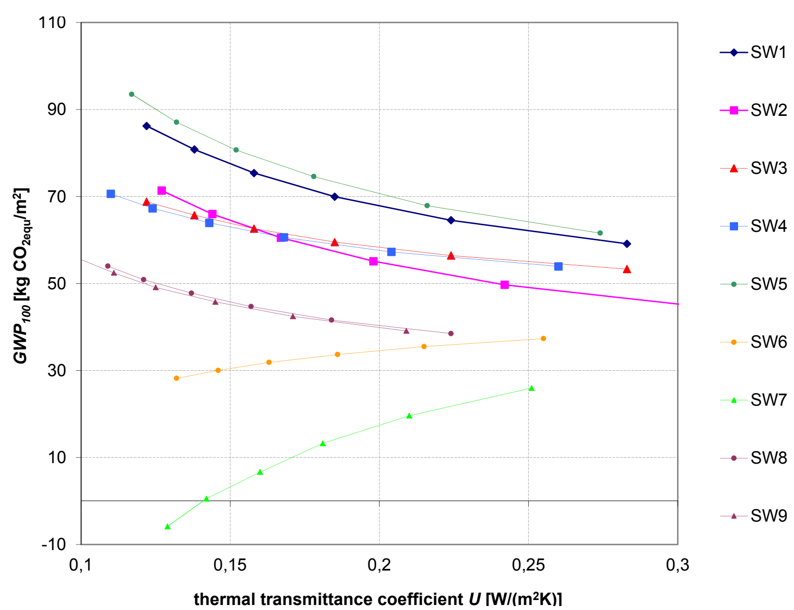


FIG. 3.2 The GWP_{100} environmental indicator of impacts on the global warming potential for exterior solid walls

- The basic SW1 structural component demonstrates high values in the range of 60 – 90 kg CO_{2equ}/m^2, which indicates a high level of environmental burden in terms of this parameter compared to the other analysed structural components. The variant with a thinner brick solid wall shows a reduced indicator value by approximately 15% when the thermal insulation system is left unchanged. The use of EPS thermal insulation in the SW3 variant and the use of mineral wool of lesser density in the SW4 variant show identical results. Compared to the SW1 variant, the parameter values of walls in a low-energy house with $U = 0.15$ W/(m^2 • K) are lower by approximately 15 – 20%.

- Thermal insulation made of XPS has proved to be the most environmentally burdensome, including in terms of this analysed indicator. The values of the SW5 variant are higher by 5% compared to the SW1 variant.

- The brick wall component using timber structure shows the positive effects of the use of wood, since the values of this indicator are decreasing with the increasing thermal protection level. In the SW6 variant, insulated with mineral wool, the parameter at $U = 0.20$ W/(m^2 • K) decreases by 50% if the thermal protection level is increased, compared to the SW1 variant. When using thermal insulation made of cellulose flakes, negative values of this environmental parameter are already achieved when the *U*-values of the wall are low.

- The exterior walls made of aerated concrete in the SW8 and SW9 variants have values that are lower by approximately 45% throughout the thermal transmittance *U* range, compared to the SW1 brick structural component.

AP

The findings in terms of the *AP* environmental indicator for exterior solid walls are as follows (Fig. 3.3):

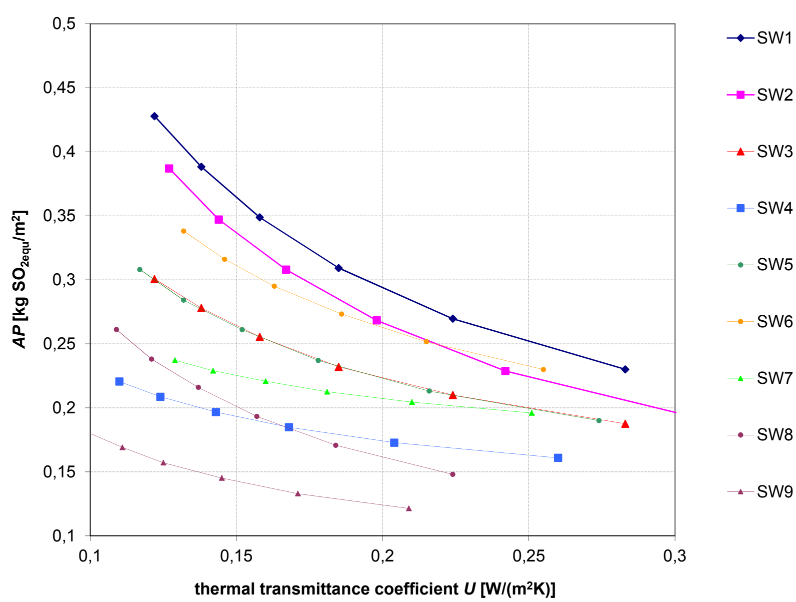


FIG. 3.3 The *AP* environmental indicator of impacts on the environment acidification potential for exterior solid walls

- An identical trend in the *AP* values is recorded in all variants. The SW1 basic component has the highest values ranging from 0.23 – 0.50 SO_{2equ}/m^2, depending on thermal transmittance.

- Considering the level of environmental burden in terms of this parameter, the variants are ranked in the following order: SW2 and SW6, SW4 and SW5, SW7, SW3, and SW8 and SW9. The variants with aerated concrete thus demonstrate the lowest values.

OI3

The best results scored by the variants for exterior solid walls (Fig. 3.4), in terms of the combined impact of the *OI*3 indicator, were recorded in the SW8 and SW9 walls, which were made of aerated concrete. On the other hand, the least favourable results were achieved by the SW1 basic wall and the SW5 variant with XPS. The use of polystyrene in the SW3 variant or mineral wool of lesser density in the SW4 variant gives the same results, which fall in the middle of all the compared variants. The score achieved by the use of mineral wool in a timber load-bearing structure in the SW6 is close to the score achieved by the SW1 basic component, and similar to the score of the SW2 variant with a thinner brick wall. The consistent use of wood or thermal insulation from cellulose flakes in the SW7 variant has only slightly variable results over the entire range of thermal transmittance and records a better result at its lowest analysed values than the wall made of aerated concrete.

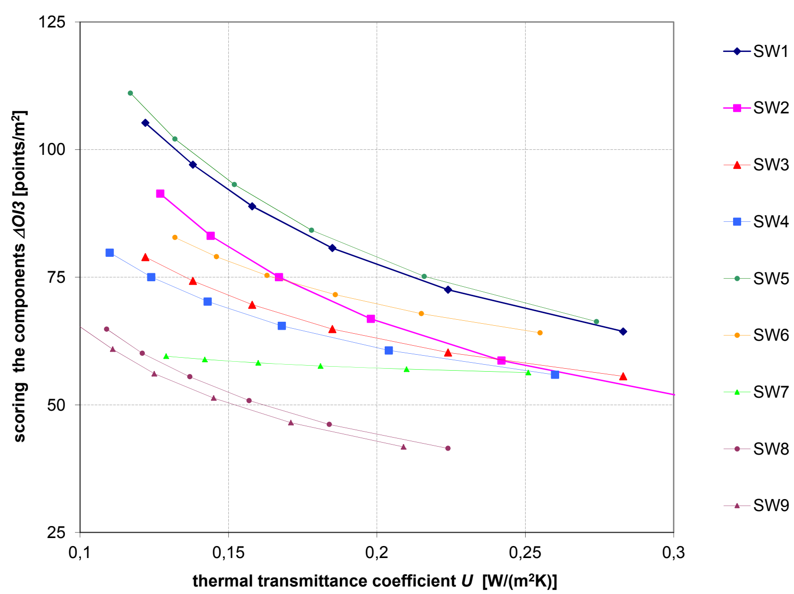


FIG. 3.4 The *OI3* combined environmental indicator for exterior solid walls

TOC

3.1.2 Lightweight Timber Walls

The analysed range, which, in the preceding case, included thermal transmittance ranging from the highest permitted value as defined by the legislation to the passive house values, is much more limited in the case of environmental indicators for lightweight timber walls. The reason for this is that better thermal protection of timber components is easier to achieve, and because the approach to increasing or reducing the thermal transmittance of timber components is often discontinuous. Light timber structures for energy efficient new buildings have thermal transmittance $U \leq 0.18$ W/(m^2 • K). As a result, the environmental indicators may not be compared up to the limit value $U = 0.28$ W/(m^2 • K), which in this case is consequently reduced to $U = 0.18$ W/(m^2 • K).

$PEC_{n.r.}$

The findings in terms of the $PEC_{n.r}$ energy indicator for lightweight timber walls, on the basis of the trends described are as follows (Fig. 3.5):

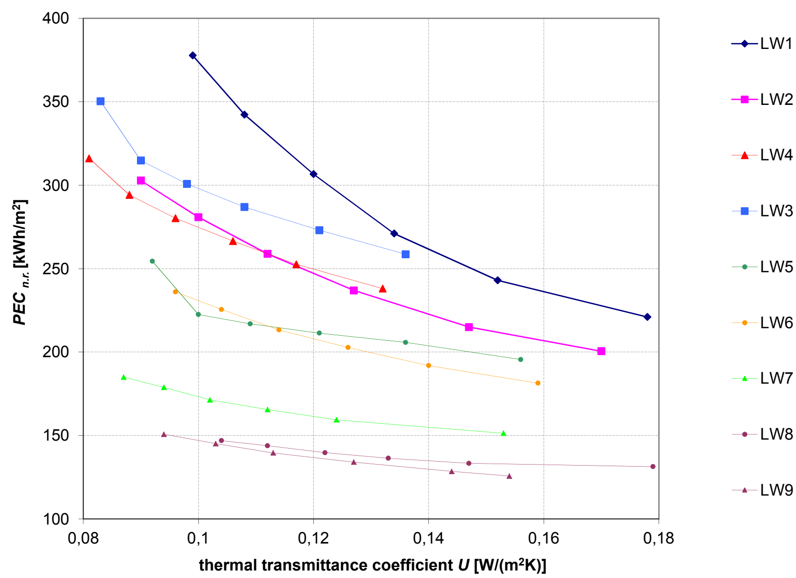


FIG. 3.5 The $PEC_{n.r.}$ indicator of primary energy content for lightweight timber walls

– The execution of the LW1 basic structural component requires 220 kWh/m^2 - 380 kWh/m^2 of primary energy at the corresponding thermal transmittance $U = 0.18$ and $U = 0.10$ W/(m^2 • K). A 50% decrease in thermal transmittance U is reflected in an approximately 80% increase in the primary energy use. This sharp increase in the primary energy use is the result of an increased thickness of façade insulation.

– When using the EPS thermal insulation in the LW2 timber component, the primary energy use is lower, and ranges between 10 and 35% compared to the LW1 basic component at both limit thermal transmittances. This variant is more acceptable in terms of the analysed parameter.

- A similar characteristic is recorded in the LW3 I-beam variant, which is more efficient than the LW1 basic variant at a high thermal protection level, and has a value below 300 kWh/(m^2 • a) at U = 0.10 W/(m^2 • K). In the case of the EPS thermal insulation used in the LW4 variant, the values are only slightly lower, i.e. by approximately 10 % at a high thermal protection level due to a thinner layer of this material.

- Better values are recorded in the LW5 variant, which has thermal insulation made of cellulose flakes filled between the I-beams, where the values drop to 200 – 220 kWh/m^2. An almost identical result is recorded when the wall is insulated with mineral wool in the LW6 variant. These values indicate that more favourable results are achieved in the components that contain larger quantities of less technologically processed wood.

- A large difference is observed in the use of natural thermal insulation. The values in the LW7 framework structure with blown-in thermal insulation made of cellulose flakes drop to 150 – 180 kWh/m^2 at limit thermal transmittances. When straw bales are used in the LW8 variant, the values are reduced by a further 15%, and are thus almost 50% lower than the LW1 basic component.

- The results for the LW8 and LW9 solid timber walls with thermal insulation made of cellulose flakes indicate virtually the same values, as well as the best results for the analysed parameter among all the solutions provided for timber walls.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for lightweight timber walls are as follows (Fig. 3.6):

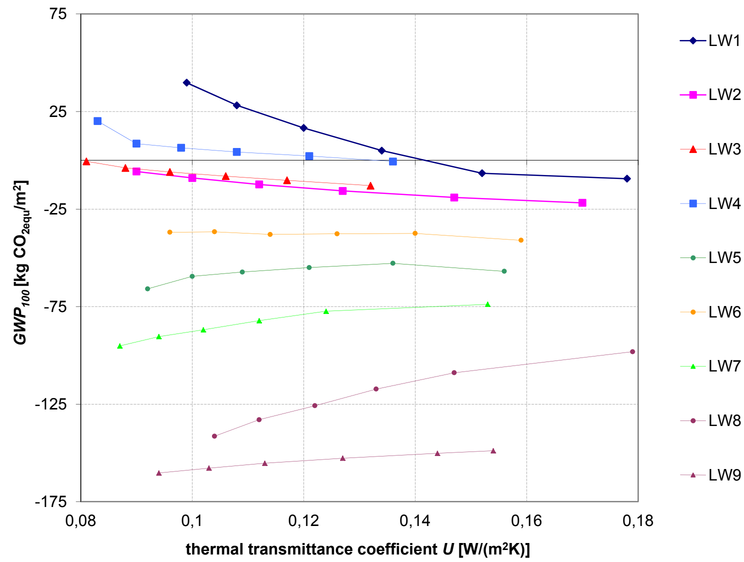


FIG. 3.6 The GWP_{100} indicator of impacts on the global warming potential for lightweight timber walls

- The LW1 basic component has the highest values compared to the remaining analysed components in this case. Due to a large proportion of wood in the component, the values at higher thermal transmittances are slightly negative and achieve 40 kg CO_{2equ}/m^2 only at a high level of thermal protection, which indicates an extremely low environmental burden in terms of this parameter, including in the case of the least thermally insulated exterior wall.

- The LW3 structural component with mineral wool fitted between I-beams has slightly positive values and an extremely low variance regardless of the achieved thermal transmittance.

- The LW2 and LW4 structural components, both with EPS thermal insulation, yield practically identical results that do not reach positive values of the analysed parameter even at a maximum thermal protection level.

- The remaining variants demonstrate a reverse trend in the analysed parameter since its value is declining by increasing the thermal protection level, which is due to a larger quantity of wood used and the natural thermal insulation. The structural components are ranked according to the declining values as follows: the LW5, LW7, and an identical trend for the LW8 and LW9. The structural components with the major part of their load-bearing structure and thermal insulation of natural origin produce the best results in terms of this environmental parameter.

AP

The findings in terms of the last *AP* environmental indicator are as follows (Fig. 3.7):

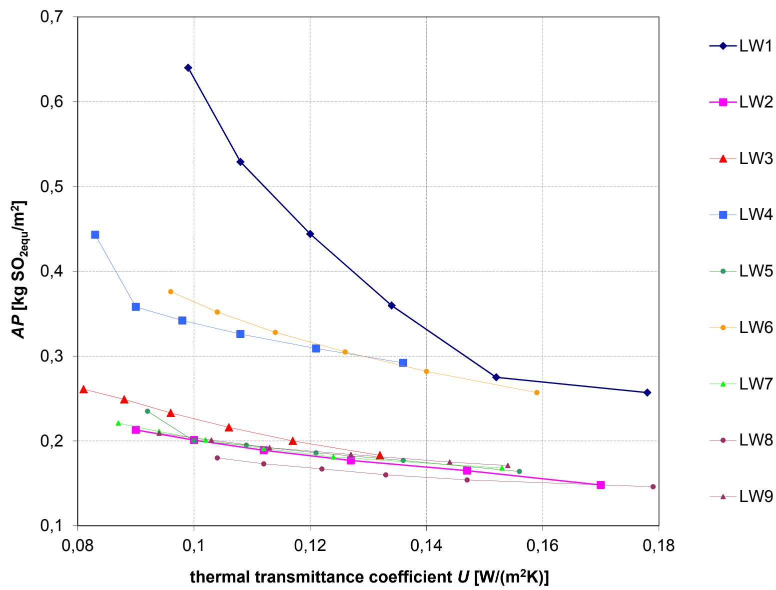


FIG. 3.7 The *AP* environmental indicator of impacts on the environment acidification potential for light wood walls

– The same trend is recorded in the values of all parameters. The LW1 basic structural component has the highest values ranging between 0.25 and 0.65 SO_{2equ}/m^2, depending on thermal transmittances.

– The LW3 and LW6 structural components, both insulated with mineral wool, have the next highest curve of values for this parameter. All the remaining structural components have practically identical values for this parameter in terms of environmental burden, with values ranging from 0.15 to 0.20 SO_{2equ}/m^2, which accounts for only one third of the values achieved at a high thermal protection level of structural components, compared to the basic structural component.

OI3

The least favourable evaluation results, based on the scoring system for the *OI*3 indicator (Fig. 3.8), are obtained by the LW1 basic structural component. Slightly lower values are recorded in the LW3 and LW6 structural components, both insulated with mineral wool. The LW4 and LW2 variants with EPS thermal insulation produce almost identical values. The next-ranked score result is recorded in the LW5 and LW7 variants with thermal insulation made of cellulose flakes. The best combined values are demonstrated by the LW8 light timber wall insulated with straw and the LW9 solid glued wood wall insulated with cellulose flakes.

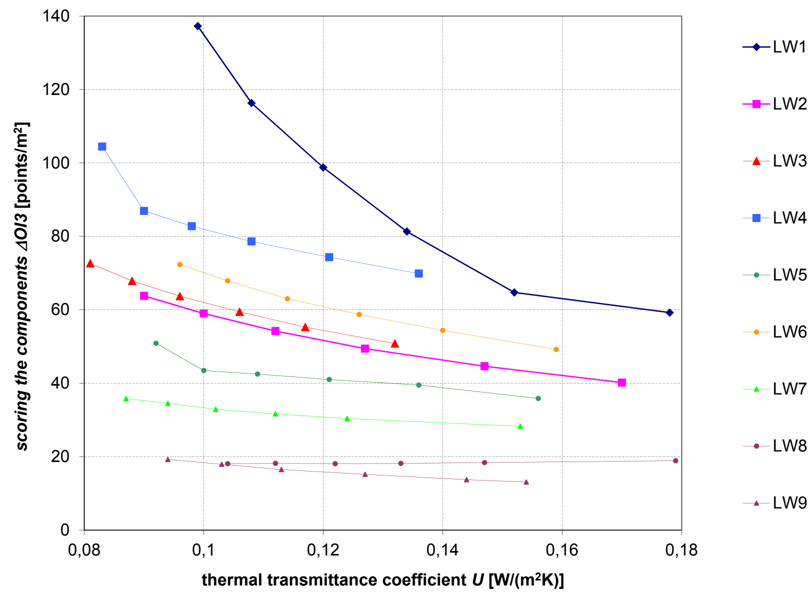


FIG. 3.8 The *OI3* combined environmental indicator for lightweight timber walls

3.1.3 Pitched and Flat Roofs

The analysed indicators for pitched and flat roofs are shown in Fig. 3.9 – 3.12, which simultaneously demonstrate a high thermal insulation performance of these structural components. The highest thermal transmittances do not normally exceed $U \leq 0.15$ W/(m^2 • K) and the roof structures for passive houses usually have the values $U \leq 0.09$ W/(m^2 • K). The movement of indicators will therefore be monitored within the range of the indicated limit values associated with the normal technological implementation.

***PEC**$_{n.r.}$*

Based on the results obtained, the findings in terms of the $PEC_{n.r.}$ energy indicator are as follows (Fig. 3.9):

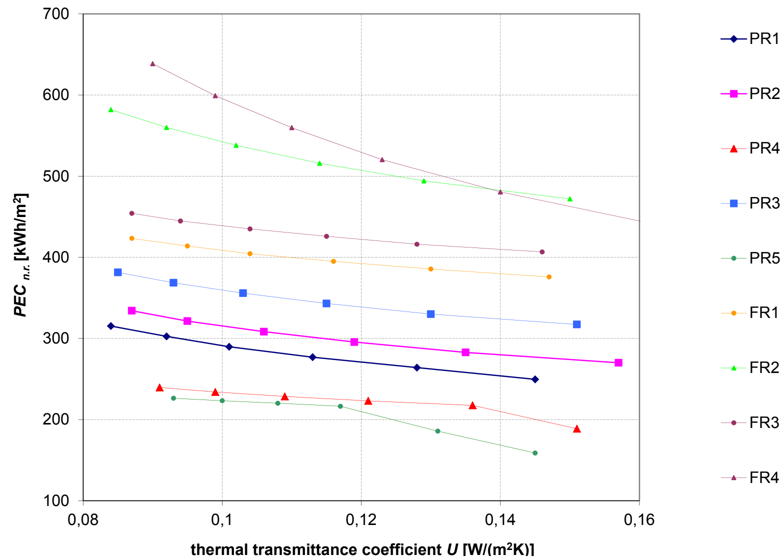


FIG. 3.9 The $PEC_{n.r.}$ indicator of primary energy content for pitched and flat roofs

- The PR1 pitched roof structural component indicates favourable results within the group of the analysed structural components. The embodied primary energy ranges between 250 and 300 kWh/m², pertaining to the thermal transmittances U = 0.15– 0.09 W/(m² • K). In order to reduce the thermal transmittance by 50%, the primary energy content in this structural component should be increased by 40%.

- A parallel trend in values is recorded in the PR2 structural component, i.e. a pitched roof with rafters over a reinforced concrete slab. The added solid layer accounts for approximately 10% higher primary energy content. A slightly larger difference in the same direction, and for the same reason, is recorded in the roof structure with an aerated concrete slab pertaining to the PR3 variant, whose value is 25% higher than the PR1 variant.

- The pitched roof made of timber I-beams in the PR4 and PR5 variants, insulated with cellulose flakes and straw, achieves the lowest values in the group of analysed structural components. Even at the highest thermal protection level, the values do not reach 250 kWh/m², which makes them 25% better than the PR1 basic structural component. Ultimately, the results obtained for the pitched roof insulated with straw are slightly better than those obtained for the pitched roof insulated with cellulose flakes.

- The flat roof made of glued wood with mineral wool insulation (FR1) has produced the best results in the group of flat roofs, but has a higher primary energy content than all the pitched roofs. Its embodied primary energy is higher by 120 kWh/m² compared to the PR1 basic structural component, which accounts for approximately 35% upward deviation at a high thermal protection level.

– The FR3 structural component with a reinforced concrete slab and mineral wool insulation has primary energy content that is higher by approximately 10% compared to the FR1 structural component. If foamed polystyrene thermal insulation is used, the values at a lower thermal protection level are higher by approximately 20% compared to those recorded in the FR3 variant. At a higher thermal protection level, however, the FR2 structural component insulated with EPS demonstrates upward deviation of approximately 25% compared to the FR3 structural component, and of almost 45% compared to the structural component insulated with XPS.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for pitched roofs and ceilings are as follows (Fig. 3.10):

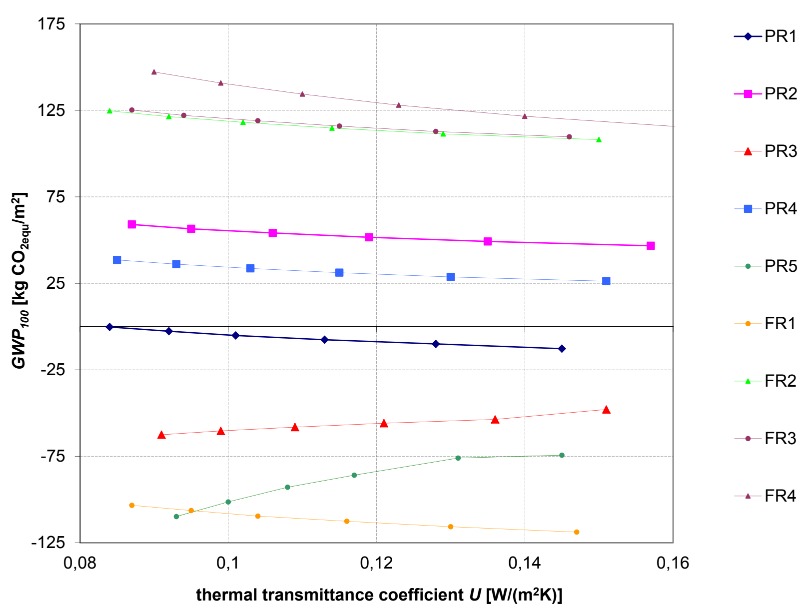


FIG. 3.10 The GWP_{100} environmental indicator of impacts on the global warming potential for pitched and flat roofs

– The PR1 pitched roof basic structural component has negative values, which approach 0 kg CO_{2equ}/m² when thermal protection levels are increased, which is typical for timber structures. Even better results among the selected pitched roofs are recorded by the PR4 and PR5 structural components made of I-beams, where the variant with straw insulation demonstrates a sharper decline in values when thermal protection levels are increased. The lowest value is observed in the FR1 flat roof made of glued wood, which, however, is brought to the same level with the value recorded in the

PR5 variant at a high thermal protection level, i.e. the value of -110 kg CO_{2equ}/m^2.

- Positive values of this environmental indicator are achieved in ascending order by the PR3 pitched roof with aerated concrete structure and the PR2 with reinforced concrete slab. An identical high value is recorded in the FR2 and FR3 flat roofs. The highest value is measured in the FR4 variant insulated with XPS, reaching 150 kg CO_{2equ}/m^2 at a high thermal protection level.

AP

The findings in terms of the last *AP* environmental indicator are as follows (Fig. 3.11):

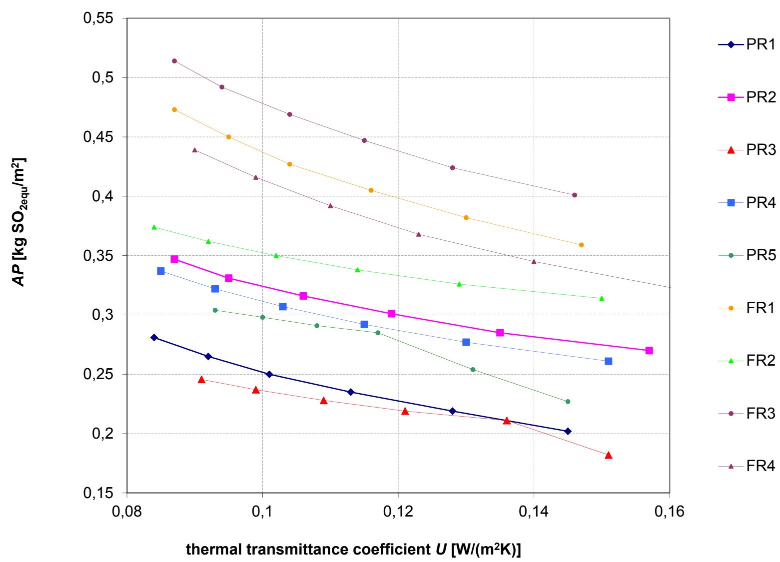


FIG. 3.11 The *AP* environmental indicator of impacts on the acidification potential for pitched and flat roofs

- The values of all variants show an identical trend. The PR1 basic structural component demonstrates favourable low values, which, depending on *U* thermal tranmittances, range between 0.20 and 0.27 SO_{2equ}/m^2. Better values are recorded only in the PR4 variant insulated with cellulose flakes, followed by the PR5 variant insulated with straw. The next ranked are the PR3 structural component with an aerated concrete slab and the PR2 structural component with a reinforced concrete slab which have almost identical values. They are followed by the FR2, FR4, and FR1 variants.

OI3

The best values of the total score results achieved for the combined effect assessed by the *OI3* indicator are measured in the PR4 and PR5 structural components (Fig. 3.12) with a pitched roof from timber I-beams, with almost no difference between the two thermal insulation materials used. The next-ranked values are recorded in the PR1 structural component. A similar upward deviation in the *OI3* indicator values is observed in the PR2, PR3, and FR1 variants, which produce almost identical results and come next in the ranking order. The least favourable *OI3* combined indicator values are measured in flat roof variants ranked in the following order: FR2, FR3, and FR4.

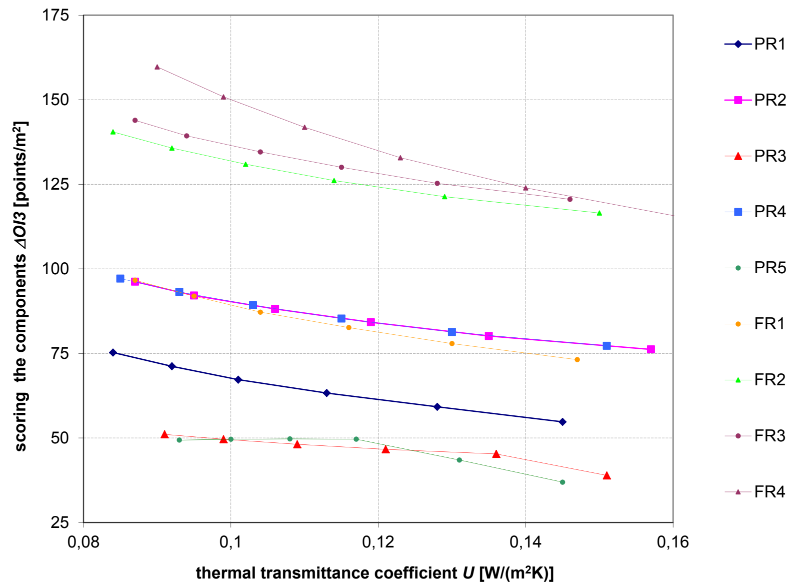


FIG. 3.12 The *OI3* combined environmental indicator for pitched and flat roofs

3.1.4 Ground Floor and Floor to Unheated Basements

Thermal transmittances in ground floor structural components normally range between $U = 0.10$ and 0.25 W/(m² • K) according to a higher degree of homogeneity in layers, and a continuous increase in thermal protection, which also represents the limits within which the fluctuation of environmental indicators is monitored.

$PEC_{n.r.}$

Based on the results obtained, the findings in terms of the $PEC_{n.r.}$ energy indicator are as follows (Fig. 3.13):

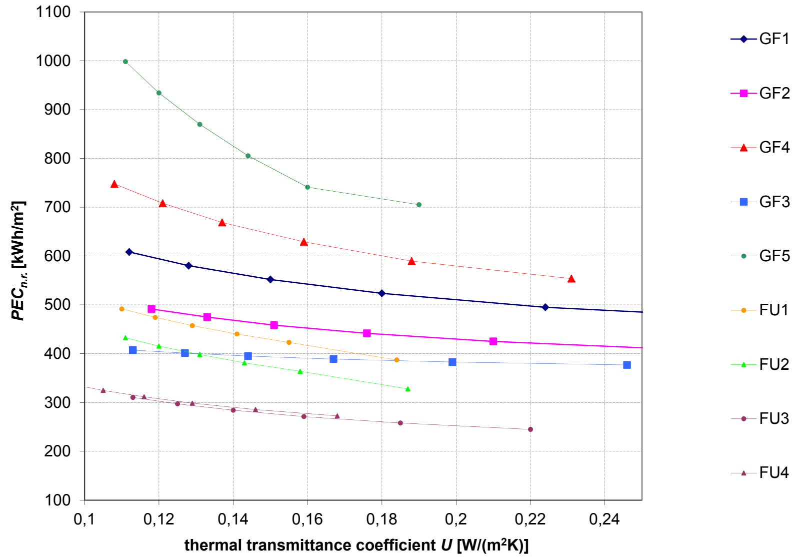


FIG. 3.13 The $PEC_{n.r.}$ energy indicator for ground floor and floor to unheated parts of a building

- The GF1 basic structural component for ground floor with EPS thermal insulation has the mean values among the variants. The primary energy content is from 500 to 650 kWh/m^2 for thermal transmittances U = 0.10 – 0.25 W/(m^2 • K). In order to reduce thermal transmittance by 50%, this structural component requires 25% more embodied primary energy, which indicates that a higher embodied energy content is inherent in those layers that do not make up the thermal protection of the component.

- The primary energy content in the GF2 structural component with mineral wool thermal insulation is lower by an average of 15%. The GF3 structural component insulated with perlite produces results that vary only slightly when thermal protection levels are increased by values not exceeding 400 kWh/m^2, which makes them as much as 35% lower than those recorded in the GF1 basic structural component at a high thermal protection level.

- The GF4 structural component with XPS thermal insulation on the interior surface of the reinforced concrete slab shows a 20% higher primary energy content than the GF1 basic structural component. The difference in the primary energy content measured in the GF5 structural component with thermal insulation made of foamed glass, however, is major, and exceeds the results recorded in the GF1 variant by almost 100% at a high thermal protection level.

- The FU1 structural component for floor to unheated parts of a building demonstrates an average of 20% lower values compared to the GF1 variant. The primary energy use in the

FU2 variant where the reinforced concrete ceiling is replaced by an aerated concrete ceiling, is reduced by an additional 10%.

- The FU3 and FU4 timber ceiling structural components have practically identical values of primary energy content, which are the lowest within the analysed group of variants. The values trend is parallel to that in the GF1 variant with a 250 kWh/m[2] variance, accounting for a 50% share at a high thermal insulation level.

GWP_{100}

The findings in terms of the GWP_{100} environmental indicator for ground floor structural components are as follows (Fig. 3.14):

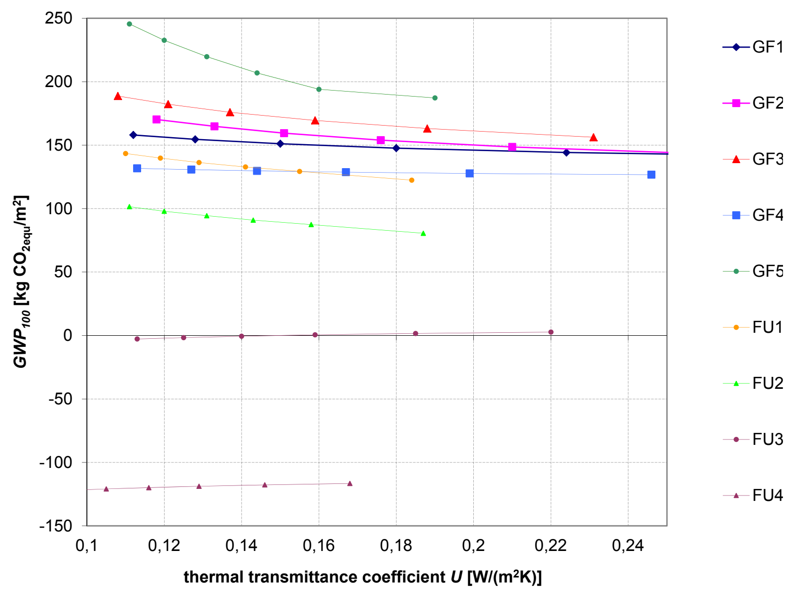


FIG. 3.14 The GWP_{100} environmental indicator of impacts on the global warming potential for ground floor and floors to unheated parts of a building

- The GF1 structural component records high values which vary very slightly when thermal protection levels are increased, and amount to 150 kg CO_{2equ}/m^2, which again indicates a very strong impact of the construction part of this variant. The use of mineral wool as thermal insulation in the GF2 variant increases the values indicated above by 10% at high thermal protection levels. When thermal insulation made of perlite is used (the GF3 variant), these values are almost 20% lower than the ones measured in the GF1 variant.

- The two structural components with thermal insulation under the foundation slab again indicate the highest values among the variants compared. The GF4 structural component insulated with XPS records 20% higher values compared to the GFI basic variant. At a high thermal insulation level, the structural component with foamed glass insulation indicates a more than 70% higher value, exceeding 250 kg CO_{2equ}/m^2, compared to the parameter value measured in the GF1 variant.

- The parameter values in floor to unheated basement structural components are better than in the previously analysed structural components for ground floor. The value obtained in the FU1 variant is 20% lower than the GF1 variant, whereas the value measured in the FU2 variant is lower by an average of 40%.

- Structural components with timber elements again produce good results, as expected. The values measured in the FU3 variant are around 0 kg CO_{2equ}/m^2 owing to a smaller proportion of wood. The lowest values, however, are recorded in the FU4 variant with a solid glued wood slab, and oscillate around -120 kg CO_{2equ}/m^2.

AP

The findings in terms of the *AP* environmental indicator are as follows (Fig. 3.15):

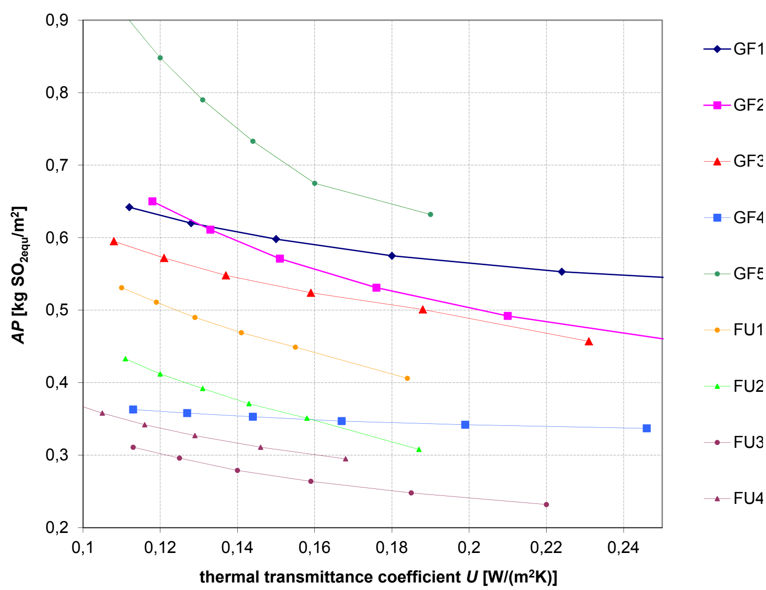


FIG. 3.15 The environmental indicator *AP* of impacts on the acidification potential for ground floor and floor to unheated parts of a building

- The same trend is recorded in all structural components. The GF1 basic structural component has high values compared to the remaining variants in the group, which range from 0.55 to 0.65 SO_{2equ}/m^2, depending on thermal transmittance *U*. The values measured in the GF2 structural component, with thermal insulation made of mineral wool, are more favourable when the thermal protection level is poor, whereas they are brought to the same level when the thermal protection level is high. The parameter value observed in the GF3 variant, insulated with perlite, is, again, little influenced by the thermal protection level and the results at a high thermal protection level reach almost half the value of those recorded in the GF1 basic structural component.

- The GF4 variant with thermal insulation made of XPS has lower values by approximately 10%. Here again, the GF5 structural component demonstrates the highest values of this parameter within the group, which exceed 0.9 SO_{2equ}/m^2 at a high thermal protection level.

- The floor to unheated basement structural components again produce lower parameter values compared to the GF1 basic variant: in the FU1 variant, they are lower by an average of 25% and in the FU2 by an average of 40%.

- The values for timber floor to the basement are the lowest in the group, including for this parameter. The FU4 structural component made of glued wood has a slightly lower value than the FU3 structural component, whose values range from 0.22 to 0.33 SO_{2equ}/m^2.

OI3

The best values in the group in terms of the combined effect of the *OI3* indicator are achieved by the FU3 and FU4 timber structural components (Fig. 3.16), in which the solid structural component imposes the lowest burden on the environment. The FU2 structural component for floor to unheated basement made of aerated concrete and the FU1 structural component made of reinforced concrete demonstrate the next best-ranked values (almost double points), with the aerated concrete variant having a lower impact on the environment than the reinforced concrete variant. The lowest combined environmental impact among the ground floor variants is achieved by the GF3 structural component insulated with perlite, followed by the GF2 variant insulated with mineral wool and the GF1 basic variant insulated with EPS. The GF4 ground floor structural component with XPS thermal insulation on the interior surface of the reinforced concrete slab has an identical environmental impact to the GF1 basic variant. The highest burden on the environment is recorded in the GF5 structural component with foamed glass insulation, where the combined environmental effect at a high thermal protection level may even be 50% higher than that in the GF1 basic variant.

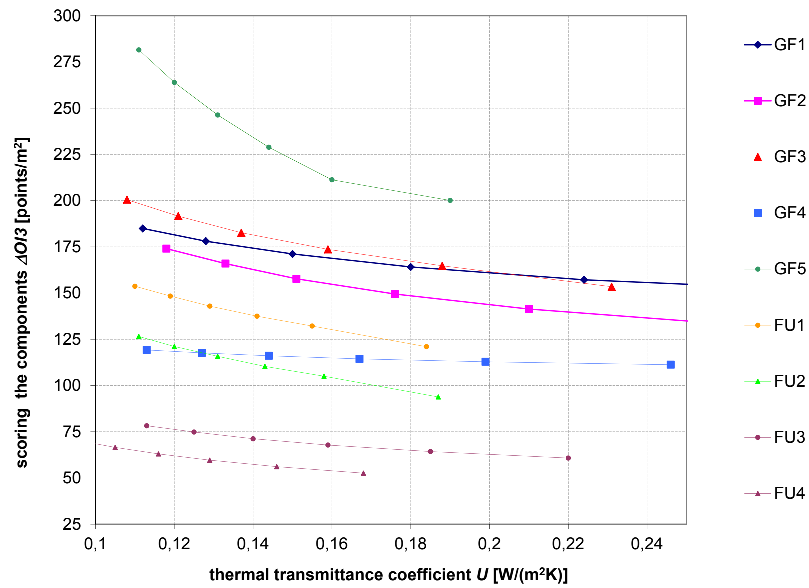


FIG. 3.16 The *OI3* combined environmental indicator for ground floor and floor to unheated basement structural components

3.2 The Primary Energy Content, Global Warming Potential, Acidification Potential, and *OI3* Indicators for Windows

$PEC_{n.r.}$

The $PEC_{n.r.}$ indicator of primary energy content for the production of windows (Fig. 3.17) is shown in terms of its dependence on thermal transmittance *U*, with window frames and glazing shown separately:

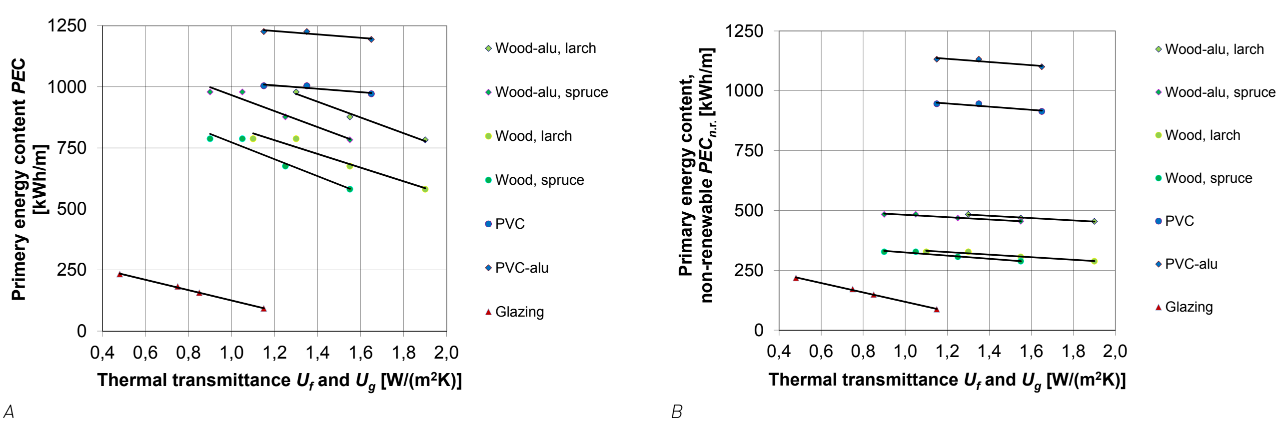


FIG. 3.17 Comparison between the total primary energy content (A) and the non-renewable primary energy content (B) for window frames and glazing in terms of its dependence on thermal transmittance

- Non-renewable primary energy content required for glazing amounts to approximately 90 – 220 kWh/m^2. Double glazing with thermal transmittance U_g = 1.1W/(m^2 • K), selected for further comparative reference, has low primary energy content indicated by the aforementioned bottom limit value. The top limit value, which is more than doubled compared to the previously indicated value, pertains to a triple glazing system with U_g=0.50 W/(m^2 • K), which is most frequently used in passive houses.

- Non-renewable primary energy used for the production of wooden window frames amounts to 290 – 330 kWh/m^2. If spruce wood is used, these values refer to the frame with thermal transmittance U_f = 1.55 – 0.90 W/(m^2 • K), and if larch wood is used, they refer to the frame with thermal transmittance U_f = 1.90 – 1.10 W/(m^2 • K). A timber frame with external layer made of aluminium requires an additional 160 kWh/m^2 of non-renewable primary energy.

- PVC frames require between 910 and 950 kWh/m^2 of non-renewable primary energy, which refers to the frames with thermal transmittance U_f = 1.1 – 1.65 W/(m^2 • K). In this case, the addition of an external aluminium layer made for the protection of the frame requires an additional 180 kWh/m^2 of non-renewable primary energy.

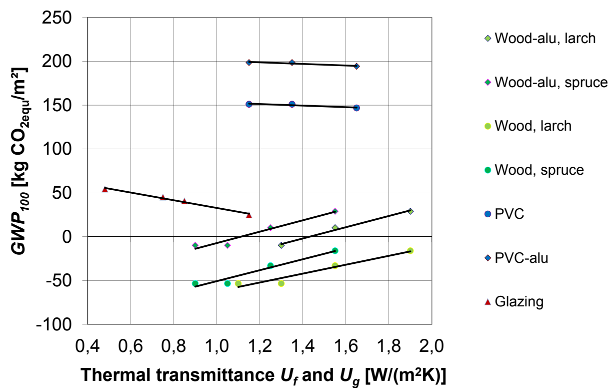
- The added primary energy content required to reduce the thermal transmittances U_f of window frames accounts for less than 15 % in timber frames and only up to 5 % in PVC frames. It may thus be concluded that in the case of window frames with identical energy efficiency, a PVC frame requires approximately three times as much primary energy as a timber frame.

- It may also be concluded that the specific primary energy used for glazing is lower than that required for window frames; however, the actual surface ratio between the glass and frame should also be taken into account. The frame surface area in a standard window (1.23 m x 1.48 m) (DIN EN 14351-1:2006-07) measuring 1.82 m^2 thus accounts for 32 % of the total window surface area. Consequently, the proportion between the primary energy used for glazing and the primary energy used for frames is usually equivalent, or the glazing may account for a 40 to 50% share of the total primary energy used for the production of the complete window.

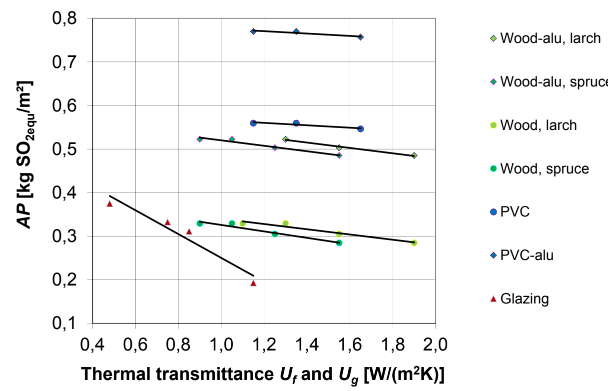
- The renewable primary energy content in glazing is approximately 10 % and in timber frames up to 50 – 60%; if an exterior aluminium layer is added for frame protection, then this figure is 10% less than the values indicated. In PVC window frames, this share accounts for 5 – 10%, with the lower values pertaining to the frames with an exterior aluminium layer.

GWP$_{100}$ and *AP*

The findings in terms of the impact of different window variants on the *GWP*$_{100}$ and *AP* environmental indicators are the following (Fig. 3.18):



A



B

FIG. 3.18 The *GWP*$_{100}$ (A) environmental indicator of impacts on the global warming potential and the *AP* (B) environmental indicator of impacts on the acidification potential for window frames and glazing in terms of their dependence on thermal transmittance

– The PVC window frames, with the option of an additional external layer of aluminium protection, have values of 150 kg CO_{2equ}/m^2 or 200 kg CO_{2equ}/m^2, respectively. When thermal protection levels are increased through glazing, the increase in this parameter is more significant and achieves values between 25 and 50 CO_{2equ}/m^2. As expected, timber frames have declining values when thermal transmittance is reduced, achieving 15 to -50 CO_{2equ}/m^2. If an additional external layer of aluminium protection is added, the values rise to -10 to +30 CO_{2equ}/m^2.

– The values recorded for the second environmental parameter increase in the same direction for all the compared elements in parallel with the decreasing thermal transmittance. The most significant difference is observed in glazing where the value of the indicator is doubled when thermal transmittance is decreased, i.e. it rises from 0.2 SO_{2equ}/m^2 to 0.4 SO_{2equ}/m^2. In wooden window frames, the values oscillate by around 0.3 SO_{2equ}/m^2 on average and increase by 60 to 70%, i.e. to 0.5 SO_{2equ}/m^2, when the external layer of aluminium protection is added. PVC window frames have higher values compared to those recorded in wooden window frames and range above 0.55 SO_{2equ}/m^2 on average, increasing to 0.75 SO_{2equ}/m^2 when the external layer of aluminium protection is added.

OI3

The weighted environmental effect of the three previously described indicators (Fig. 3.19) is also presented through an environmental score system set up for the elements of a standard dimension window. The results show that, in this respect, the environmental burden caused by PVC window frames is two to three times higher than that caused by wooden window frames.

When analysing the combined impact of the glass and the frame of standard dimensions, it is also observed that the impact of glass considerably increases with a larger glazed window surface. Windows with dimensions exceeding the reference ones are frequently found in energy efficient new buildings. Considering this fact, the environmental impact of glazing becomes even more considerable.

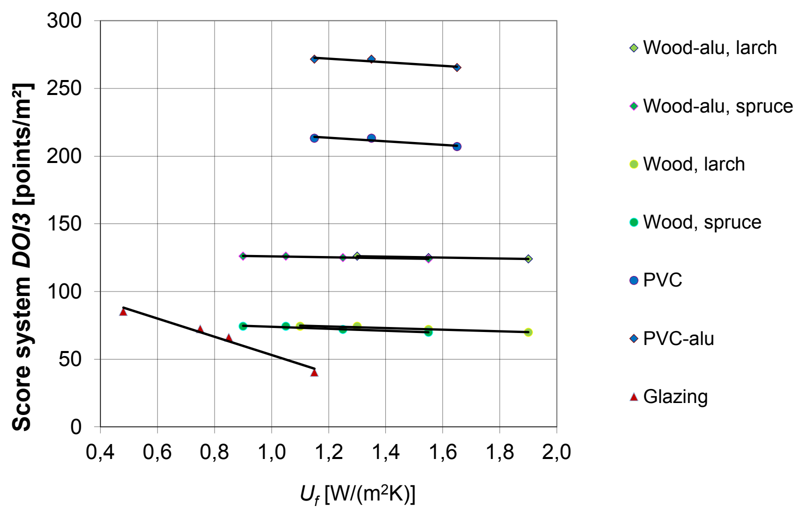
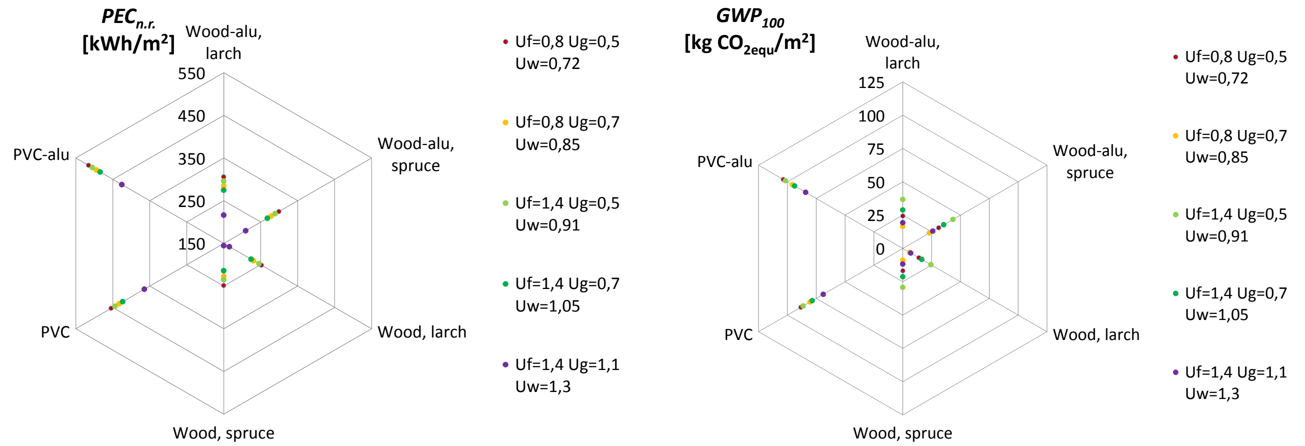


FIG. 3.19 The *OI3* combined environmental indicator for window frames and glazing according to its dependence on thermal transmittance

The changing of the two key parameters $PEC_{n.r.}$ and GWP_{100} is not analysed only for individual components (glass, frame), but also for their combinations, which result in different joint thermal transmittances of the window U_w. For the purpose of comparison, the basic combination with the reference value U_w = 1.3W/(m² • K), which is the highest thermal transmittance permitted by the legislation, has been defined. The variants with thermal transmittances between the reference values U_w = 1.3W/(m² • K) and U_w = 0.7W/(m² • K) have been designed through various combinations of more efficient glazing and frames (Fig. 3.20). The results obtained are as follows:



A *B*

FIG. 3.20 Changing the $PEC_{n.r}$ (A) and GWP_{100} (B) indicators for joinery with different efficiency

- The primary energy content in wooden windows with thermal transmittance from U_w = 1.3 to 0.7 W/(m² • K) ranges between 170 and 250 kWh/m², with the difference between the reference and high energy efficiency values amounting to 45%. If the exterior aluminium layer for the protection of the frame is added, the primary energy content increases to 210 – 300 kWh/m², i.e. 20% higher than the previous values. The primary energy content in PVC window frames ranges between 360 and 450 kWh/m², which accounts for a 25% difference between the reference and high efficiency values. If the exterior aluminium protection layer is added, the embodied primary energy is increased to 430 – 510 kWh/m², which is again up to a 20 % rise compared to the window without the frame protection. When comparing energy efficient wooden windows and PVC windows with the U_w = 0.7 W/(m² • K), the results indicate an 80% higher primary energy content in PVC windows.

- The data for the GWP_{100} environmental parameter indicate positive changes in wooden window frames, which result from a larger proportion of wood used as the material for the production of windows. In windows with low thermal transmittance, a larger proportion of wood used brings the joint value of the parameter (15 – 30 kg CO_{2equ}/m²) closer to the results achieved by the windows with reference thermal transmittance U_w = 1.3W/(m² • K) (10 – 20 kg CO_{2equ}/m²). In windows with a PVC frame, however, the increase of the GWP_{100} parameter value is not affected by decreasing thermal transmittance U_w of the window, and ranges between 90 and 100 kg CO_{2equ}/m² in highly energy efficient windows, and between 70 and 80 kg CO_{2equ}/m² at the reference thermal transmittance.

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4 The Expected Payback Period of the Measures Applied to Improve the Energy Efficiency of the Building Envelope Structural Components

When improving the energy efficiency of the thermal envelope structural components, larger quantities of non-renewable primary energy are embodied in a new building, burdening the environment with CO_2, which has been embodied in the products during their production phase. The values of both indicators obtained during the construction process (the primary energy content and CO_2 content) are compensated by the savings in the energy used for heating the building. The building envelope with a higher thermal protection level has lower transmission heat losses. This difference in the building's energy balance may be evaluated in terms of less energy needed to heat the premises. The heat generated for this purpose may also be evaluated in terms of the corresponding primary energy content and CO_2 emissions.

The calculation of the expected payback period of the primary energy and CO_2 embodied in the structural components is based on the following assumptions:

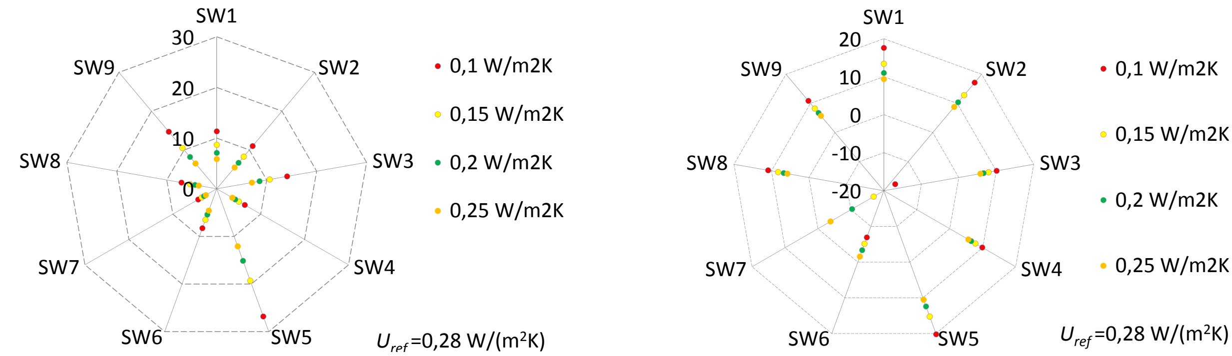
– Since the majority of energy efficient residential buildings are supplied with heat through heat pumps, the consumption of electrical energy with a specific emission of 0.53 kg CO_2/kWh and a primary energy conversion factor of 2.5 have been applied for estimation purposes. Both values have been determined (MOP, 2010) for use in cases when the supply structure of the energy product used is not defined in detail or is unknown.

– To determine transmission heat losses, the temperature deficit of 3,000°day/year has been taken into account, being the most frequent or characteristic value in the territory of Slovenia.

4.1 Exterior Solid Walls

The payback period of the embodied primary energy through operational savings is rapid in *exterior solid walls*, considering the long life cycle of masonry elements. The results shown enable the comparison between the reference construction with thermal transmittance U = 0.28 W/(m^2 • K) and a highly efficient construction with thermal transmittance up to 0.10 W/(m^2 • K) (Fig. 4.1).

TOC



A *B*

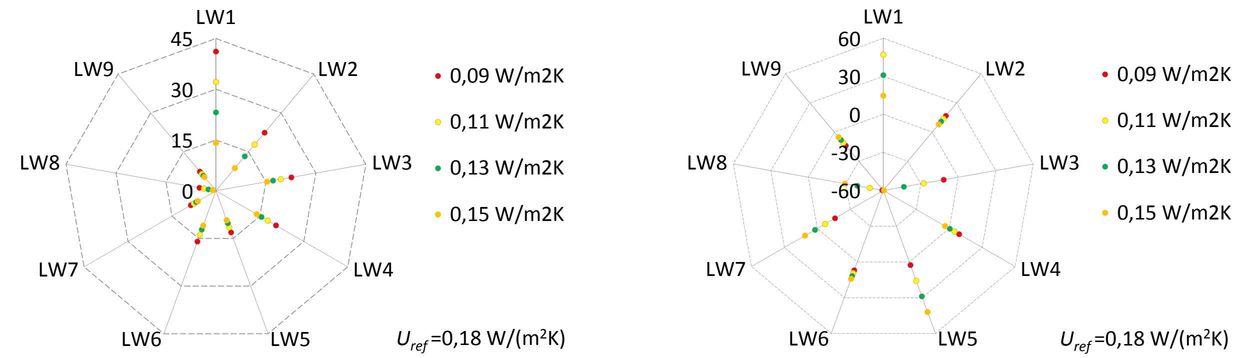
FIG. 4.1 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for solid masonry walls

In most cases, the expected payback period of additional embodied primary energy to achieve the thermal transmittance of the element U = 0.15 W/(m^2 • K) is less than 10 years, and not more than 15 years at the thermal transmittance U = 0.10 W/(m^2 • K). A notable exception is the SW5 structural component with thermal insulation made of XPS, which has a payback period of almost 30 years. The lowest values are measured in the SW4, SW7, and SW8 variants, where mineral wool of lesser density fitted to a brick wall, cellulose flakes blown into the timber framework, or mineral wool fitted to an aerated concrete wall are used for thermal protection.

The payback period of embodied CO_2 in structural components with the highest thermal protection level U = 0.10 W/(m^2 • K) is typically between 10 and 20 years. The exceptions are the SW6 and SW7 variants, where the payback period is decreasing in parallel with an increasing proportion of wood used in a structural component.

4.2 Lightweight Timber Walls

In *lightweight timber walls*, a simple comparison with the high reference thermal transmittance, as has been made in the preceding case, is not possible due to technological reasons. These structural components usually achieve thermal transmittances $U \leq$ 0.18 W/(m^2 • K), therefore the reference value U = 0.28 W/(m^2 • K) applied in the preceding case may not be used. However, the findings (Fig. 4.2) within the range of the results for e.g. U = 0.10 and U = 0.18 W/(m^2 • K) may be interpreted in terms of a transition from the structural components of a low-energy house envelope with poorer thermal protection performance to more energy efficient structural components of a passive house envelope.



A *B*

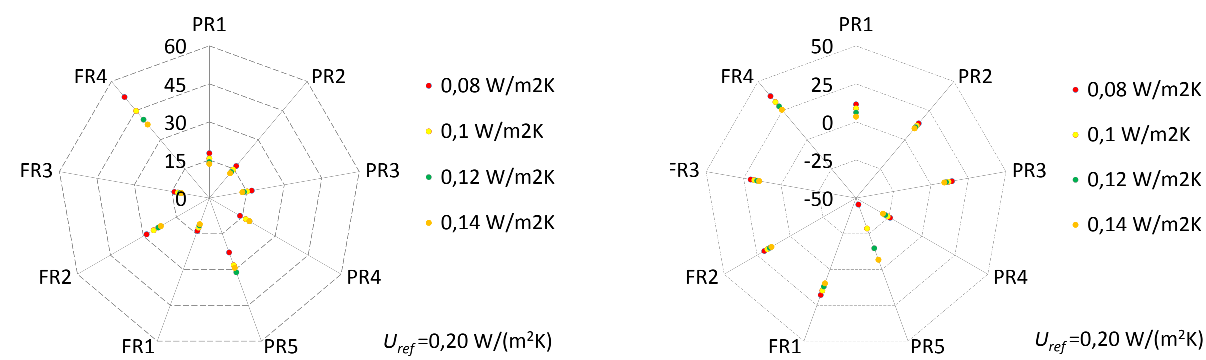
FIG. 4.2 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for lightweight timber walls

The expected payback period of added embodied primary energy in most frequently used variants of lightweight timber walls is 20 years. The payback period for the walls insulated with natural thermal insulation materials, however, is less than 10 years. The two results are thus very stimulating, particularly in comparison to the low thermal transmittance *U* of the reference structural component.

The payback period of embodied CO_2 in light timber structures is usually less than 20 years. When natural thermal insulation materials are used, the payback period declines sharply in parallel with the increasing thermal protection level, dropping below 0 value. Such a favourable result means that the added embodied CO_2 in improved structural components exceeds the emissions during operation.

4.3 Pitched and Flat Roofs

In the case of *pitched and flat roofs*, the comparison (Fig. 4.3) of energy efficient structural components is made according to the reference structural component (U = 0.20 W/(m^2 • K)).



A *B*

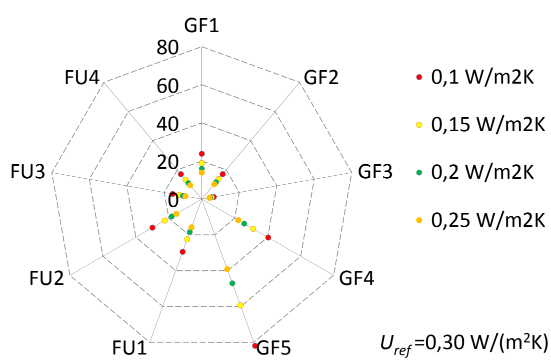
FIG. 4.3 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for pitched and flat roofs

The payback period of added embodied primary energy for structural components with a high thermal protection level is between 15 and 20 years due to increased thickness of thermal insulation. The two exceptions are the flat roof structural components with EPS and XPS thermal insulation, where the payback period is 30 or 45 years, respectively.

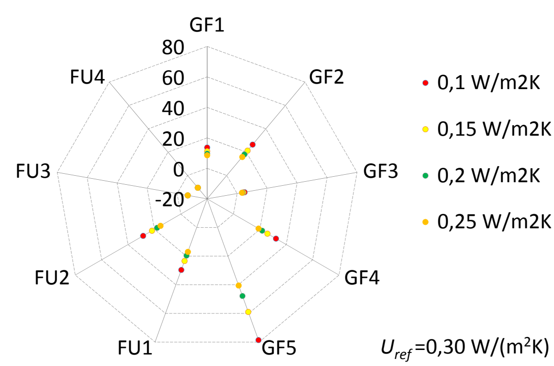
The payback period of embodied CO_2 in pitched roofs through savings is less than 20 years. When thermal insulation made of natural material is used in pitched roofs, the values drop below 0. The payback period for flat roofs is 25 years, except the structural components insulated with XPS, which record a 35-year payback period.

4.4 Ground Floor and Floor to Unheated Basement

Energy efficient *ground floor and floor to unheated basement* (Fig. 4.4) structural components are compared with those having the reference thermal transmittance U = 0.30 W/(m² • K).



A



B

FIG. 4.4 Payback period of embodied primary energy (A) and embodied CO2 (B) through savings for ground floor and floor to unheated basement

The payback period of additional primary energy content is 20 to 30 years. One exception is the structural component insulated with perlite, which has a payback period of less than 10 years. The payback period for the variants with thermal insulation on the interior surface of the reinforced concrete slab is 40 years if XPS is used for insulation, and as many as 80 years if foamed glass is used as insulation.

The payback period of embodied CO_2 in ground floor structural components is normally 30 years. The exceptions are solid structural components insulated with perlite, and timber structural components insulated with mineral wool, where the payback period is reduced to mere months. An upward deviation value is again recorded in the structural component insulated with foamed glass (i.e. 80 years).

4.5 Windows

In *windows*, the achieved thermal transmittance *U* of the elements, when compared to the previously obtained data, typically decreases at a relatively low added primary energy, which applies to both wooden frame windows and PVC frame windows. When the thermal insulation performance of a window is increased, its thermal transmittance decreases more significantly than in opaque thermal envelope structural components. Consequently, transmission heat losses decrease more significantly, thus providing higher primary energy savings during operation. The expected payback period of added embodied primary energy in the windows with lower thermal transmittances *U* is 3 to 4.5 years (Fig. 4.5). The low payback period is obtained from the comparison between the reference and most energy efficient windows U_w = 1.3 W/(m^2 • K) and U_w = 0.7 W/(m^2 • K), and the higher payback period from the comparison between the two variants with U_w = 1.3 W/(m^2 • K) and U_w = 1.1 W/(m^2 • K).

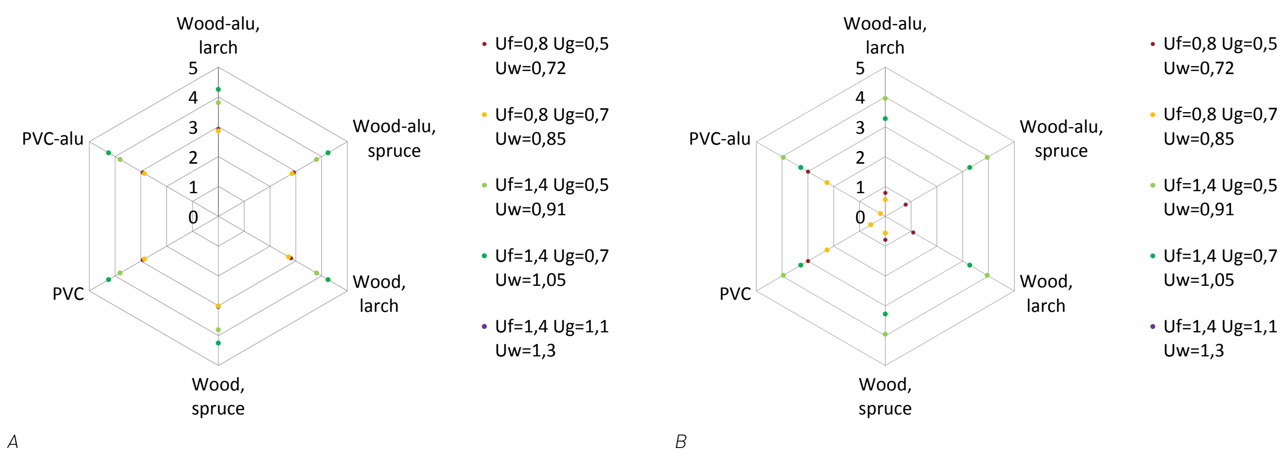


FIG. 4.5 Payback period of embodied primary energy (A) and embodied CO_2 (B) through savings for joinery

Similar favourable results are observed in the payback period of embodied CO_2 for windows through savings in CO_2 emissions during the operation of the building. The payback period for PVC windows is 2 to 4 years, depending on the thermal transmittance U_w of the windows. The payback period of the analysed windows with U_w = 0.7 W/(m^2 • K) is 3 years. The payback period of wooden frame windows is 0 to 4 years; the windows with low thermal transmittance U_w have a payback period of one year.

5 Conclusions

The analyses described above present various options for selection, and outline the key rules of incorporating and combining the materials that the planners should take into account when designing thermal envelope structural components. When planning a building, the selected construction technologies and the resulting environmental impacts produced even before the start of operation of the new building should be given equivalent consideration as the energy and environmental efficiency of the building during its operation. The results of the analyses enhance the proper understanding of the impact that the construction phase has on a more comprehensive evaluation of the impacts of buildings over their entire life cycle.

In the final part of the study, it is necessary to highlight the following basic guidelines, constituting the conclusions of the analyses presented above:

– Materials used for construction and thermal insulation have a lower impact on the environment when used in their original, natural form, and when environmentally less burdensome processes are used for their production, as well as smaller quantities of input raw materials. Thus, for example, in terms of the indicators analysed previously, the use of natural wood in construction is preferable to the use of similar products made of processed wood. Aerated concrete blocks are more suitable than bricks and thermal insulation made from straw is better than the blown cellulose insulation. Similar results are obtained when comparing the mineral wool of higher and lesser density, and EPS and XPS.

– The results of the combined environmental evaluation on the basis of three parameters (the *OI3* indicator) for solid masonry walls are less favourable than for the lightweight timber walls. The most common variants of solid masonry wall thermal protection in low-energy and passive buildings produce higher, e.g. environmentally more burdensome, results. The highest values obtained in timber construction systems are still below the lowest *OI3* values obtained in solid masonry construction systems. Even more divergent values are recorded for pitched and flat roofs. The difference between the final environmental burden values recorded in various groups of light timber and solid masonry structures may be up to 50%.

– Increasing the thermal insulation performance of the structural components of the building envelope results in enhanced energy efficiency of the building's further operation. In most structural components, this also results in increased environmental burden during the construction phase, i.e. before the start of the building's operation. The structural components with a high proportion of incorporated natural materials are exceptions to this rule. They are subject to an opposite conclusion: by increasing the use of these materials, the thermal insulation performance of the envelope is increased, while the environmental burden during the construction phase is reduced.

– Reducing the thermal transmittance of structural components requires a higher primary energy content. If, for example, thermal transmittance is reduced to half the reference values, 50% more primary energy is usually required for the production of a structural component. This points to rather high energy inputs in thermal protection systems and highlights the importance of a proper selection of combinations of materials in these systems. When thermal protection levels are increased, these relations are modified in the structural components where the construction part of the component has a major role. In this case, higher primary energy content is dictated by the structure itself, whereas thermal protection systems increase the primary energy content to a lesser extent.

– The added primary energy content, non-renewable, and the CO_2 produced during the construction phase have payback periods of 10 - 20 years in energy efficient new buildings, which is less than one third of the thermal protection system life span. When higher initial inputs in construction parts of the components are made, the payback period may be extended to 20 – 30 years of the operational period. The most favourable results in this respect are observed in windows where higher initial environmental inputs are paid back in less than 5 years.

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