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A sustainable, energy-efficient and eco-friendly wall system for building applications in Ukraine

Abstract. In response to global environmental challenges and the growing demand for energy-efficient solutions in the construction sector, the search for environmentally safe structural systems with a minimal carbon footprint had become increasingly relevant. This study aimed to develop and analyse an external wall enclosure system made of ecological materials, considering its thermal and hygrothermal performance, as well as assessing its environmental impact in terms of carbon footprint. The research results demonstrated that the proposed structure, based on a cross-laminated timber panel with insulation made from grass mats, had a thermal resistance of 4.9 m²·K/W, complying with current building code requirements. The hygrothermal analysis confirmed the internal stability of the wall assembly and the absence of condensation in the coldest month of the year – January (for city Dnipro). The calculated carbon footprint amounted to

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-23.6 kgCO₂-eq/m², indicating the carbon-negative nature of the system due to the use of bio-based materials capable of sequestering carbon throughout their life cycle. Additionally, the obtained indicators were compared with those of the most common building envelope design solutions, confirming the advantages of the proposed structure. Furthermore, a pilot architectural concept of a rehabilitation centre was developed, demonstrating the practical application of sustainable construction strategies based on the offered solution. The practical significance of this study lies in the potential integration of the developed wall design into the construction of modern buildings with enhanced energy efficiency and environmental performance. This aligns with the principles of sustainable development and contributes to reducing the climate impact of the building sector

Keywords: energy-efficient architecture; wall construction; hydrothermal analysis; bio-based insulation; CLT panels; post-war reconstruction

INTRODUCTION

Global environmental issues have become increasingly evident – air pollution, ozone layer depletion, global warming, glacier melting, ocean contamination, river eutrophication, biodiversity loss, among others. Each of these phenomena was defined and driven by human activity, particularly by the intensive development of industry to meet societal needs. These factors not only impact the natural environment but also directly affect every individual. The construction sector held significant potential in contributing to sustainable development. In 2019, the World Green Building Council (n.d.) estimated that the building sector accounted for 39% of global carbon emissions, with 28% attributed to operational stages (energy consumption for heating and cooling) and 11% resulting from materials and construction processes. According to a study by C. Li *et al.* (2025), under a business-as-usual scenario, construction emissions were projected to more than double by 2050. The challenges posed by global climate change have stimulated new initiatives aimed at preserving and protecting the environment. One such initiative was the European Green Deal, which sought to achieve climate neutrality within the European Union by 2050. For example, in the study G. Ottomano Palmisano *et al.* (2025), eight key areas of the European Green Deal were considered, which involved all the main sectors of the EU economy, including the building sector. This strategy envisions achieving near-zero greenhouse gas emissions by 2050 and fostering economic growth without increasing resource consumption. Meeting these goals was possible through the implementation of innovative construction solutions focused on the sustainable and efficient use of natural resources, transitioning away from non-renewable raw materials, and promoting the adoption of ‘green’ materials and products, as well as energy-saving measures. Such approaches can significantly reduce the consumption of non-renewable resources, lower greenhouse gas emissions, and enhance both the quality and longevity of human life.

Modern sustainability requirements have led to a growing interest in innovative building systems and technologies that promoted the adoption of resource-efficient and environmentally friendly solutions in the construction industry. J. Švajlenka & T. Pošiváková (2023) observed a notable resurgence of interest in wood as a structural

material within the construction sector. This trend was largely driven by advancements in engineered wood products, particularly in the domain of mass timber. M. Schubert *et al.* (2022) highlighted cross-laminated timber (CLT) as the most prominent innovation, alongside the well-established glued laminated timber (glulam). CLT had revolutionised the global building industry, positioning wood – a renewable and readily available natural resource – as a viable choice for the construction of environmentally responsible buildings. This shift in material and technological preferences was primarily motivated by the growing awareness of the environmental impact associated with the concrete and steel industries. O.A. Hegeir *et al.* (2022) demonstrated that timber had a significantly lower environmental impact than reinforced concrete and steel, largely due to the carbon stored in the wood. P. Chen *et al.* (2023) noted that despite their pivotal role in shaping modern urban environments, steel and concrete were associated with high energy consumption and substantial carbon emissions. X. Fang *et al.* (2023) contended that timber-based construction was gaining prominence as a sustainable alternative, driven by escalating environmental concerns and rapid urbanisation.

Thermal insulation systems and materials played a crucial role in the path toward carbon-neutral buildings. The proper selection of insulation materials was essential for ensuring the sustainability of construction projects. It affected not only a building’s energy efficiency but also its overall environmental footprint. M. Röck *et al.* (2020) demonstrated that inadequate or absent insulation results in elevated energy demanded for heating and cooling, consequently leading to increased greenhouse gas emissions throughout a building’s operational life cycle, which typically exceeded 50 years for standard residential structures. S.M.H. Castro *et al.* (2025) analysed different thermal materials and identified that prevalent synthetic insulation presented challenges, mineral wool was heavy and linked to health concerns, and common petrochemical foams (EPS, XPS, PU) required high production energy, were brittle, and present significant fire hazards. Conventional insulation materials (such as mineral wool and polystyrene-based foams) had an excessive carbon footprint due to the embodied energy in raw material extraction and manufacturing. However, according to research by F. Ye *et al.* (2025),





bio-based insulation materials – including grass-based insulation, cork, straw, mycelium-based insulation (derived from fungal root structures), and hemp fiber boards, as well as recycled wood fiber products – can have a low or even negative carbon footprint. This was because it absorbed CO₂, while growing and required less energy to manufacture than traditional materials. The study by M. Babenko *et al.* (2025) showed that an innovative material, combining mycelium and agricultural waste, was a thermally efficient alternative to traditional insulation materials, such as rock and glass mineral wool, in key sustainability metrics. O. Ranefjård *et al.* (2024) experimentally demonstrated the high thermal insulation properties of bio-based insulation materials such as eelgrass, grass, and wood fibre. The aim of this research was to develop and theoretically substantiate a structural solution for an energy-efficient building envelope composed of environmentally friendly materials, through a comprehensive analysis of its thermal performance and an assessment of its life-cycle carbon footprint.

MATERIALS AND METHODS

To assess the energy efficiency of building envelope design solutions incorporating ecological natural materials – specifically, CLT panels made of glued multi-layered wood with crosswise lamination, and environmentally-friendly grass-based insulation – the thermal and hygrothermal parameters of an opaque wall envelope structure were examined. The analysis also considered thermal bridges in the form of metallic fasteners. The Ukrainian national building code DBN V.2.6-31:2021 (2023) established the requirements for energy performance indicators of buildings, including thermal characteristics of envelope structures (the thermal insulation envelope) during the design and construction stages. This standard aimed to ensure normative sanitary and hygienic indoor climate conditions and the long-term durability of building enveloped during operation. In accordance with this standard, external envelope structures of buildings that were heated and/or cooled must comply with the requirements presented in equations (1), (2), and (3). The thermal performance of the proposed envelope was evaluated by comparing its calculated thermal parameters with established normative values for enclosing structures, using these equations. The first requirement dealt with the thermal resistance of the envelope structure:

$$R_{\Sigma pr} \geq R_{qmin}, \quad (1)$$

where $R_{\Sigma pr}$ – equivalent thermal resistance of the opaque envelope structure or its opaque section, in m²·K/W; R_{qmin} – minimum permissible value of the equivalent thermal resistance of the opaque envelope structure or its opaque section, in m²·K/W.

The second requirement concerns the difference between the indoor air temperature and the reduced temperature of the inner surface of the envelope structure:

$$\Delta Q_{int-si} \leq Q_{int-si,max}, \quad (2)$$

where ΔQ_{int-si} – difference between the indoor air temperature and the reduced temperature of the inner surface of the envelope structure measured along internal dimensions, in °C; $Q_{int-si,max}$ – maximum permissible difference, according to sanitary and hygienic standards, between the indoor air temperature and the reduced temperature of the inner surface of the envelope structure, in °C.

The third requirement set the minimum temperature of the inner surface in zones with thermal bridges in the envelope structure, which must be above the dew point:

$$\Theta_{tb,si,min} > \Theta_{si,min}, \quad (3)$$

where $\Theta_{tb,si,min}$ – minimum temperature of the inner surface in zones with thermal bridges in the envelope structure, in °C; $\Theta_{si,min}$ – minimum allowable temperature of the inner surface under design indoor and outdoor air temperatures, in °C.

The calculation of thermal performance indicators, as well as the modeling of temperature distribution and heat flux in the wall structure, was carried out under steady-state heat transfer conditions using the methodology implemented in the Physibel software suite (DSTU 9191:2022, 2023). Physibel was a software package designed for engineering analysis and two-dimensional and three-dimensional modelling based on the finite element method. Computer-based modelling and numerical analysis in construction allow engineers to avoid costly and time-consuming physical testing, while also accelerating, supplementing, and visualising the design and development process. To investigate the hygrothermal condition of the wall envelope structure, an analysis of water vapour diffusion was conducted for the coldest month of the year – January (for city Dnipro), based on the methodology outlined in Physibel (n.d.). The calculation of the hygrothermal state of the wall was performed under steady-state vapour diffusion conditions using a graphical-analytical method (DSTU-N B V.2.6-192:2013, 2014). The following assumptions were adopted: the structure was flat and thermally homogeneous; the vapour transfer resistances of the inner and outer surfaces of the structure were assumed to be zero; and within each homogeneous layer of the structure, the partial pressure of saturated water vapour varies according to a nonlinear (curvilinear) law. The vapour diffusion resistances of each layer R_{ex} and of the entire structure $R_{e\Sigma}$ were determined using the following formulas:

$$R_{e\Sigma} = \sum_{j=1}^n \frac{d_j}{\mu_j}, \quad (4)$$

$$R_{ex} = \sum_{j=1}^n \frac{d_j}{\mu_j} + \frac{\chi - \sum_{j=1}^m d_j}{\mu_{(m+1)}}, \quad (5)$$

where n – total number of layers in the construction; m – number of full layers from the inner surface to the section at distance χ ; d_j – thickness of the j -th layer, in meters (m); χ – distance from the inner surface of the envelope to the reference section, in meters (m); μ_j – vapour diffusion coefficient of the j -th layer material, in mg/(m·h·Pa); $\mu_{(m+1)}$ – vapour diffusion coefficient of the



material, in which the reference section $\chi \setminus \chi_i$ was located, in $\text{mg}/(\text{m}\cdot\text{h}\cdot\text{Pa})$.

The partial vapour pressure for the internal e_{int} and external e_{ext} surfaces of the wall structure, Pa, was determined by the formulas:

$$e_{int} = 0.01 \cdot \varphi_{int} \cdot E_{int-surf}; \tag{6}$$





$$e_{ext} = 0.01 \cdot \varphi_{ext} \cdot E_{ext-surf}; \tag{7}$$

where φ_{int} – relative humidity of internal air, in percent (%); $E_{int-surf}$ – partial pressure of saturated water vapour

at the internal surface of the building envelope, in Pascal (Pa); φ_{ext} – monthly average relative humidity of external air, in percent (%); $E_{ext-surf}$ – partial pressure of saturated water vapour at the external surface of the building envelope, in Pascal (Pa).

The assessment of the environmental impact of construction products, buildings, and structures was carried out in accordance with the EN 15978:2011 (2011) (Table 1). The quantitative indicator of environmental impact was the carbon footprint, which represented the total amount of greenhouse gases emitted directly or indirectly throughout the entire life cycle of building materials and products.

Table 1. Stages and informational modules of the building life cycle

Building assessment information														
Life cycle information modules														
 Product stage			 Construction stage		 Use stage					 End-of-life stage				Additional information beyond the life cycle
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material extraction	Transportation	Material production	Transportation	Construction and installation works	Operation	Maintenance	Repair	Restoration	Replacement	Deconstruction	Transportation	Recycling	Waste disposal	Post-life cycle benefits
					B6		Energy use							Recycling reuse
					B7		Water use							

Source: EN 15978:2011 (2011)

The integral measure of a building’s carbon footprint was the Global Warming Potential (GWP), expressed in terms of carbon dioxide equivalent ($\text{CO}_2\text{-eq}$), measured in kilograms of $\text{CO}_2\text{-equivalent}$ ($\text{kgCO}_2\text{-eq}$). In environmental assessments, the life cycle was divided into four main stages (informational modules A to C). Additionally, the potential impacts beyond the life cycle boundaries were assessed separately (informational module D). Module A described the pre-use stage, i.e., emissions during the product manufacturing and construction processes. For convenience in assessment, this module was divided into submodules: A1-A3 – extraction and supply of raw materials, production of building materials, products, and industrial structures; A4-A5 – transportation to the construction site and construction works. Module B included 7 submodules corresponding to the operational stage (B1), including maintenance (B2), ongoing or capital repairs (B3), restoration or reconstruction (B4), partial or full replacement (B5), as well as energy (B6) and water (B7) use for ancillary processes (e.g., lighting adjacent areas, lawns, irrigation systems). Module C described the end-of-life stage and was divided into 4 submodules: demolition (C1), transportation of waste from the site to recycling or disposal (C2), recycling (C3), and disposal (C4) of waste. Module D reflected possible environmental impacts beyond the life cycle of the object. This module included the benefits of reusing or recycling

materials from dismantled structures. The term ‘benefits’ here referred to the potential reduction of emissions due to converting waste into building or energy raw materials, thus reducing the need for extraction from natural environments. In the case of plant-based materials (wood or grass), additional benefits included the effective ‘locking’ of greenhouse gases in the elements of the architectural and building environment due to natural processes of carbon absorption and retention from the atmosphere during growth, known as carbon sequestration (Bjånesøy et al., 2023). The methodological basis for determining the GWP was the Environmental Product Declarations (EPD) (International EPD System, n.d.), which provided information about the characteristic values of $\text{CO}_2\text{-equivalent}$ emissions across the stages of the product life cycle, based on data obtained from research results using a standardised method. The general model for calculating the GWP in the form of $\text{CO}_2\text{-equivalent}$ was as follows:

$$GWP_{life-cycle} = \sum GWP_{i,stage}, \tag{8}$$

where $GWP_{i,stage}$ – the GWP indicator for stage i of the life cycle according to the information modules. The calculation of the global warming potential for a specific stage was reduced to summing up the CO_2 emissions for each element of the building object or structure:

$$GWP_{i,stage} = \sum_{i=1}^n GWP_{i,element} \cdot Q_{i,element}, \quad (9)$$

where n – number of elements; $Q_{i,element}$ – quantitative characteristic of the element; $GWP_{i,element}$ – characteristic value of CO₂-equivalent emissions for the i -th element.

So, the assessment of the carbon footprint of the building envelope construction included the following stages: description of the geometric parameters of the building envelope elements; inventory of materials by elements of the building envelope; determination of the material consumption for each type per 1 m² of surface area; systematisation of characteristic CO₂-equivalent emissions values across the life cycle stages based on the EPD; calculation and comparative analysis of the GWP of the proposed building envelope construction with existing solutions.

RESULTS

The building envelope design solution incorporated ecological natural materials, including CLT panels composed of glued multi-layered wood with crosswise lamination and environmentally-friendly grass-based

insulation, so computer model of the wall structure was analysed to assess the performance of the proposed design. The obtained results characterised the key thermal and hygrothermal parameters of the building envelope, including the thermal transmittance resistance with consideration of thermal bridges, the heat flux along the internal contour of the wall, the temperature of the internal wall surface, and the temperature distribution profile across the thickness of the wall structure. For the calculation of the thermal parameters of the building envelope wall construction using ecological materials, the following initial data were adopted: 1) external air temperature: $\theta_{ext} = -4.7^\circ\text{C}$ – the average value for January in the city of Dnipro, corresponding to 268.3 K (DSTU-N B V.1.1-27:2010, 2011); 2) internal air temperature $\theta_{int} = +20^\circ\text{C}$, corresponding to 293 K (World Green Building Council, n.d.); 3) calculation values of the heat transfer coefficients for the internal h_{si} and external h_{se} surfaces of the building envelope. The technical characteristics and thicknesses of the layers of the considered building envelope construction were presented in Figure 1.

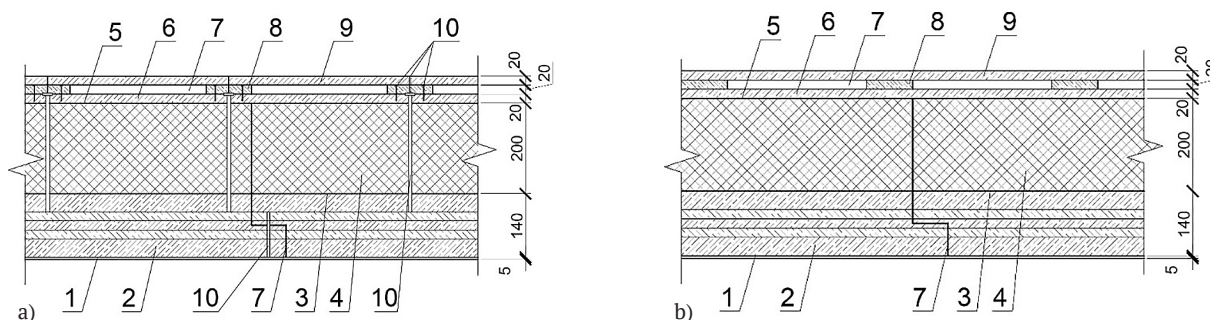


Figure 1. Cross-section diagram of the external enclosing wall structure with identification of layers, components, and their technical characteristics

Note: a – cross-section of the wall structure at the location of thermal bridges; b – cross-section of the wall structure at the location without thermal bridges: 1 – painted MDF panel, $d=0.005$ m, $\lambda=0.19$ W/K·m; 2 – CLT panel, $d=0.14$ m, $\lambda=0.19$ W/K·m; 3 – vapour barrier film (not considered); 4 – insulation with grass mats, $d=0.2$ m, $\lambda=0.04$ W/K·m; 5 – wind and water barrier (not considered); 6 – vertical wooden beam 100x20 mm, $d=0.02$ m, $\lambda=0.35$ W/K·m; 7 – air gap between wooden facade elements, $d=0.04$ m; 8 – horizontal wooden beam 100x20 mm, $d=0.02$ m, $\lambda=0.35$ W/K·m; 9 – wooden facade board, $d=0.02$ m, $\lambda=0.35$ W/K·m; 10 – metal fasteners, $d=0.001$ m, $\lambda=58$ W/K·m

Source: developed by the authors

For a detailed analysis of key thermal performance indicators, two scenarios were examined: a cross-section at a thermal bridge location, where heat loss was intensified (Fig. 1, a), and a cross-section in a homogeneous area without thermal bridges, representing the baseline wall structure (Fig. 1, b). As a result of the simulation, a two-dimensional temperature distribution across the entire wall assembly was generated (Fig. 2). This visualisation illustrated the temperature gradients within the structure, identified areas, where temperature decreased due to the influence of thermal bridges, and provided the corresponding numerical temperature values. The simulation results also provided quantitative

data, including the heat flux density along the internal wall contour and the minimum temperature on the internal wall surface, which were critical for assessing condensation risk. The temperature variation profile across the thickness of the wall structure was presented in Figure 3. The simulation results showed a stable temperature gradient from 292 K (19°C) on the interior surface to 269 K (-4°C) on the exterior surface, with a total temperature difference of 23 K. The temperature decreased gradually across the wall thickness, with the most significant drop observed in the external zone (300-400 mm). The internal surface temperature remained well above the dew point, indicating a minimal risk of condensation.

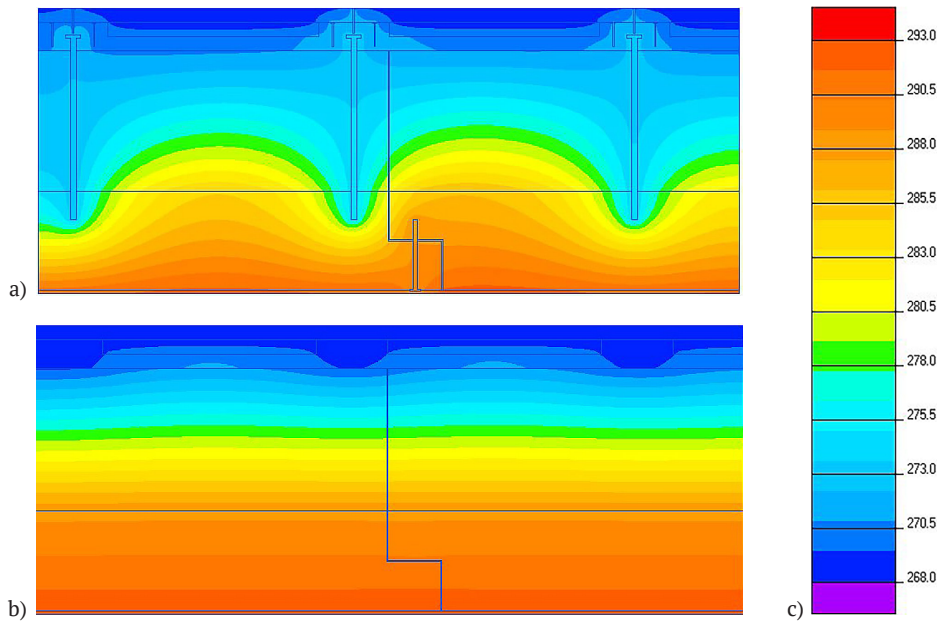


Figure 2. Temperature distribution within the wall structure

Note: a – cross-section of the wall structure at the location of thermal bridges; b – cross-section of the wall structure without thermal bridges; c – temperature on the wall surface

Source: developed by the authors

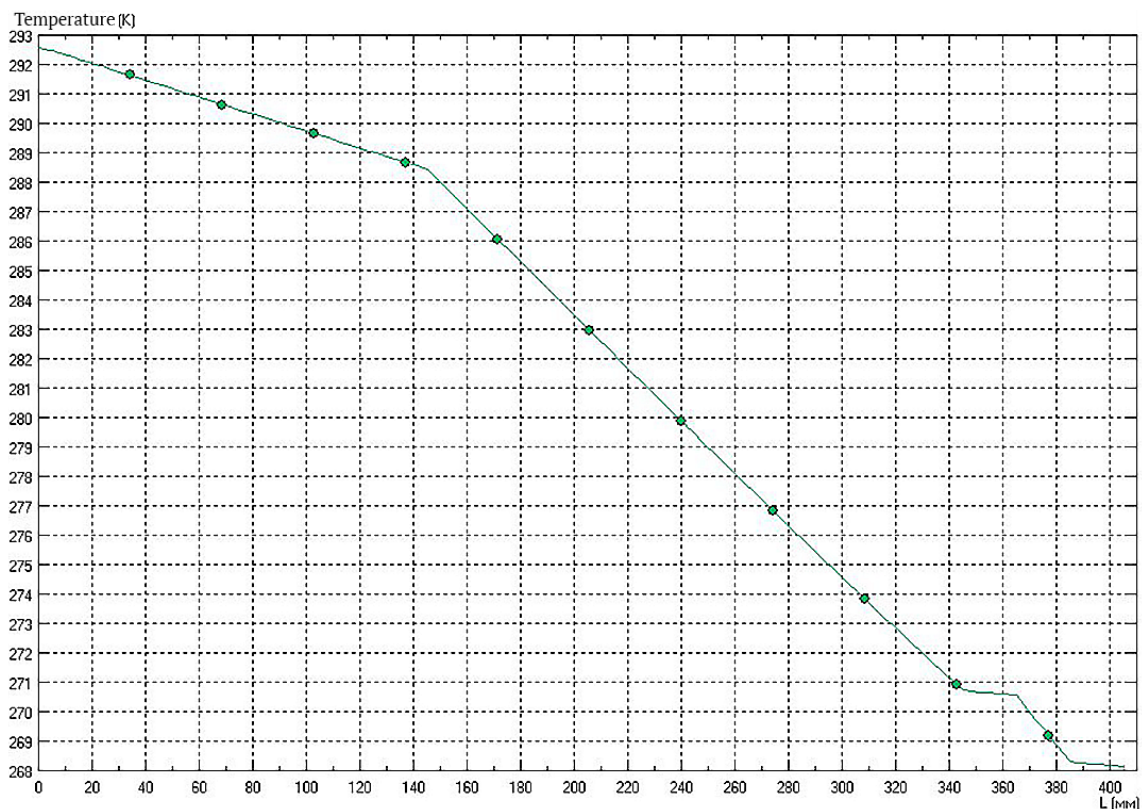


Figure 3. Temperature distribution across the wall structure thickness for January

Source: developed by the authors

The thermal transmittance resistance of the building envelope structure, denoted as the equivalent thermal resistance R_{spr} was determined in accordance with, taking

into account point thermal bridges formed by metal fasteners penetrating the insulation layer and the CLT wall panel (DSTU 9191:2022, 2023). Each metal fastener had a thickness



of 8 mm and a length of 260 mm, connecting the façade finishing elements to the wall panel. According to the adopted technical solution, four metal fasteners per 1 m² of the wall

envelope were considered. The calculated equivalent thermal resistance was $R_{spr} = 4.9 \text{ m}^2\cdot\text{K}/\text{W}$. The results of the thermal performance calculations were presented in Table 2.

Table 2. Thermal performance characteristics of the external wall envelope structure

Indicator	Values for the wall cross-section with thermal bridging elements	Values for the wall cross-section without thermal bridging elements
Average temperature of the internal surface of the structure, $\theta_{int-surf}$, K	291.6	292.7
Minimum temperature on the internal surface of the structure, $\theta_{tb,si,min}$, K	290.54	292.56
Temperature difference on the internal surface of the structure, $\Delta\theta_{int-surf}$, K	0.74	0.002
Heat flux, q , W/m ²	11.92	3.75

Source: developed by the authors

The comparative analysis of thermal performance indicators showed clear differences between the wall sections with and without thermal bridging elements. The homogeneous section maintained a higher average surface temperature (292.57 K) than the thermally bridged section (291.60 K). A difference was also observed in the minimum surface temperatures: 292.56 K for the homogeneous section versus 290.54 K for the thermally bridged section,

indicating a 2.02 K reduction. The heat flux in the thermally bridged area reached 11.92 W/m², while in the homogeneous section it was only 3.75 W/m², clearly demonstrating the substantially increased energy losses caused by thermal bridges. Nevertheless, all obtained values remained within the permissible limits. The calculated thermal parameters were compared with established normative values, and the results were presented in Table 3.

Table 3. Analysis of thermal performance of the external enclosure wall made of ecological natural materials

Designation of the construction	R_{pr} , m ² ·K/W	R_{qmin} , m ² ·K/W	ΔQ_{int-si} , °C	$Q_{int-si,max}$, °C	$\theta_{tb,si,min}$, °C	$\theta_{si,min}$, °C
Section of the wall construction at the location of heat-conductive inclusions	4.9	4.0	1.4	4.0	17.54	10.7
Section of the wall construction at the location without heat-conductive inclusions	6.3	4.0	0.4	4.0	19.56	10.7

Source: developed by the authors

The analysis of the calculation results confirmed that the proposed design solution for the building wall enclosure structure met the necessary conditions established by the national standard (DBN V.2.6-31:2021, 2023). However, it should be noted that at the locations of the metal connections between the elements of the enclosure structure, heat losses were more intense, leading to a decrease in the overall thermal resistance of the structure. For the calculation of the thermal-moisture state of the wall enclosure structure, the

following initial data were used: 1) monthly average relative humidity of external air in January for Dnipro city: $\varphi_{ext} = 86\%$ (DSTU-N B V.1.1-27:2010, 2011); 2) relative humidity of internal air: $\varphi_{int} = 55\%$ (DBN V.2.6-31:2021, 2023). Elements of the wall structure, such as the external finish with wooden facade boards and wooden beams for fastening the external finish, were not included in this calculation as it was in contact with external air. The results of the vapour permeability resistance calculation were presented in Table 4.

Table 4. Vapour permeability resistance of the wall enclosure structure

Layer of the wall enclosure structure	Layer thickness, d_p , m	Vapour permeability coefficient μ_p , mg/m·h·Pa	Vapour permeability resistance, R_e , (m ² ·h·Pa)/mg
Laminated MDF panel	0.005	0.4	0.0125
CLT wall panel	0.14	0.3	0.47
Vapour barrier film	0.00016	0.000022	7.27
Insulation – grass mats	0.2	2	0.1
$R_{e\Sigma}$			7.85

Note: MDF – medium-density fibreboard

Source: developed by the authors

So, it was indicated that the wall enclosure structure had a total vapour permeability resistance of $R_{e\Sigma} = 7.85 \text{ (m}^2\cdot\text{h}\cdot\text{Pa)/mg}$, indicating a high level of vapour resistance. The vapour barrier film provided the

dominant contribution ($R_e = 7.27$), accounting for more than 90% of the total resistance. The CLT wall panel offers moderate vapour resistance, while the laminated MDF panel and grass mat insulation were highly



vapour-permeable layers. Overall, the vapour resistance was correctly concentrated on the warm side of the structure, which was favourable for moisture protection. The temperature distribution across the thickness of the structure was adopted according to Figure 4. The saturated vapour pressure on the internal E_{int} and external E_{ext} surfaces of the enclosure structure, Pa, and the

distribution of the partial saturated vapour pressure across the thickness of the structure E_x , based on the temperature distribution at the boundary of each layer, was presented in Table 5. For constructing the distribution curve E_x , 11 points per 1°C temperature gradient across the layer thickness were used in the calculation, in accordance with the requirements of Physibel (n.d.).

Table 5. Values of temperature and partial saturated vapour pressure at the boundary of each layer of the wall structure

Temperature at the boundaries of the wall structure layers, θ_p , °C	Partial vapour pressure E, Pa
$\theta_{int-surf} = 19.6$	$E_{int-surf} = 2,283$
$\theta_1 = 19.45$	$E_1 = 2,261$
$\theta_2 = 15.5$	$E_2 = 1,762$
$\theta_3 = 15.5$	$E_3 = 1,762$
$\theta_{ext-surf} = -2.4$	$E_{ext-surf} = 501$

Source: developed by the authors

So, the temperature gradually decreased from the internal to the external surface of the wall, with the most pronounced drop occurring in the outer part of the structure. This temperature reduction led to a corresponding continuous decrease in partial vapour pressure across the wall thickness. The vapour pressure gradient was directed from the interior toward the exterior, which confirmed outward vapour diffusion under heating conditions. In the middle layers, both temperature and vapour pressure remained nearly constant, indicating similar thermal and

vapour diffusion properties of these layers. Based on the temperature-dependent saturated vapour pressure distribution, the partial vapour pressure does not exceed the saturated vapour pressure at any layer boundary. Therefore, the wall structure can be considered resistant to interstitial condensation under the given conditions. The partial vapour pressures for the internal and external surfaces of the wall structure were: $e_{int} = 1,256 \text{ Pa}$ and $e_{ext} = 431 \text{ Pa}$, respectively. The distribution of partial pressures across the thickness of the wall structure was presented in Figure 4.

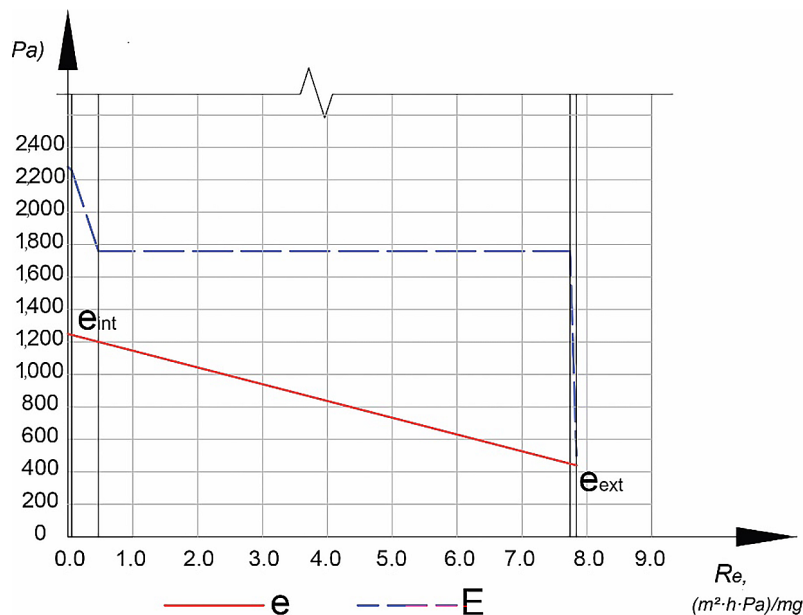


Figure 4. Distribution of partial pressures across the thickness of the wall structure

Source: developed by the authors

According to the distribution of partial pressures in Figure 4, it was established that in this design of the external wall structure, made from wooden CLT panels and insulation from grass mats, condensation of water vapour does not occur. The next step was to justify the proposed

solution from the standpoint of environmental impact. For this purpose, an inventory of the wall construction components was carried out and, based on the geometric parameters, the material consumption per 1 m² was determined, as shown in Table 6.



Table 6. Inventory results, geometric parameters and material consumption per 1 m² of external wall surface area

No.	Material name	Geometric parameters	Consumption per 1 m ² surface area
1	Painted MDF panel	t = 5 mm	0.005 m ³
2	CLT panel	t = 140 mm	0.14 m ³
3	Vapour barrier film	not considered	
4	Insulation – grass mats	t = 200 mm	0.2 m ³
5	Wind and moisture barrier	not considered	
6	Vertical wooden beam	100x20 mm, step 400 mm	0.006 m ³
7	Air gap between wooden facade elements		not considered
8	Horizontal wooden beam	100x20 mm, step 400 mm	0.006 m ³
9	Wooden facade board	t = 20 mm	0.02 m ³
10	Metal fasteners		not considered

Source: developed by the authors

The wall structure combined structural, insulating, and protective layers with a total material volume of 0.377 m³ per 1 m² of surface area. The material composition was dominated by the load-bearing CLT panel and the thermal insulation layer, which together accounted for the majority of the volume. Interior and exterior finishing layers made a relatively small contribution (0.005 m³ and 0.02 m³, respectively), while timber substructure elements added a limited

amount (0.012 m³/m² in total). Functional layers such as membranes, air gaps, and fasteners were essential for performance but had negligible material volume and were excluded from the calculation. An essential component for determining the GWP of the wall structure was the characteristic CO₂ emission values of the materials used. These data, systematised from open databases of environmental declarations for construction products, were provided in Table 7.

Table 7. Characteristic values of CO₂-equivalent emissions by life cycle stages based on EPD

Material name	Unit of measurement	GWP by life cycle stages (kg CO ₂ eq)							
		A1-A3	A4	A5	C1	C2	C3	C4	D
Painted MDF panel	1 m ³	-1.40	0.30	0.49	0.00	0.14	4.91	0.00	-2.88
CLT panel	1 m ³	-708.0	25.90	5.38	4.01	2.05	782.00	0.00	-268.0
Grass mat insulation	1 m ³	-5.01	0.13	0.62	0.00	0.09	8.77	0.35	-1.66
Wooden beam	1 m ³	-752.0	43.10	1.70	0.34	6.93	800.00	0.00	-299.0

Source: International EPD System (n.d.)

So, the life-cycle GWP results showed that all timber-based materials had strongly negative impacts at the production stage (A1-A3) due to biogenic carbon storage. The most significant carbon storage was observed for wooden beams and CLT panels, while grass-mat insulation showed a smaller but still negative value. Transport and construction stages (A4-A5) contributed relatively minor positive emissions, remaining below 50 kg CO₂eq/m³ for all materials. In contrast, the end-of-life stage (C3) generated

substantial emissions for timber products, reaching approximately 800 kg CO₂eq/m³ for CLT panels and wooden beams. Module D provided significant environmental credits, particularly for structural wood products, partially offsetting end-of-life impacts. Overall, the results highlighted the importance of carbon storage and reuse potential in bio-based materials, with structural timber elements having the largest influence on the total GWP balance. Also, these results were summarised in Table 8.

Table 8. Results of GWP determination by materials and life cycle stages of the proposed enclosure construction

Material Name	GWP according to information modules of life cycle stages and total, (kg CO ₂ eq)								
	A1-A3	A4	A5	C1	C2	C3	C4	D	ΣGWP
Painted MDF panel	-0.007	0.0015	0.0025	0.00	0.0007	0.0246	0.00	-0.014	0.008
CLT panel	-99.12	3.6260	0.7532	0.56	0.2870	109.48	0.00	-37.52	-21.93
Grass mat insulation	-1.0024	0.0264	0.1240	0.00	0.0170	1.754	0.071	-0.332	0.658
Wooden beam	-9.024	0.517	0.0204	0.0041	0.0832	9.60	0.00	-3.588	-2.387
Total GWP by stages	-109.15	4.17	0.90	0.565	0.388	120.85	0.071	-41.45	-23.654

Source: developed by the authors

To assess the energy and environmental efficiency of the proposed enclosure structure, a comparative analysis was conducted using data from the most popular existing wall constructions, which were obtained by S. Shekhorkina *et al.* (2023). In addition, the GWP of the selected

materials was evaluated across all life cycle stages, including production, transportation, construction, end-of-life processes, and potential benefits beyond the system boundary. The results demonstrated that timber-based elements such as CLT panels and wooden



beams showed significant negative emissions at the production stage due to carbon storage, although impacts increase during disposal stages. Overall, the total GWP values highlighted the environmental advantages of

bio-based materials compared to conventional wall assemblies, supporting the sustainability of the proposed design. Table 9 provided data on the enclosing structure with existing solutions.

Table 9. Comparative analysis of the proposed enclosure structure with existing solutions

Code	Description	$R_{\Sigma DP}$, $m^2 \cdot K/W$	ΣGWP , $kgCO_2\text{-eq}$
EW	Proposed enclosure structure	4.9	-23.6
CT1	Brick masonry with external insulation of expanded polystyrene and plaster	4.17	987.8
CT2	Brick masonry with external insulation of mineral wool and ceramic brick facing	4.03	3,234.9
CT3	Gas concrete block masonry with external insulation of expanded polystyrene	4.57	571.4
CT4	Gas concrete block masonry with external insulation of mineral wool and facing	4.56	2,804.0
CT5	Panel of light steel thin-walled constructions (LSTK) with an internal layer of mineral wool insulation	4.91	2,132.4
CT6	Frame-sheathing panel with a wooden frame and an internal layer of mineral wool insulation	4.23	121.9
CT7	SIP-panel with two cladding plates and expanded polystyrene between them	4.56	184.6

Source: developed by the authors

Figure 5 illustrated the superior environmental performance of the proposed solution (EW), which boasted a negative GWP value in addition to its high thermal resistance. The application of the proposed wall construction based on CLT panels and natural insulation made of grass mats was particularly relevant for construction in recreational zones of Ukraine, in accordance with the General scheme for planning the territory of Ukraine (Dipromisto, 2015). These areas required a delicate approach to design, considering their environmental protection status and the need to preserve ecosystems. The low carbon footprint of the structure (total GWP $-23.6 \text{ kgCO}_2\text{-eq/m}^2$) made it an environmentally safe alternative to traditional construction solutions. Natural materials not only reduce anthropogenic load but also contribute to the harmonious visual and functional integration of buildings into the natural environment. Thanks to its high thermal insulation properties, the structure ensured energy efficiency, which was especially important for autonomous or seasonal facilities in remote areas.

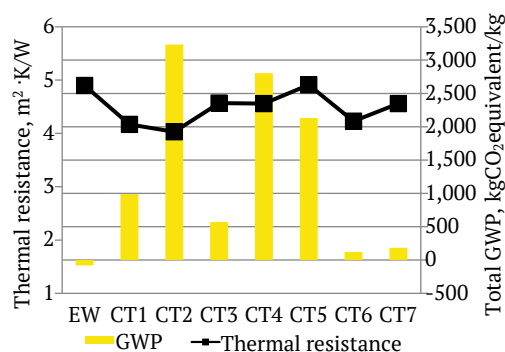


Figure 4. GWP and thermal resistance

Source: developed by the authors

Additionally, the advantages included the speed of installation and the possibility of dry construction, which minimised intervention in the landscape. This opened up broad prospects for the application of such solutions in the construction of eco-tourism facilities, campsites, rec-

reation centres, holiday homes, and other structures in the Carpathian region, Polissia, the Southern coast, and protected areas of Ukraine. Within the framework of the research project “Scientific and practical principles of designing biopositive rehabilitation facilities for veterans and civilians affected by the russian-Ukrainian war” (Grant for Fundamental and Applied Research and R&D by Young Scientists, Ministry of Education and Science of Ukraine) (Ministry of Veterans Affairs of Ukraine, n.d.), a pilot architectural concept of a rehabilitation centre was developed, demonstrating the practical application of sustainable construction strategies based on CLT technology (Fig. 6).

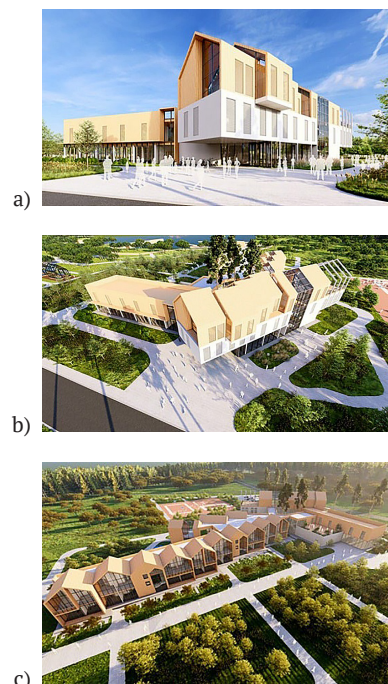


Figure 6. Architectural concept of a rehabilitation centre
Note: a – entrance area with barrier-free access; b – overall perspective; c – view of the residential modules of the rehabilitation centre

Source: developed by the authors





The project was based on three core principles of sustainable architecture: the use of local and renewable materials, the strengthening of sensory and visual connection with nature, and spatial flexibility in support of rehabilitation processes. CLT, as the primary structural and finishing material, enabled the creation of an environmentally responsible and energy-efficient building system, while simultaneously shaping a biophilic and contemporary architectural identity. The centre followed a modular, block-based composition: individual buildings were visually and functionally interconnected, while remaining structurally independent. This approach ensured adaptability, ease of transformation, and spatial separation – critical for rehabilitation facilities that required privacy, controlled circulation, and differentiated therapeutic zones (Merylova *et al.*, 2024). The building volumes were organised with varied heights and reinterpret traditional pitched roof forms in a modern architectural language, fostering an associative link to residential architecture and reinforcing users' sense of safety and comfort. Wood was prominently featured not only in the load-bearing structure but also in exterior and interior finishes, enhancing the biophilic effect. The natural texture of CLT panels remained exposed, contributing to a visually warm and emotionally stable environment. The façades were designed based on principles of rhythm and transparency: vertical wooden panels alternate with deep glazed sections, ensuring ample natural light and visual connection with the surrounding landscape. This not only improved the psychological well-being of occupants but also reduced reliance on artificial lighting, thereby contributing to energy efficiency. Thus, the implementation of wooden multi-layered constructions with plant-based insulation was entirely reasonable and meets modern requirements for sustainable construction in Ukrainian natural-recreational zones.

DISCUSSION

The analysis revealed that the proposed wall structure demonstrated a paradigm shift in environmental performance, achieving a net-negative GWP of $-23.6 \text{ kgCO}_2\text{-eq/m}^2$. This result stood in contrast to the findings of S. Shekhorkina *et al.* (2023) for conventional constructions. For instance, while solutions like brick masonry with EPS insulation (CT1: $987.8 \text{ kgCO}_2\text{-eq}$) or gas concrete with EPS (CT3: $571.4 \text{ kgCO}_2\text{-eq}$) showed a significantly positive carbon footprint, and even other timber-based systems like the wooden frame panel (CT6: $121.9 \text{ kgCO}_2\text{-eq}$) and SIP-panel (CT7: $184.6 \text{ kgCO}_2\text{-eq}$) remained carbon positive, its solution acted as a carbon sink. This superior performance can be directly attributed to the strategic selection of bio-based materials with high biogenic carbon storage capacity, specifically the CLT panels and grass mat insulation, which negative GWP in the product stage (A1-A3) effectively offset the emissions from other life cycle stages. The proposed structure successfully reconciled this exceptional environmental profile with high energy efficiency, attaining a thermal resistance (R-value) of $4.9 \text{ m}^2\text{-K/W}$. This performance was on par with the most

thermally efficient solution identified by S. Shekhorkina *et al.* (2023), the LSTK panel (CT5: $4.91 \text{ m}^2\text{-K/W}$), yet with a GWP that was two orders of magnitude lower. This underscored a critical advantage: while modern industrial materials can achieve high insulation values, it often do so at a substantial carbon cost. The results aligned with and extend the principles discussed by I. Merylova *et al.* (2024), demonstrating that the use of CLT and natural materials was not merely an aesthetic or philosophical choice but a technically viable strategy for creating buildings that were simultaneously energy-efficient and climate-positive, a crucial combination for sustainable development in ecologically sensitive regions.

The presented results significantly advanced the international discourse on carbon-negative construction. Finding of this research of a net-negative GWP of $-23.6 \text{ kgCO}_2\text{-eq/m}^2$ for the CLT and grass mat assembly resonated strongly with the work of F. Pittau *et al.* (2018), who demonstrated that timber-based buildings can act as carbon sinks due to biogenic carbon storage. However, this study provided a more granular life-cycle perspective, showing that even, when considering modules A4-A5 and C1-C4, the high biogenic carbon stored in the primary materials (CLT and wooden beams) not only compensated for emissions from other components but also secured a negative balance for the entire wall system. This finding was more pronounced than the scenarios modeled by A. Amiri & S. Junnila (2025), which comparative LCA of timber and mineral-based walls often showed timber as carbon neutral or slightly positive, but rarely achieving the significant negative GWP demonstrated here, underscoring the critical impact of combining CLT with other bio-based insulations like grass mats.

The comparative advantage over conventional materials was consistent with global trends but revealed a greater magnitude of benefit. For example, V. Cascione *et al.* (2022) in their review of exterior wall systems, confirmed that brick and concrete solutions typically exhibit a high values of GWP, which corroborated CT1-CT4 scenarios (987.8 to $3,234.9 \text{ kgCO}_2\text{-eq/m}^2$). The fact that proposed in this research solution (EW) not only avoided these emissions but also achieved a negative footprint highlighted a transformative potential. Moreover, results of this research challenged the efficiency of some modern industrial systems. The high GWP of the LSTK (CT5: $2,132.4 \text{ kgCO}_2\text{-eq}$) aligned with the findings of X. Zhong *et al.* (2021), who noted the significant embodied carbon of steel, even in well-insulated assemblies. This positions of bio-positive solution not just as an alternative, but as a necessary evolution beyond both traditional mass-based and modern lightweight industrial systems to meet ambitious decarbonisation targets in the building sector.

From an architectural design standpoint, the proposed wall system offered significant advantages that extended beyond its technical performance. The use of CLT as a primary structural material enabled a high degree of prefabrication, which accelerated the building process



and allowed for greater precision. Furthermore, the inherent aesthetic and tactile qualities of exposed wood foster a strong biophilic design connection, a principle emphasised by S.R. Kellert *et al.* (2013) to enhance occupant well-being through a direct and visual connection to natural materials. This approach allowed architects to create spaces, where the structure itself contributed to a sensory-rich and psychologically beneficial environment. The system's flexibility supported the creation of modular, adaptable spaces, aligning with the concept of "design for adaptability" promoted by sustainable building theorists, such as C.S. Goh *et al.* (2023), demonstrating that environmental sustainability and innovative, human-centered architectural design were mutually reinforcing goals. A comprehensive review on the performance and benefits of CLT as an alternative to concrete and steel in modern construction was performed by J. Abed *et al.* (2022), G.Y. Jeong (2024), and F. Ljunggren *et al.* (2025). The authors highlighted significant environmental advantages, such as a lower carbon footprint and carbon sequestration, as well as economic benefits, including faster construction times and reduced labour costs. Additionally, researchers emphasised human-centric benefits, including improved indoor air quality, noise reduction, and enhanced fire and seismic resistance. Experimental research by M. Babenko *et al.* (2018) also confirmed the high thermal properties of flax straw both as a raw material and as a lightweight, environmentally-friendly insulation made from a two-component mixture of flax straw and liquid glass. These ecological materials offered thermal performance comparable to traditional insulation products, while offering significant advantages in reducing environmental impact and contributing to healthier indoor environments. N. Ijjada & R.R. Nayaka (2022) conducted a review on eco-friendly thermal insulation materials and highlighted the benefits to curtail heat ingress, CO₂ emission, embodied energy, and safety for health. But wide adoption of natural, sustainable materials for thermal insulation remained limited. A. Ali *et al.* (2024) considered that key barriers to their use were their susceptibility to moisture and low fire resistance. Compounding this was a notable scarcity of research dedicated to their effective use.

CONCLUSIONS

The study confirmed the effectiveness of the developed enclosure structure, made of ecological materials, from

both a thermotechnical and ecological perspective. The thermal performance analysis confirmed that the proposed wall system, based on CLT panels and grass mat insulation, complied with Ukrainian building code requirements for heat protection. The thermal resistance for the proposed wall system was calculated taking into account the thermal bridges formed by metal fasteners and was 4.9 m²·K/W. The calculation of the thermal-moisture state of the wall enclosure structure demonstrated that in this design of the external wall structure, condensation of water vapour does not occur. An especially important advantage was the low carbon footprint of the structure: the total GWP was -23.6 kgCO₂-eq/m², which was significantly lower than the similar indicators of traditional constructions, for example, brick masonry with external insulation of expanded polystyrene and plaster (GWP of 987.8 kgCO₂-eq/m²) or gas concrete block masonry with external insulation of expanded polystyrene (GWP of 571.4 kgCO₂-eq/m²). This was achieved by using plant-based materials that can sequester carbon throughout their life cycle, as well as the low energy intensity of their production and potential for reuse. In the context of implementing sustainable development principles, the European Green Deal objectives, and the requirements of Ukraine's post-war reconstruction, the proposed structural solution was a promising option for designing modern, energy-efficient buildings with minimal environmental impact. Building on these results, future research will focus on the experimental validation of the developed theoretical models under controlled laboratory conditions that simulate real-world operating environments. Further architectural investigations will address the scaling and adaptation of the offered wall system across different building typologies and climatic requirements.

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Стійка, енергоефективна та екологічно чиста стінова система для будівельного застосування в Україні

Анотація. У відповідь на глобальні екологічні виклики та зростаючий попит на енергоефективні рішення у будівельному секторі пошук екологічно безпечних конструктивних систем із мінімальним вуглецевим слідом стає актуальним. Метою цього дослідження було розроблення та аналіз системи зовнішньої стінової огорожувальної конструкції з екологічних матеріалів з урахуванням її теплотехнічних і гіротеплотехнічних характеристик, а також оцінка її екологічного впливу за показником вуглецевого сліду. Результати дослідження показали, що запропонована конструкція на основі панелі з перехресно-клеєної деревини з утепленням із трав'яних матів має термічний опір $4,9 \text{ м}^2\cdot\text{К}/\text{Вт}$, що відповідає чинним вимогам будівельних норм. Гіротеплотехнічний аналіз підтвердив внутрішню стабільність стінового вузла та відсутність конденсації у найхолоднішому місяці року – січні (для міста Дніпро). Розрахований вуглецевий слід становив $-23,6 \text{ кгCO}_2\text{-екв./м}^2$, що свідчило про вуглецево-негативний характер системи завдяки використанню біоматеріалів, здатних акумулювати вуглець протягом усього життєвого циклу. Крім того, отримані показники було порівняно з найпоширенішими рішеннями огорожувальних конструкцій, що підтвердило переваги запропонованої структури. Також, було розроблено пілотну архітектурну концепцію реабілітаційного центру, яка демонструє практичне застосування стратегій сталого будівництва на основі запропонованого рішення. Практична значущість дослідження полягає в потенційній інтеграції розробленої конструкції стіни у сучасне будівництво з підвищеною енергоефективністю та екологічними показниками. Це відповідає принципам сталого розвитку та сприяє зменшенню кліматичного впливу будівельної галузі

Ключові слова: енергоефективна архітектура; стінові конструкції; гіротеплотехнічний аналіз; біоізоляція; CLT-панелі; післявоєнна відбудова