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REVEALING TIMBER STRUCTURES POTENTIAL IN DECARBONIZATION OF LOW-RISE RESIDENTIAL BUILDINGS

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Abstract. The article presents the results of theoretical studies on embodied carbon for load-bearing wall structures prevailing in low-rise buildings consturction practice in order to reveal the potential of timber structures in decarbonization of the construction sector. Seven types of wall structures were considered in the study. CO_2 emissions were determined using the environmental product declarations for relevant materials considering sequential life-cycle stages (raw material supply, production and transportation of building products, construction process, building waste transportation and disposal) with regard to recycling benefits. A lightweight timber framed wall panel was shown to have minimum carbon emissions at each life-cycle stage leading to lowest total carbon embodied.

Keywords: carbon footprint, low-rise residential buildings, wall structures, life cycle, decarbonization.

Introduction. In 2019, the European Commission adopted the European Green Deal [1] as a new strategy for the development of all areas of the economy to achieve climate neutrality. The post-war reconstruction of Ukraine opens up wide opportunities for the transformation of the construction industry through the introduction of green construction technologies using low-carbon building materials. The creation of new quality dwellings, safe for the health of residents and the environment, will be especially relevant in rural communities that were destroyed during hostilities. Rationale of the choice of load-bearing elements of low-rise buildings for fast resource- and energy-efficient reconstruction can be performed by an advance assessment of the carbon footprint of the structural solutions prevailing in our country.

Recent publications review. A decarbonisation strategy covers the reduction of embodied carbon throughout the whole life cycle of a building. Today a lot of works by various scientists are devoted to transformation the construction industry into a decarbonized one. These studies involve the environmental performance of different types of buildings, and propose algorithms for evaluating and measures of minimizing the carbon footprint.

The article [2] analyzes the environmental indicators of industrial prefabricated buildings of various types. The authors define a carbon footprint that quantifies the sum of direct and indirect greenhouse gas emissions associated with the life cycle of buildings. In the article [3], the authors systematize the data available on the quantitative determination of the embodied carbon, and also demonstrate the use of a hybrid method of assessment the life cycle of buildings. Both papers provide the results comparison of determination the total carbon emissions for two construction technologies - traditional monolithic reinforced concrete and prefabricated reinforced concrete panels. The advantages of the panelized prefab system are also demonstrated in the work [4].

The authors [5] offer an extensive review of embodied energy and carbon data for

223 building materials based on environmental product declarations, focusing on innovative and insulating materials.

Recently, it also begun to appear studies on the carbon footprint of buildings built using wood as an ecological and sustainable material. In the article [6], the authors analyzed the carbon footprint for lightweight timber-framed residential buildings, which are representative of the USA. The authors of [7] propose increasing the use of wood in construction as a future strategy for reducing embodied greenhouse gas emissions by buildings. This study systematizes already published data on greenhouse gas emissions during the life cycle of timber houses. In the article [8], the authors report on the study of the potential for reducing greenhouse gas emissions in the construction sector by replacing steel and concrete building structures with timber ones, as well as traditional construction with prefabricated structures. The results of [9] research confirm the positive effect of using prefabricated timber frame systems in multi-story construction.

All the studies analyzed confirm that the reduction of the carbon footprint of buildings can be planned and achieved at the early design stage through the appropriate selection of materials with minimal emissions at all life cycle stages and a high potential for reuse and recycling after demolition. As the timber has high ecological characteristics, its application in low-rise construction can significantly reduce the carbon footprint in recovery of rural communities of Ukraine. For the widespread implementation of decarbonized structural solutions using timber in construction practice, it is necessary to obtain visible data that will demonstrate their advantages for private developers. In respect of above, the purpose of the work is to study the carbon footprint of load-bearing wall structures of low-rise buildings, taking into account energy efficiency requirements.

Materials and methods. Quantitative assessment of the environmental impact of construction products is performed according to European standard EN 15978:2011 [10]. It considers the whole life cycle, which includes four main stages: production; construction; operation; end of life. Separately, it is recommended to take into account the potential benefits of reuse or recycling after dismantling. The methodological basis of the calculations is environmental product declarations (EPD), which contain data on the carbon footprint of specific products at all life-cycle stages. Since the basis of resource-efficient buildings is also the reduction of energy consumption, along with the assessment of emissions, it is necessary to comply the requirements for heat transfer resistance.

The methodology of this study consisted of the following stages: 1) the selection of types of load-bearing wall structures of low-rise buildings for an analysis; 2) specification of geometric parameters in accordance with the requirements of minimum heat transfer resistance (R_{min}=4.0 $m^2 \cdot K/W$) [11]; 3) determination of material consumption by each type per typical unit; 4) inventory of the carbon footprint of materials through EPD [12]; 5) calculation and comparative analysis of the carbon footprint of wall structures.

The following types of load-bearing wall structures were chosen as the most typical in low-rise construction: CT1 - brickwork with external expanded polystyrene foam insulation and plaster facing; CT2 - brickwork with external mineral wool insulation and ceramic bricks facing; CT3 - aerated concrete blocks masonry with external expanded polystyrene foam insulation and plaster facing; CT4 - aerated concrete blocks masonry with external mineral wool insulation and ceramic bricks facing; CT5 - light gauge steel framed panel with internal mineral wool insulation and drywall facing; CT6 – lightweight timber framed panel with internal mineral wool insulation between drywall and oriented strand board facing; CT7 – structural insulated panel with insulating polystyrene foam core between two oriented strand board structural facings.

The geometric parameters of the wall structures were refined before determining the CO_2 emissions considering the new requirements for the minimum heat transfer resistance. The thickness of the insulation was determined to adjust the cross-section dimensions of the lightweight metal profiles and lumber. The thickness of masonry made of bricks and aerated concrete blocks were 380 mm for all cases. For the heat transfer resistance calculation the methodology of [11] was used to determine the of wall structures of low-rise residential buildings.

The quantities of materials for each type of wall structure was determined based on the assumption of the standard size of a wall panel in frame construction, which is 1.2 x 2.5 m (width x height). These dimensions were considered as a typical unit for determination the carbon footprint. Material quantities for a typical unit of wall structure were represented as a self-weight.

Data on heat transfer resistance, components and material quantities for typical unit of load-bearing wall structures considered are summarized in table 1.

Table 1. Data on heat transfer resistance, components and material quantities for typical unit of load-bearing wall structures

Wall structure	Heat transfer resistance, R, m^2·K/W	Components and materials of load-bearing wall structures	Density of material, kg/m^3	Self-weight of material for a typical unit, kg
CT1	4,17	Ceramic brick – 380 mm	1600	1824
		Extruded polystyrene foam – 120 mm	35	12,6
		Sand Cement Plaster – 20 mm	1800	108
CT2	4,03	Ceramic brick – 380 mm	1600	1824
		Mineral wool – 120 mm	100	36
		Ceramic facing brick – 120 mm	1300	468
CT3	4,57	Aerated concrete blocks – 300 mm	400	360
		Extruded polystyrene foam – 50 mm	35	5,25
		Sand Cement Plaster – 20 mm	1800	108
CT4	4,56	Aerated concrete blocks – 300 mm	400	360
		Extruded polystyrene foam – 50 mm	35	5,25
		Ceramic facing brick – 120 mm	1300	468
CT5	4,91	OSB – 18 mm	1000	54
		Light gauge steel profile– 1,0 mm 50x200 mm (3 pcs.)	2.34 kg/l.m.	17,6
		Mineral wool – 200 mm	100	60
		Drywall – 12,5 mm	800	30
CT6	4,23	OSB – 18 mm	1000	54
		Sawn timber - 50x175 mm (3 pcs.)	600	39,4
		Mineral wool – 170 mm	100	51
		Drywall – 12,5 mm	800	30
CT7	4,56	OSB – 18 mm	1000	54
		Sawn timber - 50x150 mm (2 pcs.)	600	26,25
		Extruded polystyrene foam – 150 mm	35	15,75
		OSB – 18 mm	1000	54

For further calculation of the carbon footprint of the wall structures cases adopted for low-rise buildings based on EPD, the amount of CO_2 emissions ($kgCO_2eq$) was determined considering the following stages of the product life cycle: C_{be} – raw material supply and production of building products; C_{bt} – building products transportation to the site; C_{bp} – construction process; C_{d1} – building waste transportation; C_{d2} – building waste disposal; C_r – recycling benefits.

Emissions during operation and dismantling were not included in the analysis. The first one, because the study examines a typical unit of a wall structure without reference to a specific architectural and planning solution of a low-rise building, engineering and technical equipment and other characteristics that determine the generation of emissions during this stage of the life cycle. The second one, due to the fact that CO_2 emissions on this stage are caused by the operation of machines or mechanisms, while their amount, types and terms of operation will depend on the volume of disassembly, which in turn also corresponds to specific parameters of a low-rise building.

A special feature of the EPD [12] is the presentation of the carbon footprint using different units of measurement for different products. For example, data are given per 1 ton of material for brick and light gauge steel profile, per 1 m^3 of aerated concrete block, OSB and wood, per 1 m^2 of extruded polystyrene foam, mineral wool and plasterboard, and per1 kg of plaster. In addition, different manufacturers use different distances to estimate emissions at the transportation stage, which depends on the specifics of the market.

In order for the obtained results on the carbon footprint to be comparable, the EPD data [12] were recalculated per weight of 1 kg and a distance of 100 km for each material. The data obtained on the carbon footprint of wall structures materials after all estimations are presented in the table 2.

Table 2. Estimated data on the carbon footprint of wall structures materials

Material	CO_2 emissions, $kgCO_2eq/kg$, for considered life-cycle stages					
	C_{be}	C_{bt}	C_{bp}	C_{d1}	C_{d2}	C_r
Ceramic brick	0,147	1,412541	0,000143	0,00649	0,00339	-0,00563
Aerated concrete block	0,336	4,209302	0,0022	0,00416	0,0048	-0,00366
Ceramic facing brick	0,147	14,26667	0,000143	0,00649	0,00339	-0,00563
Sand Cement Plaster	0,394	0,0072	0,0417	0,00829	0,0148	-0,00224
Extruded polystyrene foam	2,742	0,052975	0,01856	0,00774	3,3978	-1,41
Mineral wool	0,80586	2,0942	0,01944	0,001998	0,00828	-0,03078
OSB	0,1717	3,363995	0,08704	0,007514	0,5457	-0,4862
Drywall	0,2268	0,039357	0,03024	6,108E-17	2,928E-14	-3,324E-14
Light gauge steel profile	2,58	8	0,0498	0,017	0,00326	-0,0015
Sawn timber	0,058859	3,18	0,003238	0,00303462	0,00143177	-0,211813

Results. The carbon emissions of the particular wall structure at separate stage of the life-cycle were calculated as the sum of the products of the self-weight of each material composing the wall and the corresponding material CO_2 emissions. As a result of calculations, data on carbon dioxide emissions for every single stage of the life cycle as well as the total carbon footprint for each considered type of load-bearing wall structure of low-rise buildings were obtained. The data calculated are presented in table 3. Comparative diagram of total carbon footprint considering the heat transfer resistance of wall structures is presented on figure 1.

Table 3. Carbon emissions for considered life-cycle stages and the total carbon footprint for load-bearing wall structures of low-rise buildings

Wall structure	CO_2 emissions, $kgCO_2eq$/typical unit, for considered life-cycle stages						
	C_{be}	C_{bt}	C_{bp}	C_{d1}	C_{d2}	C_r	Total CO_2
CT1	345,23	2577,92	5,00	12,83	50,59	-28,28	2963,30
CT2	365,93	9328,67	1,03	14,95	8,07	-14,01	9704,63
CT3	177,91	1516,40	5,39	2,43	21,16	-8,96	1714,34
CT4	204,15	8192,43	0,96	4,58	21,15	-11,35	8411,91
CT5	4605,23	576,01	883,25	299,73	87,34	-54,50	6397,05
CT6	59,49	297,02	6,62	0,51	29,89	-27,82	365,70
CT7	63,28	447,62	9,78	1,01	112,49	-80,28	553,90

*t.u. is a typical unit.

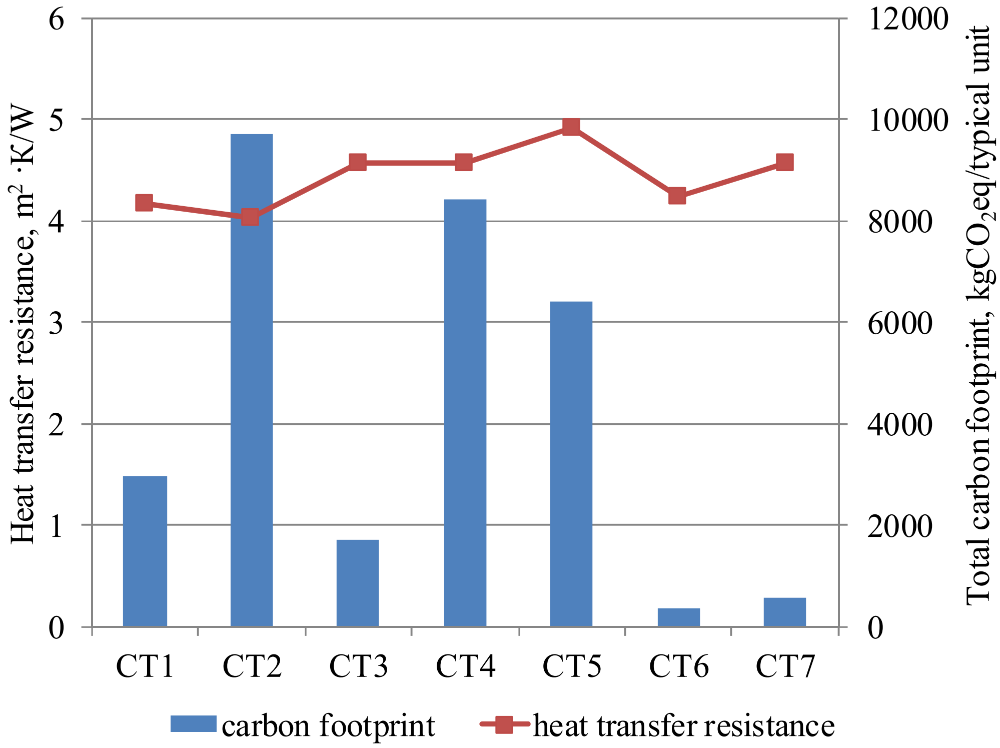

Fig. 1. Comparative diagram of total carbon footprint considering the heat transfer resistance of wall structures

Conclusions. From the data obtained, it can be seen that the highest emissions at the production stage of correspond to the CT5 wall structure with light gauge steel profile and mineral wool insulation (C_{be}=4605.23 kgCO_2eq/t.u.), while for other types this value is several times lower namely 345.23 and 365.93 kgCO_2eq/t.u. for CT1 and CT2 brick walls; 177.91 and 204.15 kgCO_2eq/t.u. for CT3 and CT4 walls made of aerated concrete blocks.

At the stage of transportation of building materials, the largest emissions have both variants of walls with ceramic brick facing which equal to C_{bt}=9328,67 kgCO_2eq/t.u. for CT2 ceramic brick wall and C_{bt}=8192,43 kgCO_2eq/t.u. for CT4 wall with aerated concrete blocks. Emissions for the CT1 wall are also significant, amounting to C_{bt}=2577.92 kgCO_2eq/t.u., as well as for CT3 wall, amounting to C_{bt}=1516,40 kgCO_2eq/t.u.

As for the stages of construction process and building waste transportation, it can be seen that for all wall types the emissions are not significant and vary within C_{bp}=1,03..9,78 kgCO_2eq/t.u. and C_{d1}=0,51..14,95 kgCO_2eq/t.u.. The exception is the CT5 variant with light gauge steel profile, which is characterized by emissions of C_{bp}=883.25 kgCO_2eq/t.u. and C_{d1}=299.73 kgCO_2eq/t.u.

The highest emissions of carbon dioxide when storing waste in landfills are created by CT7, CT5 and CT1 structures, which are insulated with extruded polystyrene foam, C_{d2}=112,49 kgCO_2eq/t.u.; 87,34 kgCO_2eq/t.u. and 50,59 kgCO_2eq/t.u., respectively.

The minimum carbon emissions at all stages corresponds to the lightweight timber framed panel (CT6 type) which reveal its effectiveness for low-rise buildings decarbonization.

The largest values of total carbon footprint associate with the walls with ceramic brick facing and equal to 9704.63 kgCO_2eq/t.u. for CT2 brick wall and 8411.91 kgCO_2eq/t.u. for CT4 wall with aerated concrete blocks. Lightweight timber framed wall panel (CT6 type) is characterized by the minimum carbon footprint of 365.70 kgCO_2eq/t.u. with the optimal respective value of heat transfer resistance R=4.23 m^2 K/W.

The data obtained on embodied carbon confirm the high potential of timber structures in achieving the goals of decarbonization in the construction sector, creating resource-efficient recyclable building structures withal ensuring the energy efficiency of buildings.

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ВИЯВЛЕННЯ ПОТЕНЦІАЛУ ДЕРЕВ'ЯНИХ КОНСТРУКЦІЙ У ДЕКАРБОНІЗАЦІЇ МАЛОПОВЕРХОВИХ ЖИТЛОВИХ БУДИНКІВ

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В 2019 році Європейською комісією було прийнято Європейський Зелений Курс як нову стратегію розвитку всіх сфер економіки для досягнення кліматичної нейтральності. Післявоєнна відбудова України відкриває широкі можливості до трансформації будівельної галузі шляхом впровадження зелених технологій будівництва із використанням будівельних

матеріалів з низьким втіленим вуглецем. З огляду на екологічні характеристики деревини, її використання в малоповерховому будівництві може сприяти істотному зменшенню вуглецевого сліду при відновленні сільських громад України. Для широкого запровадження в будівельній практиці декарбонізованих конструктивних рішень з використанням деревини необхідне отримання наочних даних, що демонструватимуть їх переваги для приватних забудовників.

Розрахунок вуглецевого сліду стінових конструкцій малоповерхових будівель виконувався на типову одиницю розміром 1.2x2.5 м (т.о.) з дотриманням рекомендацій європейських норм EN 15978:2011 для наступних етапів життєвого циклу: C_{be} – виробництво будівельних матеріалів; C_{bt} – транспортування будівельних матеріалів; C_{bp} – будівельно-монтажні робіти; C_{d1} – транспортування будівельних відходів; C_{d2} – зберігання відходів на звалищах; C_r – зменшення викидів від рециклінгу. До аналізу не були включені викиди на етапі експлуатації та демонтажу.

Згідно отриманих даних найбільшими викидами на етапі виробництва будівельних матеріалів характеризується стінова конструкція СТ5 з ЛСТК та утепленням з мінеральної вати C_{be}=4605,23 кгCO_2екв/т.о., тоді як для інших типів ця величина є на порядок нижчою – для стін із цегли 345.23 та 365,93 кгCO_2екв/т.о., для стін з газобетонних блоків 177,91 та 204,15 кгCO_2екв/т.о. На стадії транспортування будівельних матеріалів найбільші викиди мають обидва варіанти стін з облицюванням керамічною цеглою – C_{bt}=9328,67 кгCO_2екв/т.о. для стіни СТ2 з цегли керамічної та C_{bt}=8192,43 кгCO_2екв/т.о. для стіни СТ4 з газобетонного блоку. Так само істотними є викиди для стіни СТ1, що становлять C_{bt}=2577,92 кгCO_2екв/т.о., та СТ3, які дорівнюють C_{bt}=1516,40 кгCO_2екв/т.о. Що стосується стадій виконання будівельно-монтажних робіт та транспортування будівельних відходів, то для всіх варіантів стін викиди не є значними і варіюються в межах C_{bp}=1,03..9,78 кгCO_2екв/т.о. та C_{d1}=0,51..14,95 кгCO_2екв/т.о. Виключенням є варіант СТ5 з ЛСТК, який характеризується викидами C_{bp}=883,25 кгCO_2екв/т.о. та C_{d1}=299,73 кгCO_2екв/т.о. Найбільші викиди вуглекислого газу при зберіганні відходів на звалищах утворюють конструкції СТ7, СТ5 та СТ1, які мають утеплення екструдованим пінополістиролом – C_{d2}=112,49 кгCO_2екв/т.о., 87,34 кгCO_2екв/т.о. та 50,59 кгCO_2екв/т.о. відповідно. Мінімальні значення викидів на всіх етапах мають стіни у вигляді дерев'яних каркасно-щитових панелей.

Підсумкове значення вуглецевого сліду є найбільшим для стін з облицюванням керамічною цеглою і складає 9704,63 кгCO_2екв/т.о. для цегляної стіни СТ2 та 8411,91 кгCO_2екв/т.о. для газобетонної стіни СТ4. Мінімальний вуглецевий слід 365,70 кгCO_2екв/т.о. при оптимальному значенні опору теплопередачі R=4,23 м^2 К/Вт має каркасно-щитова панель з дерев'яним каркасом з внутрішнім шаром утеплювача з мінеральної вати.

Отримані дані про викиди вуглецю підтверджують високий потенціал дерев'яних конструкцій у досягненні цілей декарбонізації в будівельному секторі, створюючи ресурсозберігаючі будівельні конструкції, що придатні до повторного використання (рециклінгу), із забезпеченням енергоефективності будівель.

Ключові слова: вуглецевий слід, малоповерхові житлові будинки, стінові конструкції, життєвий цикл, декарбонізація.