Thermal Performance and Energy Efficiency of Lightweight Steel Buildings: a Case-Study

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Abstract. Steel façade systems follow the actual tendencies in construction offering robust and sustainable solutions, able to answer to actual conditions and to offer adequate interior thermal comfort. The modern sandwich panels provided by the current façade system producers combine the required thermal resistance by varying the thermal insulation material and its thickness with the required structural demands. In addition, the façade layer could be over-coated with different materials, thus offering the required architectural aspect. Other advantages of the systems rely on industrialized prefabrication, fast installation and adaptability. They could also be disassembled and reused. The study presents an analysis of some envelope solutions existing on the market for buildings made of thin-walled cold-formed steel structural systems. The study consists in an annual energetic analysis of Mineral Wool (MW)-based system and a more sustainable recycled-PET thermal wadding-system. The analysis includes for input the own-produced energy by power grids and additional national grid energy while for output heating / cooling and electric appliances are considered. The study is completed by a life-cycle environmental analysis. The study revealed that when the thermal insulations have nearly the same U-value, the environmental impact of the recycled-PET thermal wadding-based system is smaller than that of MW-based system. Although the environmental impact of the recycled-PET thermal wadding is higher in the production stage, the insulation quantity of the material needed for PET-recycled thermal wadding to accomplish the required thermal resistance is much smaller than that of MW. Moreover, the original material for the recycled-PET thermal wadding is 100% recycled which implies a certain benefit of circularity to the material. The study also proves that the glazing ratio has also an impact on the thermal performances of studied systems: by reducing the overall glazing ratio of the envelope, the solar gain drops significantly, which leads to an increased heating energy demand, in order to meet indoor thermal comfort.

1. Introduction

Commercial and residential buildings are bound to approximately 32% of global energy use and around 10% of the total direct CO_2 emissions related to energy consumption [1]. Buildings have a significant energy-saving potential by means of renovation and improvement. The Energy Performance of Buildings Directive provides that the EU countries must set minimum energy performance demand for new buildings and for some of the renovated buildings [2].

By reducing the energy losses through the building envelope, the thermal insulation materials have a major contribution to the improvement of the global energy efficiency and sustainability of buildings. In the context of adopting the EU energy savings regulations and meeting its targets to reduce greenhouse gas emissions, insulating materials have gained importance and the global demand for thermal insulations in building applications is predicted to increase at a compound annual growth rate (CAGR) of 4.5% between 2016 and 2027, while, in the EU the demand for thermal insulation materials is estimated to increase at CAGR of 3.48% (between 2015-2027) [3].

Driven by governmental measures to improve the cost efficiency and the energy efficiency of buildings, action 5 in the Communication 'Towards an integrated strategic energy technology (SET) plan: Accelerating the European energy system transformation' [2] refers to the 'Development of new materials and technologies, for the market uptake of energy efficiency solutions for buildings'. In this direction, over the last decade, new thermal insulation solutions using advanced materials (such as vacuum panels, aerogel, phase changing materials etc.) were more extensively developed. In the same time, it was encouraged the advancement of insulation solutions with a higher rate of reusability and/or recycling along with the advancement of thermal insulation materials made from the recycling of waste, as the non-renewable resources are rapidly consumed.

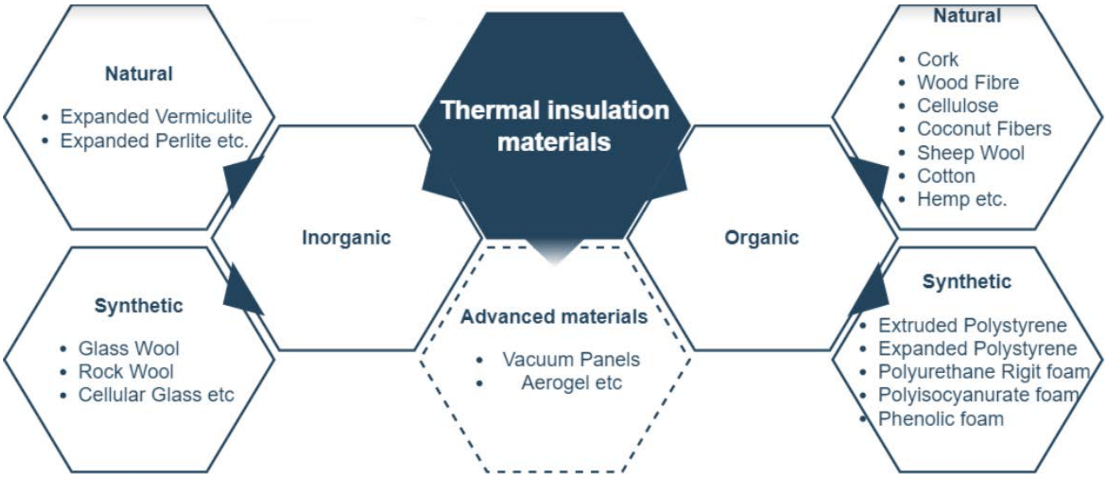

Figure 1. Classification of thermal insulation materials [4]

PET (Polyethylene Terephthalate) consumption has increased due to its widespread use in packaging and fibres manufacturing [5], reaching a total global consumption of 23.5 million tons in 2016, from which 26.3% were used for bottled water, 26.1% for carbonated soft drinks and 18.6% for other drinks [6]. Considering the numerous reactions and processes needed for PET production, the recovery or recycling of it becomes compelling for both, economic reasons and environmental benefits. As such, one of the feasible methods in disposing PET waste is the use in other industrial areas [7]. After sorting, cleaning and shredding into flakes, recycled PET waste is used to produce various end segment products like luggage, automotive parts, industrial strapping, sheet and films, PET containers, polyester carpet fibres and clothing. In the building sector, in the last decade, the use of polyester fibres made from the recycling of post-consumer PET bottles has been developed into thermal insulation wadding production.

2. Alternative building thermal insulations: recycled-PET thermal wadding

Thermal insulation materials are classified in numerous forms in the literature, predominantly in two main groups (figure 1): inorganic and organic, in agreement with the origin of the raw materials from which are made. Each one of the two dominant groups is then divided into natural and synthetic insulation materials, according to the production process. In addition, there are other composite products and new technology materials which are in an endless improvement and progress [4].

The environmental perspective of thermal insulation products has been lately taken into consideration and the use of the so-called secondary raw materials is more and more in the spotlight. Thermal insulation wadding produced with polyester fibres made from the recycling of post-consumer PET bottles is one of such insulation materials developed in the last decade [7].

The manufacture of polyester fibres starts with the recycling of post-consumer PET bottles from differentiated waste collection. These are afterwards washed, ground to flakes and used in fibres production [8]. The layers of raw material for thermal insulation wadding are obtained by guiding the polyester fibres mechanically in the same direction. Eventually, the thermal insulation wadding is obtained by overlapping and thermal bonding (ca. 180ºC) two or more layers of raw material wadding with the desired density and thickness [9].

Table 1. Technical performances of the recycled-PET thermal wadding [9]

		Thickness [mm]			
		15	20	37	
Density [kg/m^3]	15			0.058	λ [W/mk][a]
				0.638	R [m^{2}K/W][a]
	30		0.052		λ [W/mk][a]
			0.383		R [m^{2}K/W][a]
	55	0.046			λ [W/mk][a]
		0.323			R [m^{2}K/W][a]

[a] λ represents the thermal conductivity and R-value is a measure of resistance to heat flow through a material of a given thickness ($R = l/\lambda$, where l is the thickness of material in metres and $\lambda$is the thermal conductivity in W/mK)

Recycled-PET thermal wadding has both thermal (table 1) and acoustic insulation properties, being also a breathable material. On the strength of the polyester fibres' characteristics, the product's physical features remain unchanged over time. Due to the fact that recycled-PET thermal wadding is manufactured entirely with polyester obtained from post-consumer PET bottles ensures a refrain of CO2 emissions. No chemical or other textile agents are used in the production process, which means that the recycled-PET thermal wadding contains no harmful substances for human health [8].

The recycled-PET thermal wadding is available in various densities and thickness, meeting the technical performances desired and regulations in force in a matter of thermal insulation and reaction to fire.

3. Environmental impact analysis: recycled-PET thermal wadding vs. mineral wool thermal insulation

The potential environmental impact was presented relating to GWP as an indicator, using life cycle assessment method (LCA) for the evaluation [10], following the rules of EN 15804 [11] and EN 15978 [12]. The objective is to show the performance of the thermal insulation materials by comparing mineral wool insulation (MW_100) with thermal wadding made from recycled PET bottles (PET_150.

The thickness of each thermal insulation was chosen in addition to comply with (nearly) the same thermal transmittance (U-value) of the analysed thermal insulation system (table 2).

Table 2. Technical performances: Mineral wool vs PET wadding

	Units	MW_100	PET_150
Thickness	[mm]	100	150
R	[m^2K/W]	2.50	2.77
U	[W/m^2K]	0.40	0.36
Net weight	[kg/m^2]	9.00	3.20

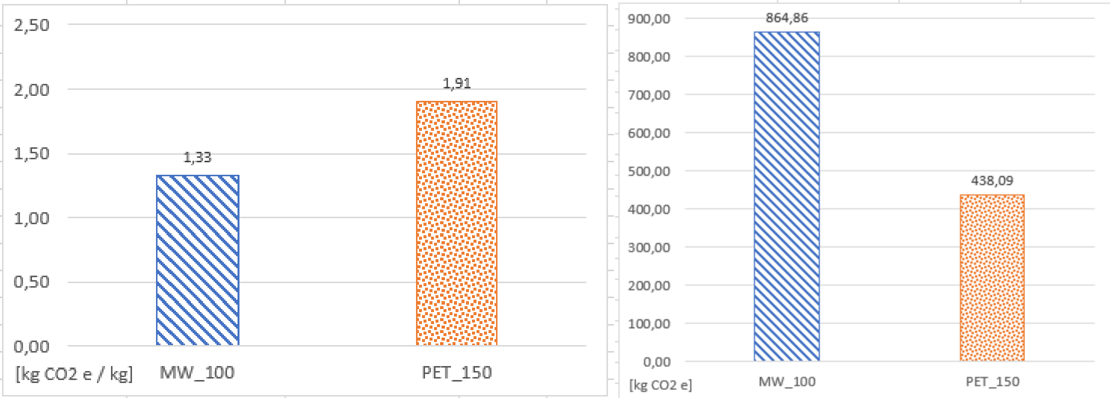

Figure 2. Potential environmental impacts of the thermal insulation materials in the production stage [kg CO_2 e / kg] (left) and total environmental impacts of the needed thermal insulation in the production stage [kg CO_2 e] (right)

Figure 2 (left) outlines the greenhouse gas (GHG) emissions for each thermal insulation per 1 kg of material produced. The assessment of the 'Production stage' refers to the stages A1 (raw materials extraction), A2 (transportation of the raw materials to the manufacturer) and A3 (thermal insulation production), being based on GaBi Product Sustainability Software [13], on Environmental Product Declarations (EPD's) by Freudenberg Performance Materials Group [8] and on Technical Approval for Wadding Mattresses for Thermal and Phonic Insulation [9].

As the results show, in the production stage (modules A1-A3), the emissions for 1 kg of recycled-PET thermal wadding are higher than for 1 kg of mineral wool. However, due to the difference of material needed, in order to achieve the same U-value in the study case (649 kg for mineral wool in comparison with 229 kg for recycled-PET thermal wadding), the total environmental impact of PET_150 (438,09 kg CO_2 e) is smaller than the total environmental impact of MW_100 (864,86 kg CO_2 e), as seen in figure 2 (right). The above values were computed for the insulation of a base unit as described below.

4. Energetic efficiency and LCA of thermal insulation systems – a case study

4.1. Base model description

The model (Figure 3) represents a base unit of 5x5m, representing a two-floor open space, with a pitched roof at the second floor able to benefit and use the sun for both natural light and PV panels. The south façade is a glass curtain, offering lightning on the first floor, but protected from the sun by external photo-voltaic shading lamellae. Also, the angle and the orientation of the roof allow the disposition of the solar PV panels on the roof.

Figure 3. 3D render of the proposed model

4.2. Façade systems configuration

Table 3 shows the considered values for the different envelope configurations. The first system (MW_100) uses 100 mm mineral wool insulation which leads to an overall thermal resistance of the component of 2,65 m²K/W, which is almost double than the minimal value according to the Romanian norms [14]. The second system (PET_150) uses an alternative material from recycled plastic bottles with a thickness of 150 mm. This has similar U-value to the mineral wool option.

Table 3. Façade systems key values

Component	d [mm]	R [m²K/W]	U [m²K/W]
Walls v1_ MW_100	100	2.65	0.38
Walls v2_PET_150	150	2.93	0.34
Bottom slab	296	4.84	0.21
Middle slab	248	3.22	0.31
Roof	200	5.19	0.19
Openings	-	1.38	0.72

4.3. Energy evaluation results

The energy evaluation was carried out using Graphisoft Archicad 21, Energy Evaluation add-on [15]. A single thermal block using 3D zone-tool was defined for the whole model (Figure 4). In order to test the different envelope configuration, composite structures by materials were created for each component.

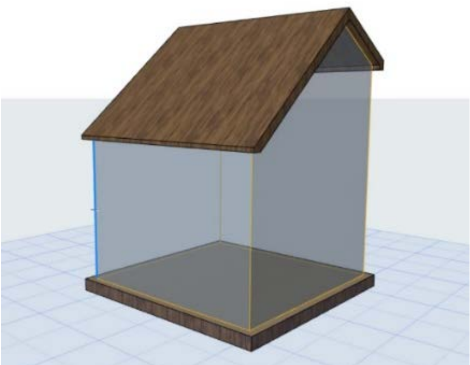

Figure 4. 3D thermal block view of the analyzed volume

In addition to the envelope values presented in Table 3, the following data were considered for the simulation scenario:

- Treated floor area: 23,04 m²
- Ventilated volume: 118,41 m³
- Air-conditioning system capacity: 12000 BTU
- Heating: two 2500 electric space heaters
- Light sources: LEDs
- PV panels: twelve 250W polycrystalline cell panels

Table 4 presents the evaluation results for a full-year considering the above mentioned parameters. The evaluation treated the study taking into account a total of 10% glazing ratio. Results show that the building performance is good, MW_100 and PET_150 presenting similar values, of 616 kWh/y and respectively 662,8 kWh/y on the same glazing ratio. The amount of solar energy produced on site is around 1269 kWh with a potential production under ideal conditions of 3427,29 kWh.

Table 4. Simulation results

Façade system	Lighting and equipment [kWh/a]	Solar gain [kWh/a]	Heating [kWh/a]	Cooling [kWh/a]	On-site energy PV energy generation [kWh]
MW_100	694.6	3528	662.8	2230.4	1269
PET_150	694.6	3528	616	2244.6	1269

4.4. Life cycle analysis

For the evaluation of the environmental impact, the LCA method follows the rules of EN 15804 [11], ISO 14044 [10] and EN 15978 [12]. The building assessment includes the following life cycle stages: 'Production stage' (with modules: A1 - raw materials extraction, A2 – transportation to the manufacturer, A3 – materials production), 'Construction stage' (A4 – transportation to the construction site, A5 - building construction), 'Use stage' (B6 - operational energy use), 'End-of-life stage' (with modules: C1 – deconstruction/demolition, C2 - transport to waste processing, C3 – waste processing for reuse, recovery and/or recycling, C4 - disposal) including all transport, storing and related energy use [11]. In the assessment, the GWP was calculated using GaBi Product Sustainability Software [13] and for recycled-PET thermal wadding, the information about modules A1-A3 was based on Environmental Product Declarations (EPD's) by Freudenberg Performance Materials Group [8] and Technical Approval for wadding mattresses for thermal and phonic insulation [9].

4.4.1. System boundary conditions. The following data were considered for the LCA scenarios:

- the assessment was carried out considering the following building components: foundation (6.24 m^3), lightweight steel load bearing structure, cold-formed studs, envelope (interior and exterior steel sheet with a core of insulation material – mineral wool or recycled-PET thermal wadding), triple glazed windows, PVC door;
- in the construction stage, the assessment included all the transportation of construction materials from the manufacturer to the building site, equipment transportation, workers transportation and the building of the structure;
- the operational lifetime of the building considered was 25 years;
- due to the relatively short lifetime of the building no maintenance, refurbishment, repair or any elements replacements were considered.

4.4.2. End-of-life. The end-of-life scenario for the case study (table 5) was managed regarding currently available data [16], [17] and reports [18] about the recycle/reuse amount of materials in the construction sector.

Table 5. End-of-life scenarios for construction materials used in the case study

Construction materials	Recycling [%]	Landfill [%]	Incineration [%]
Hot rolled steel (braces, connections)	93	7	-
Cold-formed steel sections	93	7	-
Steel sheets	89	11	-
Steel rebars	85	15	-
Concrete	-	100	-
Mineral wool	-	100	-
Recycled-PET thermal wadding	100	-	-
Extruded polystyrene	-	-	100
OSB	-	-	100
Windows and doors	98.65	1.35	-

4.5. Life cycle assessment results

According to the results, there is a minor difference between the environmental impacts of studied cases, the highest environmental impact being given by the case when the thermal insulation is executed using mineral wool. The difference in total CO_2 equivalent of the cases occurred in the production stage and in the use stage, where the energetic efficiency of the thermal insulation wadding ensured a slight benefit to the PET_150 studied case. Table 6 presents the LCA results for each stage of the assessed scenarios:

Table 6. LCA results of the scenarios

Scenario	MW_100 [t CO_2 e]	PET_150 [t CO_2 e]
Lifecycle impacts (A-C)	**60,00**	**58,62**
- Production stage (A1-3)	16,78	16,28
- Construction stage (A4-5)	1,55	1,55
- Use stage (B6)	36,04	35,17
- Demolition stage (C1-2)	5,62	5,62

5. Impact of glazing ratio on thermal performances

In addition to previous scenarios, different glazing ratios (6% and 10%) for the building envelope have been tested for a more detailed energy balance simulation and to find the related influence upon the environment.

Table 7. Energy evaluation results for 10% and 6% glazing ratio

Façade system	Glazing ratio [%]	Lighting and equipment [kWh/a]	Solar gain [kWh/a]	Heating [kWh/a]	Cooling [kWh/a]	On-site energy PV energy generation [kWh]
MW100	10	694.6	3528	662.8	2230.4	1269
MW100	6	694.6	2275	894.5	1571.4	1269
PET150	10	694.6	3528	616	2244.6	1269
PET150	6	694.6	2275	841.3	1574.1	1269

The results offered in table 7 demonstrate that by reducing the overall glazing ration of the envelope, the solar gain drops as well significantly, which leads also to increased heating energy demands, in order to meet indoor thermal comfort as the solar gain has a direct influence on the indoor air temperature.

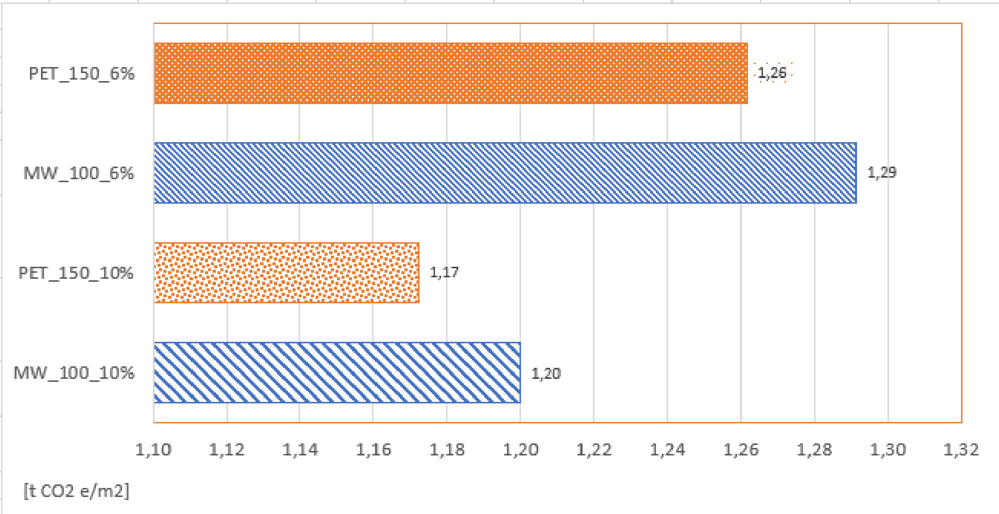

Figure 5. Life cycle impacts (stages A-C) / m^2 [t CO_2 e / m^2]

In terms of environmental impact, a decrease in glazing ratio and a smaller solar gain for the building contributed to an increase to the GWP 100 (Global Warming Potential over 100 years) of each case scenario. The comparative study shows (figure 5) that the life cycle impacts record an expansion of emissions between 7.3% (for the case study in which is used mineral wool) and 7.5% (for the case study in which is used recycled-PET thermal wadding).

6. Conclusions

In this paper, a comparative study between envelope solutions existing on the market for buildings made of thin-walled cold-formed steel structural systems was accomplished. The envelope solutions were based on recycled-PET thermal wadding or on a mineral wool. The energy and environmental benefits associated with the use of the two envelope solutions have been evaluated with a life cycle approach.

The results show that using thermal insulating wadding obtained from post-consumer PET bottles in a building envelope does not involve a significant reduction of the environmental impact when compared to the envelope solutions based on mineral wool with similar thermal insulation function. The environmental impact of the recycled-PET thermal wadding is higher than the environmental impact of the mineral wool thermal insulation in the production stage (kg CO2 eq/kg) but, the insulation quantity of the material needed for PET-recycled thermal wadding to accomplish the required thermal resistance is notable smaller than that of mineral wool.

When considering the entire life cycle of a building with the compared thermal insulations having nearly the same U-value, the environmental impact of the recycled-PET thermal wadding-based system is slightly smaller than that of MW-based system (1.17 t CO_2 eq / m^2 vs. 1.20 t CO_2 eq / m^2). However, an important influence in the results balance would develop when the recycled-PET thermal wadding is used for envelopes with considerable surface area (larger than those of the residential buildings), where the small difference between the benefits of the two thermal insulating solutions would grow directly proportional.

Additionally, the recycled-PET thermal wadding is 100% suitable for recycling at the end-of-life, without losing its physical features over time, which helps the circularity of the material. Furthermore, the recycled-PET thermal wadding is obtained without using any chemical or other textile agents, which earns the benefit of limiting the harmful substances for human beings and the natural environment.

The study also proves that the glazing ratio has also an impact on the thermal performances of studied systems: for the climatic conditions defined in the study case, the results showed that by reducing the glazing ratio of the envelope, the solar gain drops accordingly, which leads to an increased heating energy demand and to an increased environmental impact.

The energy efficiency and the LCA calculations are recommended to be carried out on a case-by-case basis, as the performances of the buildings' components depend on climate and on the type of use of the building.

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