

Carbon footprint of thermal insulation materials in building envelopes

Roman Kunič 

Received: 25 March 2015 / Accepted: 25 May 2017 / Published online: 17 June 2017
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Abstract With increasing world population and economic development, the strain on resources is increasing. Energy consumption during construction and use of building is enormous. In this study, a quantitative comparison of various thermal insulation materials used in construction, from most commonly used to new, highly efficient insulation materials, was performed. It was demonstrated that the evaluation and consideration of environmental impact per unit weight of thermal insulation materials are inappropriate and can lead to misleading decisions, since it is imperative that the analysis considers the difference in the density of each thermal insulation material, as well as differences in their thermal conductivity. Furthermore, the environmental neutrality, i.e. the time needed to offset the carbon footprint of the manufacturing and the installation of thermal insulation materials in the building envelope with the difference between the carbon footprint of the heat losses in the heating season through a currently averagely insulated external envelope and a well-insulated external envelope, is achieved in very short-time periods. For the thermal insulation materials with the lowest environmental impact, it is reached in less than one heating season and soon after tenth heating seasons for the insulation with the highest environmental impact.

Keywords Building envelope · Carbon footprint · Global warming potential (GWP) · Thermal insulation · Sustainable construction

Abbreviations

CFC	Chloro-fluoro-hydrocarbons
EPS	Expanded polystyrene
GWP	Global warming potential
LCA	Life cycle assessment/analysis
LCCA	Life cycle cost assessment
LCI	Life cycle inventory
PU	Polyurethane
VIP	Vacuum insulation panel
XPS	Extruded polystyrene
CO ₂ -eq	CO ₂ equivalent
U	Thermal transmittance W/(m ² K)
AHDD	Annual heating degree days K day = 86,400 K sec
R	Thermal resistance (m ² K)/W
ρ	Density kg/m ³
λ	Thermal conductivity W/(m K)

Introduction

The impact of society on the environment is becoming more and more intense. The consumption of resources is getting beyond the absorption capacity of the environment. The world economy has since the beginning of the industrial revolution until

R. Kunič (✉)
Faculty of Civil and Geodetic Engineering, University of
Ljubljana, Jamova 2, SI-1000 Ljubljana, Slovenia
e-mail: roman.kunic@fgg.uni-lj.si

now relied on the exploitation of relatively cheap energy, raw materials and other resources.

Providing thermal comfort in buildings during heating (i.e. winter) and cooling (i.e. summer) seasons demands great attention, because environmental temperature is one of the most critical factors determining human comfort (EPBDr 2010). Thus, the main purpose of thermal insulation is to retard heat flow and thereby ultimately diminish the degree of discomfort experienced by the building occupants, or the size of heating or cooling plant and the consumption of fuel required to mitigate this discomfort (Pohl 2011).

Following the results of the analysis by (Anastaselos et al. 2017), the implementation of external insulation with the use of EPS as thermal insulation material for the external walls and floors (as part of an external thermal insulation composite system), together with the use of XPS in a flat roof construction, as part of an inverted roof technique, was found to be the optimum. Providing thermal comfort in buildings strongly depends on multiple factors, such as mode of operation (i.e. manual or automatic) and user behaviour (Hudobivnik et al. 2016). In this study, the authors emphasized the importance of ventilation regime and its impact on the thermal response of the building envelope. The results show that differences in heavy and lightweight constructions cannot be neglected and should be considered, and thermal performance of low weight construction enhancements are highly appreciated. Similar conclusions were also arrived at by other authors (Stazi et al. 2015; Stazi et al. 2016) on an example of a residential building situated in central Italy.

According to studies (Špegelj et al., 2016), the glazing size in the south facade thus provides to have a substantial impact on the energy efficiency of the building, which has direct impact on energy consumption during heating and cooling period. Beside recommendation to have south-facing windows, enlarged to optimum size, are other authors (Korjenic and Klarić, 2011) suggesting a need to pay attention to the optimisation of the thermal quality of exterior elements. Furthermore, Stazi with co-authors (Stazi et al. 2014), confirmed that the effect of the mass is more appreciable for hot and dry periods (summer and intermediate seasons) and for hot climates rather than for the winter or for cold ones together with passive cooling techniques.

Construction sector presents at least 10% of the gross national income in most countries. Additionally, buildings in their lifetime globally consume 40% of material

and energy, and produce as much waste (Kunič 2007). In the life cycle of buildings globally, most of energy, 90%, is spent during their operational phase (Citherlet and Defaux 2007; Newsham et al. 2009), while in Europe this share accounts to 42% (Nelson et al. 2002). Therefore, a greater emphasis has to be given to the conservation of non-renewable energy sources and reduction of the consumption of raw materials and other resources, in concert with the recycling and waste management at the end of the life cycle of a building (Košir et al. 2010).

To achieve sustainability, society has to strive towards: minimizing the consumption of matter and energy; reusability and recyclability of the material; human satisfaction; and minimum environmental impacts and embodied energy. It is important to minimize our consumption, because when a material is consumed, its chances for future use are diminished and their potential utility to future generation is lost (Roberts 1994; Pearce et al. 1995). The aim is to design healthy and comfortable indoor environment with the lowest possible energy use and not the opposite; the lowest energy use based on the physiological minimum (Dovjak et al. 2012).

Investment costs of thick thermal insulation layers are higher, but the operating costs are significantly lower, even to the extent that highly insulated building is cost-effective throughout its life cycle (Kunič and Krainer 2009). As it does not require any additional changes in the construction project, using the thicker insulation is by far the most important and most (cost) effective investment leading to energy savings (Kunič and Krainer 2010; Vattenfall 2015).

Insulation in the building thermal envelope can be made of a variety of insulating materials, which differ in their chemical composition (organic and inorganic), their origin (derived from new raw materials, partially or totally recycled), their specific weights (minimum 12 kg/m^3 up to approximately 600 kg/m^3), their thermal conductivity (λ ranges from less than $3 \text{ mW}/(\text{m K})$ to over $45 \text{ mW}/(\text{m K})$) and in the resistance to physical (moisture, elevated temperature, presence of UV radiation, pressure, shear, laminated and other strength) and chemical factors (the presence of organic solvents, moisture, oxidation, reaction to fire, ...).

The aim of this study was to perform a quantitative comparison of various thermal insulation materials used in constructions, from most commonly used to new, highly efficient materials, by calculating their carbon footprint equivalent, which is the most significant

environmental indicator. The carbon footprint of various (15 in total) insulation materials was calculated. The obtained values were compared to the actual effect of the respective thermal insulation. The transparency of the comparison was achieved by taking into account the specific weight of each material, as well as differences in their thermal conductivity (λ). Moreover, a study of environmental neutrality of different types of insulation materials was carried out. The environmental neutrality was defined as the time (measured in heating seasons) required to compensate the environmental impact of the production and installation of the selected insulation with the difference between the carbon footprint of the heat losses in the heating season through a currently averagely insulated external envelope and a well-insulated external envelope ($U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$) of an average building. Heating season means winter time with daily average temperatures below $12 \text{ }^\circ\text{C}$, which represents 230 days for Ljubljana, Slovenia, a Central European city (N $46^\circ05'$ E $14^\circ51'$) with typical continental climate and slight influence of northern Mediterranean climate due to the relative proximity of the Adriatic Sea. The climate is described as warm temperate, which means 'Cfb' type according to Köppen-Geiger climatic classification (Kottek et al., 2016) and '5A' type according to ASHRAE standards (ASHRAE 90.1 2004; ASHRAE 90.2 2004). It is characterised by cold winters and warm summers with high values of precipitation. The coldest month of the year is January with the average daily temperature of $-1.2 \text{ }^\circ\text{C}$ and minimum values reaching $-21.0 \text{ }^\circ\text{C}$. The warmest month is July with the average daily temperature of $20.4 \text{ }^\circ\text{C}$ and maximum temperature of $33.4 \text{ }^\circ\text{C}$ (Energy Plus 2016).

Environmental impact assessments

As solutions are sought to reduce the environmental impacts of buildings, life cycle assessment (LCA) is seen as an objective measure for comparing building designs. LCA is a rational, quantified approach to determining specific environmental impacts of a product or system through its entire life cycle. LCA clearly has an important role to play in assessing the sustainability of buildings.

Studies found LCA to have started in the 1960s (Hunt et al. 1992). However, it gained prominence in the 1990s (Bribian et al. 2011). The most common, e.g.

IPCC Greenhouse gas emissions, Ecopoints 97, and Eco-indicator 99 (PRé Consultants, 2010), are focused on the following indicators: acidification, eutrophication, ozone depletion, various types of ecotoxicity, air contaminations, usage of resources and greenhouse gas emissions. Carbon footprint is expressed in terms of the amount of emitted carbon dioxide or its equivalent of other greenhouse gases. Emissions are assessed based on the most important greenhouse gas— CO_2 , which serves as the base. Carbon footprint is the total greenhouse gas emissions, which are directly or indirectly caused by an organization, product, service, or other activity that causes or contributes to greenhouse gas emissions in a given period of time. It is defined in units of CO_2 equivalent ($\text{CO}_2\text{-eq.}$) and was, because of clarity, the only indicator used in this analysis. In carbon footprint calculations, in addition to CO_2 , other greenhouse gases (methane (CH_4), nitrous oxide (N_2O) and chlorofluoro-hydrocarbons (CFC), etc.) are included. These gases are by far more powerful greenhouse gases than CO_2 , but are generally produced in significantly lower amounts.

A comprehensive review on aerogels (Cuce et al. 2014) confirmed its promising thermal insulation and other superior features, among them low embodied energy per specific U value and possibility of future predictions of decreasing material price. The environmental, energy and economic LCAs from cradle-to-cradle in accordance with the latest European Standards (EN 15804 2012) for external walls with variable thicknesses of different insulations were conducted (Silvestre et al. 2013). The LCA study (Dylewski and Adamczyk, 2014) of various thermal insulation materials took into account different thermal conductivity (λ) and density (ρ) values. Results were expressed also as annual environmental load per inhabitant in Europe, by underlining that thermal insulation of external building walls has great ecological efficiency (the ratio of ecological benefits to economic cost).

The overall environmental impact caused by the co-utilisation of waste wood with coal was evaluated by using LCA as established by Society of Environmental Toxicology and Chemistry (SETAC 1991). This provides opportunities to evaluate direct environmental impact, to identify possible improvements and to reduce energy resource consumption. Thus, the environmental impact of co-utilising lignite and waste wood in an industrial steam boiler was evaluated. The results obtained by researchers (Skodras et al. 2014) show that co-

utilisation is technically feasible and can meet strict environmental standards. A net decrease of CO₂ emissions can be achieved by the thermal use of waste wood, as well as conservation of fossil fuel resources, minimisation of waste disposal and reduction of impacts on health. The results obtained from the study of Adan and Fuerst (Adan and Fuerst, 2016), who used the difference-in-difference analysis method, confirm that the observed energy consumption decreases significantly in dwellings subjected to upgrades such as cavity wall insulation, loft insulation and a new efficient boiler. The single most effective energy efficiency measure when installed alone was found to be cavity wall insulation, reducing annual gas consumption by 10.5% and annual total energy consumption by 8.0% in the year following the installation. Comparing bundles of different energy efficiency measures, it was found out that dwellings retrofitted with both cavity wall insulation and a new efficient boiler experience the largest reductions in annual gas and total energy consumptions of 13.3 and 13.5%, respectively. This is followed by a mean annual reduction of 11.9 and 10.5% in gas and total energy consumptions, respectively, for dwellings with all three energy efficiency measures installed in the same year. Contrary to expectations, installing cavity wall insulation on its own was found to be more effective in reducing measured energy consumption than combining loft insulation with a new efficient boiler.

In order to reduce the energy demand, improvements in the building envelope have been studied (Navarro et al. 2015) based on different aspects, such as thermal insulation, thermal inertia and combining both of them. They analysed the thermal performance of different constructive systems, and a similar methodology was used to consider internal heat loads by simulating scenarios with occupancy. This paper strives to analyse the thermal performance of an insulated constructive system and another one with phase change materials (PCMs) located in the envelopes as passive cooling system. The experiments were done during the summer period. The results of the experimental campaign show that the insulation effect when internal gains are involved is harmful, because heat loads cannot be easily dissipated to outdoors without increasing the energy consumption. Moreover, when adding PCM to an insulated constructive system, this effect is maximised because the PCM stores the heat produced by the inner loads and the external conditions; hence, the heat dissipation to the outer environment is limited.

Nowadays, the focus on building energy consumption in the use phase prevails over the interest concerning the energy impacts linked to all the other phases of the construction process. However, the reduction of operational energy could lead to shift in the impacts from one stage to another. Thus, a study (Paganin et al. 2017) was conducted that compared strategies to improve energy efficiency in the use phase with a life cycle approach. Exhibition halls are peculiar buildings from the geometry, construction and use points of view, and rarely addressed in energy and life cycle energy analysis studies. Therefore, a representative hall of the Milan Trade Fair, used as a building energy simulation model, was taken into account. The operational energy appears artificially low due to the short-use period during the year. When compared with the calculated embodied energy of the envelope and structure, it is found that 57 years would be needed to balance energy spent in the construction and in the use phase. Further on, some retrofit interventions are proposed and analysed. Insulation interventions are not attractive from the aspect of economic payback time. However, when the embodied energy of the retrofit interventions is compared with the energy savings in the use phase, interesting energy payback times are obtained.

In the Netherlands, the CO₂ performance has been introduced as an energy management programme to facilitate continuous energy efficiency and carbon performance improvement in non-industrial sectors. The research (Rietbergen et al. 2017) was based on descriptive analysis of energy efficiency and CO₂ emission reduction measures and quantitative analysis of CO₂ emission reductions. The research results indicate that the CO₂ performance has improved various energy management practices at the administrative level, while the internalisation of energy management practices at lower levels in the organisation has just gradually started. The annual CO₂ emission reduction rate due to energy efficiency improvement and fuel switching amounted to 3.2%/per year (2010–2013). However, the first estimates suggest that about 1.0–1.6% of these CO₂ emission reductions per year can be attributed to the CO₂ performance.

In Spain, there is a regulated procedure to certify the energy performance of buildings according to their CO₂ emissions. Consequently, some software tools have been designed to simulate buildings and to obtain their energy consumption and CO₂ emissions. In a study

conducted by Ruá and Guadalajara (Ruá and Guadalajara, 2015), investment, maintenance and energy consumption costs were calculated for different energy performance levels and for various climatic zones in a single-family home in Spain. According to the results, for buildings to be more energy efficient, higher construction and maintenance costs are required, which are not compensated by lower energy costs. Therefore, under current conditions, economic criteria do not support the improvement of a dwelling's energy efficiency. Among the possible measures to promote energy efficiency, the price for CO₂ emissions is suggested in the analysis, including the social cost. For this purpose, the cost-optimal methodology is used. In different scenarios for the discount rate and energy prices, various prices for CO₂ are obtained, depending on climatic zone and energy performance level. Lakraflí with co-researchers (Lakraflí et al. 2017) have investigated the effect of the thermal insulation by leather wastes (wet-blue chrome shavings and buffing dust) and carpentry wastes (wood shavings and sawdust) on the energy consumption of a model building using the average climatic data of the city of Casablanca (Morocco), by evaluating the effect of the above material wastes on thermal comfort and building energy consumption. The type and the thickness of the materials were considered for the purpose of better indoor conditions. The average temperatures of buildings supposed to be thermally insulated compared to those obtained without insulation clearly show the thermal insulation ability of the tested materials during the cold and warm periods of the year. Increasing the thickness of the insulator makes indoor environment increasingly comfortable. Because of their performance, leather and carpentry wastes can compete with conventional insulating materials, such as polystyrene and cork. Study of environmentally friendly materials that are mostly considered as waste (Dikmen and Ozkan, 2016) confirmed that the thermal conductivity value of each analysed material could be considered as comparable to that of conventional and popular thermal insulation materials being used by the construction industry worldwide. Thus, there are many benefits, such as: Firstly, producing natural materials does not harm the environment in the way toxic materials used to produce conventional insulation boards do. Secondly, when these materials are put back into the production cycle as raw material, instead of treating them as waste to be disposed of by burning, the embodied carbon and nitrogen are prevented from being released into the

environment as harmful gases and ashes. Thirdly, using these natural materials does not pose any threats to human or environmental health. And finally, the embodied energy and life cycle costs of natural materials are considerably lower than those of toxic and environmentally harmful conventional insulation materials.

The LCA methodology involves four steps (ISO 14040 2006; PAS 2011). The goal and scope definition step spells out the purpose of the study and its breadth and depth. The second step of the LCA methodology is called life cycle inventory (LCI), where the environmental inputs and outputs associated with a product over its entire life cycle, are quantified. Inventory analysis entails quantifying the inventory flows for a product system. Inventory flows include inputs of water, energy and raw materials, and releases to air, land and water.

For buildings, the life cycle generally starts with the extraction of raw resources from the natural environment or recovery of materials from a previous use. The raw resources are then manufactured into useable products, such as steel, concrete, etc. The finished products are then shipped to the site, consuming energy in the process. On the site, the products are assembled into a building. During the service life of the building, it consumes energy. Finally, the building is removed/demolished and its materials disposed of either as construction waste or recycled for reuse. Each of these steps consumes energy and materials, and produces waste. The purpose of the LCA is to quantify how a building product or system affects the environment during each phase of its life (Berry et al. 2014).

Materials and methods

Thermal insulation materials

In recent years, analyses concerning thermal insulation and its economic and environmental influence on constructions, have expanded. An author of one such works, Bjørn Petter Jelle (Jelle 2011), stated to have investigated both state-of-the-art and possible materials and solutions beyond those, compared and studied various properties, requirements and possibilities, such as: thermal conductivity, perforation vulnerability, building site adaptability and cutability, mechanical strength, fire protection, fume emission during fire, robustness, climate ageing durability, resistance towards freezing/thawing cycles, water resistance, costs and environmental impact. He also

emphasized that there exists no single insulation material or solution capable of fulfilling all the requirements with respect to the most crucial properties—not one material is superior in all respects. Promising future thermal insulation materials could be nano insulation materials, dynamic insulation materials and load-bearing insulation materials, or even some material or solution hitherto not yet thought of.

The study presented in this paper focused on 15 most often used thermal insulation materials: EPS, ‘grey’ reflective EPS (with infra-red reflector additives), XPS, PU—polyurethane, low-density glass wool, high density glass wool, rock wool of two different densities, wood wool of two different densities, recycled cellulose, cork, foamed glass, aerogel, and VIP (a vacuum insulated panel

VIP—is a form of thermal insulation board consisting of a nearly gas- and moisture-tight enclosure (multilayer foil) surrounding a rigid core, from which the air has been evacuated—around 10^{-3} of normal air pressure). The materials for building thermal insulation differ in density (16 to 380 kg/m³, relation 1: 24) and thermal conductivity (6 to 90 mW/(m K), relation 1: 15), as is shown in Table 1 and graphically presented in Fig. 1 a and b. Detailed description (chemical and physical composition) of the listed insulation materials is available in technical documentation of the materials’ manufacturers and various literature sources (Pfundstein et al. 2008). For all further calculations only most commonly used densities as well as most commonly used thermal conductivities for thermal insulations for building envelopes were taken into account.

Review of reports given in promotional documents of insulation materials showed that the biggest difference is in citing the environmental impact per unit weight (according to standard (EN 15804 2013) this represents the declared unit) of the product ‘per se’, which means that this comparison does not take into account the differences in specific weights, or different values of thermal conductivity (λ). For all further analyses, square meter (m²) was of outside thermal envelope construction taken into account as a functional unit (to be in accordance to standard (EN 15804 2013)). Similar to our assumptions, (Vilches et al. 2016) concluded that 1 m² of area as a functional unit enables comparison between different studies. On the other hand, when the entire building is used as functional unit, the results can only be used for the development of one single building.

Thermal conductivity (λ) and density (ρ) of thermal insulation materials are not always directly related. By rising the density of thermal insulation material firstly, the thermal conductivity is lowered (better insulation), but above certain density value (above densities used for constructions without additional loads to thermal insulation) the conductivity rises, and at the same time the thermal insulation property falls. All high density thermal insulation materials analysed in our calculations are used primarily under high static load (in flat roofs, terraces, as a layers in floating floors, in contact compact facades, etc.), and thus have higher thermal conductivity in comparison to thermal insulations with low densities.

Carbon footprint calculations

Following the common LCA methodology (ISO 14040 2006; PAS 2011), the scope and goal of the study was to compare the environmental impact of selected thermal insulation materials. Environmental impact was analysed with the ‘cradle-to-gate’ variant, an assessment of a partial product life cycle from manufacturing (‘cradle’) to the factory ‘gate’ (i.e., before it is transported to the consumer). The aim of this study is beside others also to mutually present and compare different thermal insulations with the exclusion of regional or other specific influences as much as possible. Thus, the ‘cradle-to-gate’ method was implemented. The use phase and the disposal phase of the product were omitted because of lack of reliable data. Available data concerning life time and end of life are not reliable enough, especially in case of different use of thermal insulation in various constructions, where for the same thermal insulation material in construction practice different life times could be expected (Buyle et al., 2013). We could easily expect much lower life time for flat roof systems, facades and terraces, and probably also for non-massive buildings. Much more reliable data are available for whole buildings and some separate typical constructions. The calculations included emissions caused by the installation, but did not include the possible emissions caused during the service life of a building, its operational phase. Since the analysed insulation materials might differ in service life, the results of the analysis that would account for service life of insulation materials might be different. However, reliable data of service life of analysed insulation materials were not available and were therefore not included in the calculations.

Table 1 Density, thermal conductivity and required thickness of different thermal insulation materials to obtain thermal transmittance $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$; the data are compiled from (critical overview of) thermal insulation found in producer's documentations, from years of experience in construction practice and from various literature, such as (Pfundstein et al. 2008; Aste et al. 2009; Jelle 2011; Moran et al. 2017)

	Density		Thermal conductivity		Required thickness of thermal insulation for thermal transmittance (U value) of $0.20 \text{ W}/(\text{m}^2 \text{ K})$, for most commonly used densities and thermal conductivities of thermal insulations
	(ρ)		(λ)		
	From	To	From	To	
	kg/m ³	kg/m ³	mW/(m K)	mW/(m K)	cm
EPS	10	30	34	45	17.5
EPS with reflective additives	12	28	30	35	15.2
XPS	28	45	31	44	18.0
PU polyurethane	28	100	22	30	11.8
Glass wool–low density	15	40	34	40	17.0
Glass wool–high density	40	150	30	45	18.0
Rock wool–low density	20	120	33	42	18.9
Rock wool–high density	120	200	35	48	21.3
Wood fibre wool–low density	50	270	38	60	23.7
Wood fibre wool–high density	350	600	75	110	42.6
Cellulose–recycled	30	80	40	50	20.8
Cork	100	220	45	70	23.7
Foam glass	90	200	38	80	28.4
Aerogel	60	160	13	24	8.0
VIP	150	300	3	11	2.8

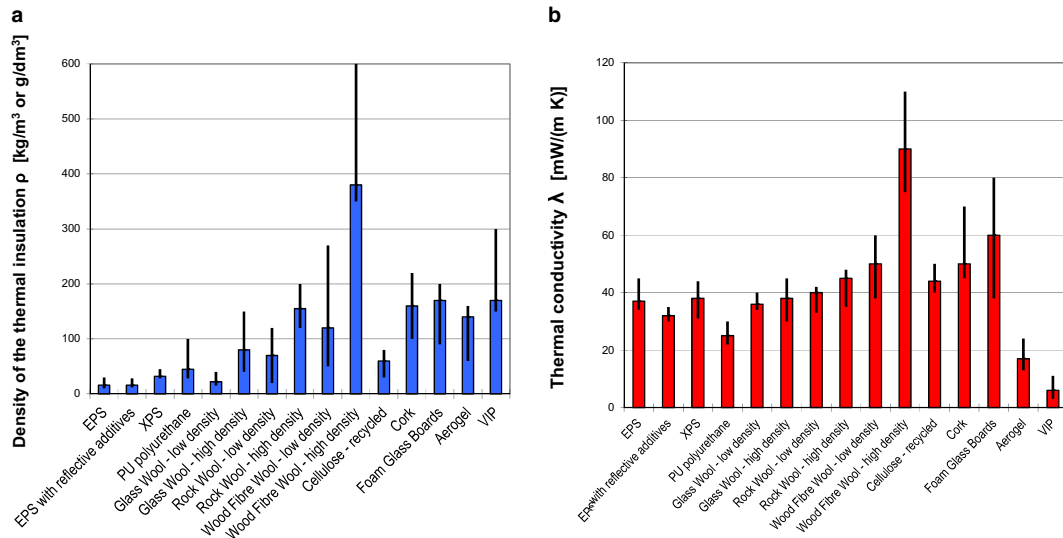


Fig. 1 a, b density ρ (kg/m³ or g/dm³) (a or left graph), and thermal conductivity λ (mW/(m K)) (b or right graph), of the different thermal insulations. Blue and red bars represent average most commonly used thermal insulations for building purpose,

whereas black lines (error bars) represent variations of densities or thermal conductivities of different types of insulation materials used for other purposes (i.e. industry or other technical use)

The environmental burdens associated with each insulation material were considered from raw material acquisition, through the manufacturing/processing stages, accounting for the production and use of fuels. Electricity and heat, as well as taking into account transportation/distribution impacts at all points along the product supply chain. Declared unit, according to (EN 15804 2013), for the calculation was determined to be 1 kg of the specific thermal insulating material. Based on the determined goal and scope of the study, the life cycle inventory of input/output data for the LCA calculations was compiled. Data of energy inputs, raw materials, products, co-products, waste, and releases to air, water and soil and the upstream life cycle impacts of input materials were not analysed specifically for this project. Instead, sound secondary life cycle data were sourced from Ecoinvent database 3.1 (Ecoinvent 2014). Table 2 shows a list of data that were used in carbon footprint calculations. The data collected were modelled in Simapro software environment (SimaPro Analyst Indefinite v7.1, Ecoinvent database, Product Ecology Consultants—PEC, the Netherlands) (Simapro v7.1 2009; Ecoinvent 2014). Emissions and consumptions were translated into environmental effects, which were grouped and weighed. Carbon footprint was calculated with methodology IPCC 2013 GWP 100a V1.02 (Climate Change 2013), which contains the climate change factors of IPCC with a timeframe of 100 years.

Emissions, appearing in the future, 100 years after the start of the process, were taken into account. IPCC characterization factors for the direct (except CH₄) global warming potential of air emissions were used. They do not include indirect formation of dinitrogen monoxide from nitrogen emissions, do not account for radiative forcing due to emissions of NO_x, water, sulphate, etc., in the lower stratosphere as well as upper troposphere, do not consider the range of indirect effects given by IPCC (Climate Change 2013), and do not include indirect effects of CO emissions.

Carbon footprints of different insulating materials were calculated by taking into account the thickness of the thermal insulation that is required for fulfilling the condition of the heat transfer (U value) 0.20 W/(m² K). Additionally, carbon footprint of thermal insulation materials was compared with that of other building materials. The comparison was performed between the environmental impacts caused by the insulation of the entire exterior building envelope (the average equivalent area of 400 m²) with the impact on the environment of other building materials (reinforced concrete, fired clay bricks, flat window glass, PVC, stainless steel and aluminium elements) (Zabalza et al. 2009). Some authors, among them (Melo, de C. A., Jannuzzi G.M., 2015), have analysed pay back through energy savings of CO₂ emissions reduction caused by higher energy efficiency in the building sector.

Table 2 List of qualitative data for the calculation of the carbon footprint

	Input data
Mass balance of the materials used	<ul style="list-style-type: none"> •Weight of the finished product •Weight of each of the materials used in the product •Source of individual materials •Weight of waste material
Energy	<ul style="list-style-type: none"> •Electricity consumption per product •Consumption of fuel (diesel, heating oil, gasoline, wood, etc.) per product
Water	<ul style="list-style-type: none"> •Water consumption per product (drinking water and process water) •The amount of waste water in the product and handling •Emissions of pollutants in water (type and quantity) per product
Other waste and emissions	<ul style="list-style-type: none"> •Emissions of pollutants into the air (type and quantity of pollutants) per product •Other waste materials associated with the production processes, e.g. filters, ash, etc.
Type of transport	<ul style="list-style-type: none"> •Type of transport vehicles for the transport of materials •Distances •The proportion of unused (empty) vehicles and the proportion of unused return travel
Packaging	<ul style="list-style-type: none"> •Packaging weight and type of material for the protection and packaging

The research presented in this paper was focused on the evaluation of the environmental impacts of insulation in the external envelope of the building. With the aim to perform transparent comparison; only the environmental impact of the insulation was considered and the environmental impact of all the other elements, such as bearing wall, protective construction, fasteners, adhesives, finishes and plasters, was neglected. As a justification, it has to be noted that the majority of the selected systems of facades, walls and roofs use very similar methods of attachment and composition, irrespective of the type of heat-insulating material. The results of the evaluation are therefore applicable to any construction complex in the external building envelope (outer wall, flat or pitched roofs, floors on the ground, etc.).

Heat losses through external building envelope

Heat losses of the building occur through outer walls, ceilings, floors, thermal bridges, other conduction thermal transfer, radiation and ventilation (natural or forced). Calculation procedures followed the standard (EN ISO 13790 2008), but only conductive thermal losses through external building envelope during heating (winter) season were taken into account (i.e. without summer cooling).

The total thermal transmittance (EN ISO 6946 2008) of the external building envelope can be expressed as:

$$U_{BE} = [R_i + R_{BEtot} + R_{INS} + R_e]^{-1} \quad (1)$$

U_{BE}	thermal transmittance of external building envelope	W/(m ² K)
R_i	thermal resistance of inner air (convection)	(m ² K)/W
R_{BEtot}	total thermal resistance of bearing construction (concrete and plaster)	(m ² K)/W
R_{INS}	thermal resistance of thermal insulation	(m ² K)/W
R_e	thermal resistance of external air (convection)	(m ² K)/W

Thermal resistance of thermal insulation layer:

$$R_{INS} = d_{INS}/\lambda_{INS} \quad (2)$$

d_{INS}	thermal insulation thickness	m
λ_{INS}	thermal conductivity of insulation	W/(m K)

Construction supporting the model external envelopes was assumed to be made of the highest conductivity and lower thickness, so reinforced concrete wall (thermal conductivity of 2.04 W/(m K)) with a thickness of 15 cm, which was on one-side plastered with a 2-cm thick cement-lime plaster (thermal conductivity of 0.85 W/(m K)) that was taken into account. Values of

thermal resistance for inner (R_i) and outer (R_e) air were taken as $0.125 \text{ (m}^2 \text{ K)/W}$ and $0.043 \text{ (m}^2 \text{ K)/W}$, respectively.

Heat losses through external wall could be determined as:

$$q_{BE} = U_{BE} \cdot \Delta T \quad (3)$$

q_{BE}	heat losses through unit area of external building envelope	W/m^2
ΔT	Thermal difference	K

Specific annual energy requirement for heat losses through external building envelope, neglecting heat efficiency of inner space heating system, is calculated by:

$$E_{BE a} = AHDD \cdot U_{BE} \quad (4)$$

$E_{BE a}$	specific annual energy requirements for heat losses through external building envelope	$\text{J/(m}^2 \text{ year)}$
$AHDD$	annual heating degree days	$\text{K} \cdot \text{day} = 86,400 \text{ K} \cdot \text{sec}$

Calculations are made for Ljubljana (capital city of Slovenia) with annual heating degree days method (3300 K day) (PURES 2010). Heating degree days method is used to measure how much and for how long (in days) the outside air temperature (in Celsius) was lower than the base temperature. Efficiency 0.90 for heat generation was taken into account. Calculations for heat losses according to stationary heat transfer and energy balances in buildings, described in standards (EN ISO 13790 2008) together with local climatic data (Energy Plus 2016) have been taken into account.

Energy consumption on fuel mix depends on geographical location, so carbon footprint of the heat losses through the unit area of external building envelope was taken into account as an average value of available energy sources as $0.250 \text{ kg CO}_2\text{-eq.}/(\text{kW h})$ (or $0.0694 \text{ kg CO}_2\text{-eq.}/\text{MJ}$) (STAT 2012; Ecoinvent 2014), which represent a GWP of mixture of energy use.

Determination of environmental neutrality

For the purpose of calculating environmental neutrality (the time required for the carbon footprint of the manufacturing and installation of the respective insulation to be offset by the difference of heat loss in the

heating season), the current average value of the thermal transmittance of the building envelope in Slovenia, $U = 0.52 \text{ W/(m}^2 \text{ K)}$, was taken (STAT 2012). Thermal insulation thicknesses were calculated in the way that a thermal transmittance value of $0.20 \text{ W/(m}^2 \text{ K)}$ of new, renovated external envelope is achieved.

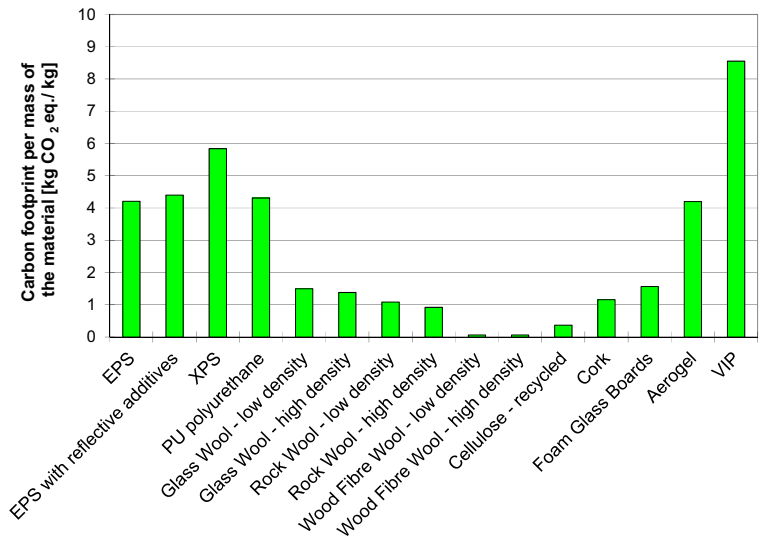
Environmental neutrality is time period when carbon footprint of heat losses through external envelope (m^2) is equal to carbon footprint of installed thermal insulation (m^2). In this time are environmental influences of installing thermal insulation equal to their influences of lowering heat losses on average external envelope taken into our analysis.

Results and discussion

In Fig. 2, carbon footprints of various insulating materials according to their weight, without taking into account different densities and differences in the thermal conductivity of the material (λ), are shown, just as an illustration of how inappropriate is comparison of declared unit (according to standard (EN 15804 2013)) of carbon footprint per mass of the insulation materials. As for the specific effect of thermal insulation, with the same levels of thermal transmittance (U) to be achieved, different amounts of a particular material are needed (Fig. 3). Therefore, the comparison in Fig. 2 cannot serve as the criterion to determine thermal insulating materials with low environmental impact. The analysis should consider the difference in density of each thermal insulation material, as well as differences in their thermal conductivity (according to standard (EN 15804 2013), in this case m^2 of external thermal envelope is the correct functional unit).

Actual environmental impact, expressed in terms of $\text{CO}_2\text{-eq.}$ emissions for various thermal insulation materials included in the analysis, should therefore be compared based on the same level of thermal transmittance (U) value to be achieved. In Table 3, the necessary thickness of individual type of thermal insulation material, as well as their mass per unit area needed to achieve the thermal transmittance of the outer building envelope of $U = 0.20 \text{ W/(m}^2 \text{ K)}$, are presented. Furthermore, the carbon footprint of the selected thermal insulation materials per unit area (m^2) that is needed to achieve thermal transmittance $U = 0.20 \text{ W/(m}^2 \text{ K)}$ is given. These values, according to (EN 15804 2013) as functional units, allow valid comparison and should be used

Fig. 2 Carbon footprint of different thermal insulation materials per kilogramme mass of the selected material, presented as an illustration of inappropriate presentation of environment impact of thermal insulations



when decisions over thermal insulation are taken based on the smallest environmental impact.

In Fig. 3, the carbon footprint per unit area of the envelope (m²) is shown, while in Fig. 2, the carbon footprint with respect to the unit mass of the insulating material is presented. The maximal environmental impact caused by the installation of thermal insulation in the building envelope in order to achieve thermal transmittance value of 0.20 W/(m² K), is 75.6 kg CO₂-eq. per square meter of the building thermal envelope surface (Table 3).

Comparison of carbon footprints of the thermal insulation materials (Fig. 3) shows that wood-based insulations, in this case wood wool, cause minimal

environmental impact, recycled cellulose, most often newsprint, also has low impact on the environment. In both products, wood wool and recycled cellulose, a significant part of the carbon footprint is due to the additives that prevent rot, decay and burning. Mineral, glass and stone wool (especially of low-density) also have low impact on the environment.

In view of the overall environmental acceptability and the use of resources and environment, synthetic or plastic materials have a high environmental impact, compared to natural materials (e.g. wood wool) (Martínez-Rocamora et al. 2016). Carbon footprint of plastics (EPS) is 4.205 kg of CO₂-eq. per kilogramme of

Fig. 3 Carbon footprint of thermal insulation materials needed to achieve the value of thermal insulation of the building envelope $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$; presented per unit area of building thermal envelope (m²)

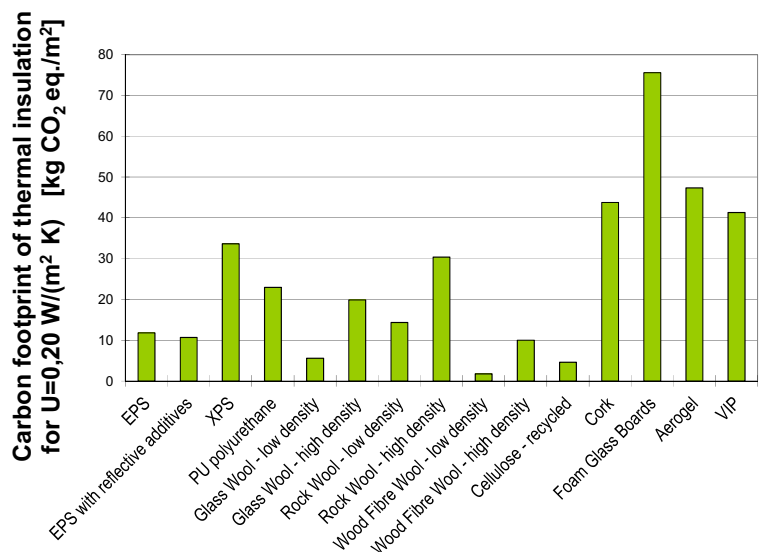


Table 3 Physical properties and carbon footprint of various thermal insulation materials enabling thermal transmittance $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$ per unit area of the building envelope (m^2)

Thermal insulation material	Carbon footprint per mass of most commonly used material for building envelopes	Required weight of thermal insulation per surface (1 m^2), for $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$	Carbon footprint of thermal insulation per surface unit (1 m^2), for $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$
	kg CO_2 -eq./kg	kg/ m^2	kg CO_2 -eq./ m^2
EPS	4.205	2.803	11.8
EPS with reflective additives	4.400	2.424	10.7
XPS	5.840	5.757	33.6
PU polyurethane	4.307	5.326	22.9
Glass wool–low density	1.494	3.750	5.6
Glass wool–high density	1.380	14.393	19.9
Rock wool–low density	1.082	13.256	14.3
Rock wool–high density	0.920	33.023	30.4
Wood fibre wool–low density	0.062	28.407	1.8
Wood fibre wool–high density	0.062	161.919	10.0
Cellulose–recycled	0.367	12.499	4.6
Cork	1.156	37.876	43.8
Foam glass	1.565	48.292	75.6
Aerogel	4.200	11.268	47.3
VIP	8.551	4.829	41.3

weight of material, which is much higher than the carbon footprints of natural thermal insulation materials, which range on average from 0.062 to 1.156 kg of CO_2 -eq. per kilogramme of the material (Fig. 1). However, synthetic or plastic materials are extremely robust, compact, stable, more easily installed, require less maintenance, usually more resistant to external influences, often have lower thermal conductivity, despite the extremely low densities (on average 12 to 35 kg/m^3) (Table 1). These features put them in advantage compared to others, even natural insulating materials, although the latter have significantly smaller impact on the environment (Fig. 2), while on average a bit higher thermal conductivity (Table 3). As a result of the listed factors, artificial materials are often introduced as being comparable with other insulating materials of the same thermal insulation efficiency (the same amount of thermal transmittance U) (Fig. 3).

The analysis determined that thermal-insulating materials with the greatest environmental impact are extruded polystyrene, polyurethane foam, foam glass and mineral wool of high density (Fig. 3). The reason is mainly their relatively high density and consequently large mass of material required to achieve a certain degree of thermal insulation, as well as in many cases

their manufacturing processes that have high impact on the environment.

The environmental impact caused by the insulation of the entire external building envelope, assumed to be 400 m^2 , with thermal transmittance $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$, compared to the impact on the environment of other materials used in buildings, is small. That is true even in the case of thermal insulations with high carbon footprint, such as XPS, which causes the environmental impact of 13.4 t CO_2 -eq. This footprint equates to 75.1 t of reinforced concrete (Table 4). However, it has to be emphasized that an individual building of 400 m^2 contains about three times as much concrete. Furthermore, the same impact is made by 56.5 metric tonnes of fired clay bricks (an average, individual house contains about four times as much), or 6.7 t of PVC products, or 8.4 t of steel products or only 1.6 t of aluminium, partly produced from recycled raw sources, for causing the same environmental impact as implementing thermal insulation. Carbon footprint values of construction materials mentioned in Table 4 were obtained from Ecoinvent database 3.1 (Ecoinvent 2014). It is necessary to emphasize that implementing thermal insulation only brings significant energy savings in opposite to other bearing and protection building materials, such as concrete, mortar, bricks, PVC and aluminium.

Table 4 Carbon footprint of different thermal insulation materials needed to achieve heat transfer of $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$ in 400 m^2 of the whole external building envelope with the carbon footprint of other construction materials

Thermal insulation material	Carbon footprint for 400m^2 of external whole building envelope with $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$	Equivalent carbon footprint as with reinforced concrete	Equivalent carbon footprint as with mortar	Equivalent carbon footprint as with construction brick	Equivalent carbon footprint as with flat construction window glass	Equivalent carbon footprint as with polyvinyl-chloride (PVC)	Equivalent carbon footprint as with construction steel	Equivalent carbon footprint as with construction aluminium
	t	t	t	t	t	t	t	t
EPS	4.7	26.3	19.6	19.8	4.8	2.3	2.9	0.6
EPS with reflective additives	4.3	23.8	17.7	17.9	4.4	2.1	2.7	0.5
XPS	13.4	75.1	55.8	56.5	13.7	6.7	8.4	1.6
PU polyurethane	9.2	51.3	38.1	38.6	9.4	4.6	5.7	1.1
Glass wool–low density	2.2	12.5	9.3	9.4	2.3	1.1	1.4	0.3
Glass wool–high density	7.9	44.4	33.0	33.4	8.1	4.0	4.9	0.9
Rock wool–low density	5.7	32.1	23.8	24.1	5.9	2.9	3.6	0.7
Rock wool–high density	12.2	67.9	50.4	51.1	12.4	6.1	7.6	1.4
Wood fibre wool–low density	0.7	3.9	2.9	3.0	0.7	0.4	0.4	0.1
Wood fibre wool–high density	4.0	22.4	16.6	16.8	4.1	2.0	2.5	0.5
Cellulose–recycled	1.8	10.2	7.6	7.7	1.9	0.9	1.1	0.2
Cork	17.5	97.8	72.7	73.6	17.9	8.7	10.9	2.0
Foam glass	30.2	168.9	125.5	127.1	30.9	15.1	18.8	3.5
Aerogel	18.9	105.8	78.5	79.6	19.3	9.4	11.8	2.2
VIP	16.5	92.3	68.5	69.4	16.9	8.2	10.3	1.9

Table 5 Carbon footprint of built-in thermal insulation and the difference between the average insulated building envelope (carbon footprint of heat losses per heating season of 11.5 kg CO₂-eq./m²), i.e. a well-insulated building envelope (thermal transmittance $U = 0.20$ W/(m² K) with carbon footprint of heat losses per heating season of 4.4 kg CO₂-eq./m²) per unit area (m²) of the building envelope

Thermal insulation material	Carbon footprint per unit area (m ²) of thermal insulation for $U = 0.20$ W/(m ² K)	Carbon footprint of difference of heat losses through existing average external envelope and heat losses through well-insulated envelope ($U = 0.20$ W/(m ² K)), per unit area (m ²) of external building envelope										
	kg CO ₂ -eq./m ²	1st	2nd	3rd	4th	6th	9th	11th				
Heating season												
Carbon footprint		kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²	kg CO ₂ -eq./m ²
EPS	11.8	4.7	-2.4	-9.5	-16.6	-30.8	-52.1	-66.3				
EPS with reflective additives	10.7	3.6	-3.5	-10.6	-17.7	-31.9	-53.2	-67.4				
XPS	33.6	26.5	19.4	12.3	5.2	-9.0	-30.2	-44.4				
PU polyurethane	22.9	15.8	8.7	1.7	-5.4	-19.6	-40.9	-55.1				
Glass wool—low density	5.6	-1.5	-8.6	-15.7	-22.8	-37.0	-58.3	-72.5				
Glass wool—high density	19.9	12.8	5.7	-1.4	-8.5	-22.7	-44.0	-58.2				
Rock wool—low density	14.3	7.2	0.1	-6.9	-14.0	-28.2	-49.5	-63.7				
Rock wool—high density	30.4	23.3	16.2	9.1	2.0	-12.2	-33.5	-47.7				
Wood fibre wool—low density	1.8	-5.3	-12.4	-19.5	-26.6	-40.8	-62.1	-76.3				
Wood fibre wool—high density	10.0	2.9	-4.2	-11.3	-18.4	-32.6	-53.9	-68.0				
Cellulose—recycled	4.6	-2.5	-9.6	-16.7	-23.8	-38.0	-59.3	-73.5				
Cork	43.8	36.7	29.6	22.5	15.4	1.2	-20.1	-34.3				
Foam glass	75.6	68.5	61.4	54.3	47.2	33.0	11.7	-2.5				
Aerogel	47.3	40.2	33.1	26.0	18.9	4.7	-16.5	-30.7				
VIP	41.3	34.2	27.1	20.0	12.9	-1.3	-22.6	-36.8				

Negative italicized numbers indicate that the carbon footprint of installed thermal insulation is already covered by lower thermal energy losses and its carbon footprint

In Table 5, carbon footprint due to the installation of various thermal insulations in the building envelope per unit area (m^2) to achieve the requirements of U value $=0.20 \text{ W}/(\text{m}^2 \text{ K})$ is presented and compared to the environmental balance of carbon footprints in the following heating seasons. It can be noticed that already in the eleventh heating season the balance of all thermal insulations is negative, and the carbon footprint savings by reducing heat loss are greater than the carbon footprint due to the installation of insulation. Moreover, half of the analysed thermal insulation materials achieve this balance before the end of the third heating season.

In addition to relatively low carbon footprint, thermal insulation materials also contribute significantly to energy savings of buildings. Therefore, they belong to the very top of the most effective measures and investments to save energy and reduce indirect impacts on the environment, which has been proved by this analysis and confirmed by the results of other studies (Takano et al. 2014; Vattenfall 2015).

The so-called environmental neutrality, i.e. the time needed for the carbon footprint due to the installation of thermal insulation to equal the carbon footprint of the difference of heat loss in the heating season between the current average external insulated building envelope and well-insulated building, is achieved relatively soon for each of the analysed insulation materials. By thickening of the insulation layer, the carbon footprint due to the installation of thermal insulation increases, but the value of heat transfer (U) decreases, therefore reducing the carbon footprint of the heat loss through the building envelope.

From Table 5, where the requirement of thermal transmittance of the building envelope is the value of $U = 0.20 \text{ W}/(\text{m}^2 \text{ K})$, it can be concluded that the carbon footprint of the heat loss reduction due to the installation of thermal insulation (Ecoinvent 2014) throughout the building envelope is significant compared to the footprint of the initial ‘investment’ in the insulation installation. Soon after tenth heating seasons, the savings of environmental impacts are higher even than impacts caused by the installation of the thermal insulation with the highest environmental impact (foam glass). The analysis showed that before eleventh heating season reduced environmental impact of buildings due to energy savings resulting from implementation of thermal insulation is higher than the impact of inserting insulation itself. More than one half (8 out of 15) of all of the evaluated thermal insulation types achieve environmental neutrality even before the end of the third

heating season, and four-fifths or 80% (12 out of 15) before the end of the sixth heating season. One of the most widespread thermal insulation types, expanded polystyrene (EPS), achieves environmental neutrality shortly after the completion of the first heating season (before end of second heating season). The smallest impact on the environment is caused by thermal insulation of wood wool; the environmental neutrality is reached shortly after installation (before end of first heating season). This proves the extremely low carbon footprint of installation of wood-wool insulation. Furthermore, thermal insulation materials have long life spans, during which the thermal conductivity does not deteriorate. Therefore, multiple returns of environmental impact caused by their installation in the building envelope are guaranteed.

Conclusions

The carbon footprint calculations of insulation materials demonstrated that the evaluation and consideration of their environmental impact per unit weight is inappropriate and can lead to misleading decisions, since it is imperative that the analysis considers also the difference in density (ρ) of each thermal insulation materials, as well as differences in their thermal conductivity (λ). Furthermore, the most effective measure to reduce the environmental impact of buildings is the correct choice of thermal insulation materials. Synthetic or plastic materials have poorer performance in comparison with natural materials, in view of the overall environmental impact assessment. At the same time, these materials are extremely robust, compact, stable and more easily installed. They require less maintenance, are usually more resistant to external influences, and often have lower thermal conductivity, despite their extremely low density. Nevertheless, artificial materials can have a desirable carbon footprint reduction in the long run, comparable to other thermal insulation materials, providing the same thermal insulation efficiency (i.e. the same amount of thermal transmittance transfer U).

Comparison of carbon footprints of all 15 analysed thermal insulation materials and other building materials, such as reinforced concrete, mortar or plaster, brick clay, window glass, PVC products, structural steel and aluminium, also supports the concept that a relatively small carbon footprint ‘investment’ in thermal insulation materials yields significant savings in the operational time of a building. This holds true even if the building is to be thermally insulated well above the currently prescribed

levels by the applicable regulation in most countries, also in Slovenia.

It can be concluded that the environmental effects of thermal insulation materials in comparison with other building materials, which are embedded in the average building, are small. In addition, it should be noted that due to energy savings that thermal insulation materials provide in each heating season after their installation, they significantly contribute to the reduction of buildings' environmental impact. Therefore, thermal insulation should be ranked at the top of the most effective investments for energy saving and consequent reduction of environment impact of buildings.

The results of this paper could give useful tips for selecting energy efficient building technologies, leading to considerable reduction of carbon footprint mainly with thermal insulations of the external envelope or of the building as a whole.

While the results of the conducted study represent guidelines to architects, designers, investors and other stakeholders in building industry, the growing popularity of implementing low-, zero- or even plus-energy buildings, using light weight instead of massive constructions, dictates further research of building envelope configurations and their impact on the environment.

Acknowledgements This work was supported by the Slovenian Research Agency (Programme P2-0158), and by the European Regional Development Found, Research and development programmes (TRL 3-6), sustainable and innovative construction of smart buildings (smart buildings and home, including wood chain: TIGR4smart) (Programme C3330-16-529003).

Many thanks to the anonymous reviewers for their assistance in improving the quality and originality of the manuscript.

Compliance with ethical standards

Conflict of interest The author declares that he does not have any conflict of interest.

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