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EMBODIED GLOBAL WARMING POTENTIAL OF DIFFERENT THERMAL INSULATION MATERIALS FOR INDUSTRIAL PRODUCTS

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ABSTRACT

There is a significant potential in reducing the environmental impacts of various industrial products through the optimisation and improvement of their design. On one hand we are improving their efficiency in the phase of their use and on the other hand we can design them in a way that causes less harm to the environment in the production phase through eco design. In this study we performed a comparison of 12 thermal insulation materials used for industrial products. Review of available documentation of insulation materials and other product information showed that the there is a lack of comparable data between them. The primal goal of the research was therefore to compare the embodied global warming potential of thermal insulation materials, expressed in terms of CO_2-eq., for achieving a certain value of thermal resistance. The paper clearly demonstrates that the consideration of environmental impact of thermal insulation materials per unit weight is inadequate and can lead to deficient material selection, since we would need to take into account also the differences of material density and their thermal conductivity. The calculations and findings in this paper could help in selecting more environmentally friendly thermal insulations.

Keywords: global warming potential, ecodesign, insulation material, product design.

INTRODUCTION

Industrial products and appliances represent a significant share in consumption of natural resources and energy. They are also responsible for a number of other important environmental impacts. In 2014, greenhouse gas emissions (GHG) by manufacturing in the EU-28 were 853.7thousand tons of CO_2 equivalent (CO_2-eq.) and presented19% of total emissions in CO_2-eq. [1]. The EU Commission set the objective to reduce GHG emissions by 80-95% by 2050 compared to 1990. Concrete milestones to achieve this goal, with targets of 40% and 60% reductions in 2030 and 2040 are stated in its Low Carbon Economy Roadmap [2].

In line with the EU international headline targets, actions towards environment friendly alternatives should be taken in all sectors and hierarchical levels. Industrial products and appliances are subject to energy labelling measures under the EU's Energy Labelling Directive [3] as well as ecodesign measures under the EU's Ecodesign Directive [4]. There is a significant potential in optimising and improving the design of industrial products and appliances and with that reducing the impacts on the environment at the beginning of the product life-cycle as well as on their end [5].

With this ecodesign approach in industrial products and appliances a careful selection of materials is of utmost importance to ensure minimal burden on the environment. Materials needed for the final product are selected based the needed energy and emissions for the production processes. A consideration about the end-of life of the product is also important part of it. Several researchers were already focusing on this topic [6, 7]. Applying thermal insulation (TI) has proved itself as an extremely efficient strategy in lowering the operational energy use and emissions in industrial products. In order to successfully manage the lowering of the environmental impacts in the use phase, we are now increasingly focusing also on the embodied energy in the materials, since they represent a good potential for further optimization. Many studies analysing the embodied energy and CO_2 emissions of TI materials have already been performed [8-12].

Significant progress is being made on TI materials towards the improvement of the performance of industrial products and appliances, especially household refrigerators. Yoon *et al*. (2013) developed a strategy for optimization of insulation thickness of a domestic refrigerator-freezer. Yusufoglu *et al*. [13] improved the energy efficiency of household refrigerators with adding phase change materials (PCM).Similarly Oró *et al.* [14] studied the energy performance and CO_2 reduction using PCM for storing thermal energy in cold chain. Hammond and Evans [15] analysed the application of Vacuum Insulation Panels (VIP) in cold storage. We see that studies on the evaluation of environmental impact of TI materials for industrial product and appliances are receiving more interest among researchers.

With this study, we focused on the quantification of embodied energy and CO_2 emissions of TI materials used in industrial design products. Weperformed an objective comparison of various TI materials (more commonly used ones as well as also more rarely used ones, that are still developing in the industry - i.e. super-insulators), by calculating their GWP. We compared the values that we have obtained, with regard to their thermal insulation performance characteristics. The foundation for the comparison was calculating the material GWP taking into account the density (ρ) as well as their thermal conductivity (λ).

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MATERIALS AND METHODS

Using the LCA methodology [16], the aim of this study was to discover the differences in GWP for the production phase for the selected TI materials. GWP was analysed including stages of production called also "cradle-to-gate". This includes stages of raw material acquisition, transport to the factory, and processes of manufacture (before delivery to the customer). The accounting includes the use of fuels, electricity or other means of energy delivery and includes also transportation impacts during the production stages. The values do not include emissions caused the use phase of the product or the end-of-life phase.

The basic unit for comparison was 1 kg of specific TI material. Information about GWP of different TI materials was sourced and compiled from Ecoinvent database 3.1 [17], which holds high quality and consistent data for materials over different industrial sectors. Included are GWP emissions to air from energy inputs, raw material extraction, products and co-products, waste and the upstream life cycle impacts of input materials.

Our study focused on 12 most commonly used TI materials used in industry for various products: glass wool with low-density, glass wool with high-density, rock wool of two different densities, wood wool of two different densities, expanded polystyrene (EPS), reflective EPS or 'grey' EPS (with infra-red reflector additives), extruded polystyrene (XPS), polyurethane (PU), aerogel, and vacuum insulation panel (VIP). Selected materials differ in their density (22 kg m^{-3} to 400 kg m^{-3}, relation 1 : 18) and their thermal conductivity (6 mW m^{-1} K^{-1} to 90 mW m^{-1} K^{-1}), relation 1 : 15, as is shown in Table-1. Detailed data about the selected insulation materials (chemical and physical composition) is available in TI manufacturers` documentations, and various literature sources [18, 19]. Additionally, we compared GWP of TI materials with other materials which are used for certain assembled industrial products, such as steel, stainless steel, aluminium, PVC or glass.

Based on this starting point we defined the research goals, which would at the end help us in selecting the most appropriate thermal insulation material regarding also the embodied GWP:

a) To calculate GWP of various TI materials on the basis of kilogram CO2-eq. per kilogram mass of material.
b) To calculate GWP of TI materials per surface unit (1 m^2), enabling various thermal resistances, R (m^2KW^{-1}).
c) To evaluate GWP for various TI materials needed to achieve R of 1.0 m^2 K W^{-1} in comparison with some non-insulation materials mostly used for industrial products and equipment.

RESULTS AND DISCUSSIONS

Review of technical specification of analysed insulation materials and other product information revealed that there is a significant difference between them in accounting the embodied CO_2emissions of the product according to the unit weight. It revealed itself that this comparison does not consider the differences of density (ρ) or different values of thermal conductivity (λ) of the material. This approach may lead to partly correct or even wrong decision on the selection of environmentally friendly insulations.

In Figure-1 GWP of various TIs per unit weight of material is presented, without considering their density (ρ) or the differences in their thermal conductivity (λ). For achieving the same level of thermal resistance (R) with different TI material, various amount of material is needed in terms of its weight. For example, only 0.68 kg of EPS with reflective additives is needed to achieve heat resistance R of 1.0 m^2 K W^{-1}, comparing to 7.31 kg of high density rock wool for the same effect.

Densities of TI materials for industrial use vary from 22 kg m^{-3} to 400 kg m^{-3} (Figure-2). The values of thermal conductivity of various insulation materials are also different (Figure 3) and are more or less in the range of 31 mW m^{-1} K^{-1} to 90 mW m^{-1} K^{-1}, with the exception of insulation materials also known as super insulators - aerogel and vacuum insulation panels (VIP). They have a significantly lower value of thermal conductivity: aerogel 16 mW m^{-1} $K^{-1}$and VIP only 6 mW m^{-1} K^{-1} respectively.

On Figure-3 value of thermal conductivity (λ) of various compared TI materials is shown as an illustration of inadequate information regarding the decision to use the material in industrial products. Thermal conductivity value alone cannot be the only criterion for choosing the TI materials since we are missing the information on their environmental impact. For making an environmentally low impact decision regarding the material choice, we need also the information of their density together with the data on their embodied GWP.

In order to present a comparable analysis of embodied emissions in terms of CO_2-eq. of the analysed thermal insulation materials, we need to get them on the same identifier such as the R value to be achieved. In Table-2 we therefore calculated the GWP of various types of TI materials, as well as their mass per unit area needed to achieve the thermal resistance of the thermal barrier (R=1.0 m^2 K W^{-1}). Furthermore, the GWP of the selected TI materials per unit area (m^2) that is needed to achieve various thermal resistances of 1.0, 2.0, 3.0 and 4.0 is also given.

The highest embodied GWP of the analysed TI materials in order to achieve thermal resistance value of 1.0 m^2 K W^{-1} is 11.30 kg CO_2-eq. per square meter of the thermal VIP barrier surface, whereas the lowest is in low density Wood fibre wool with the value of 0.4 kg CO_2-eq. per square meter. Presented data allows us to make a valid comparison between the different TI materials and making a decision to use the ones with the lowest carbon emissions produced during the production process.

Table-1. Density(ρ), thermal conductivity(λ) and required thickness of various thermal insulation materials to obtain various thermal resistances.

	Density (ρ)			Thermal conductivity (λ)						
Thermal insulation material used for industrial products and equipment	**from**	**to**	**Most commonly used for thermal barriers of industrial products**	**from**	**to**	**Most commonly used for thermal barriers of industrial products**	**Required thicknesses of thermal insulation for various thermal resistances (*R* in units (m^2 K W^{-1})), for use in industrial products and equipment**			
							***R*=1.0**	***R*=2.0**	***R*=3.0**	***R*=4.0**
	kg m^{-3}	kg m^{-3}	kg m^{-3}	mW m^{-1} K^{-1}	mW m^{-1} K^{-1}	mW m^{-1} K^{-1}	mm	mm	mm	mm
Glass Wool - low density	15	40	30	34	40	35	35	70	105	140
Glass Wool - high density	40	150	100	30	45	36	37	74	111	148
Rock Wool - low density	20	120	90	33	42	38	38	76	114	152
Rock Wool - high density	120	200	170	35	48	43	43	86	129	172
Wood fibre wool – low density	50	270	140	38	60	50	50	100	150	200
Wood fibre wool – high density	350	600	400	75	110	90	90	180	270	360
EPS	10	30	22	34	45	35	35	70	105	140
EPS with reflective additives	12	28	22	30	35	31	31	62	93	124
XPS	28	45	36	31	44	36	36	72	108	144
PU polyurethane	28	100	50	22	30	24	24	48	72	96
Aerogel	60	160	140	13	24	17	17	34	51	68
VIP	150	300	170	3	11	6	6	12	18	24

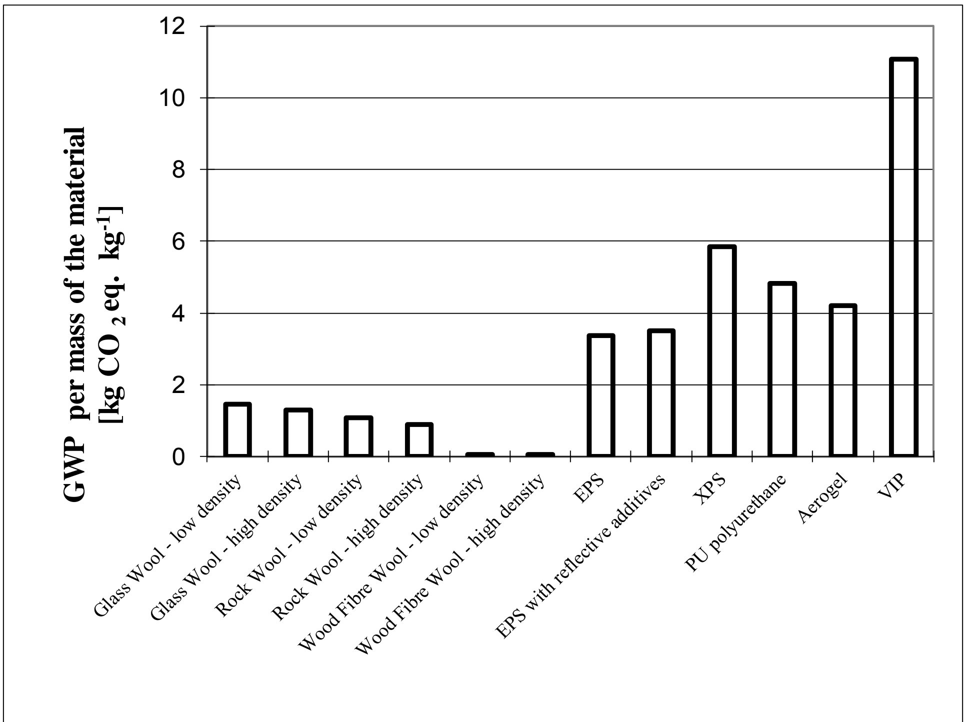

Figure-1. GWP in kilogram CO_2-eq. of various thermal insulation materials per kilogram mass of the selected material.

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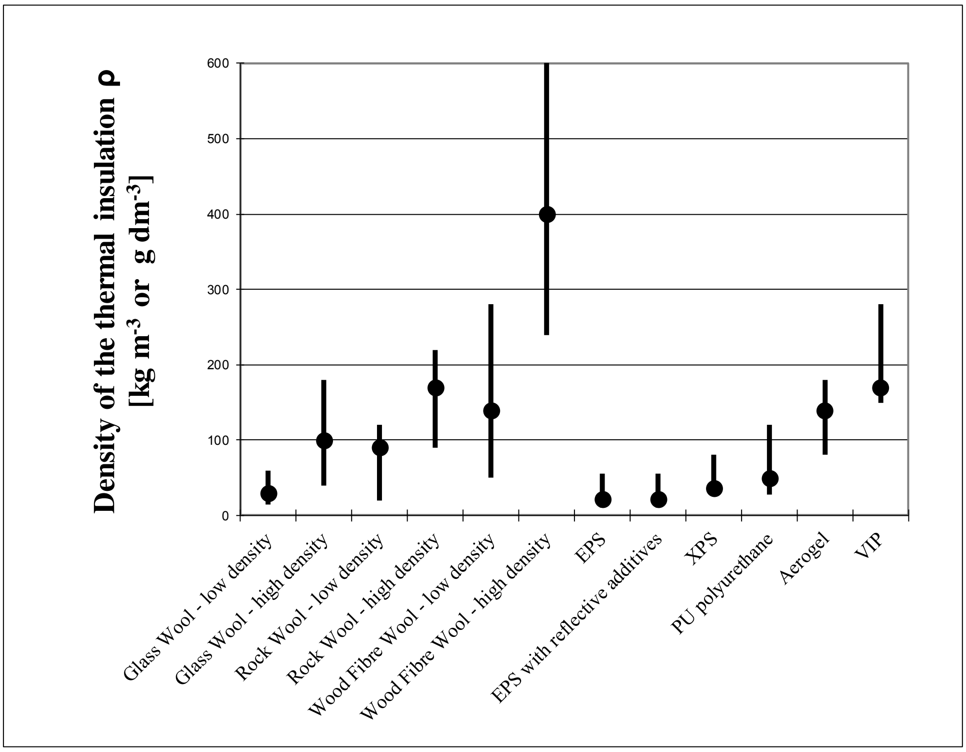

Figure-2. Density ρ (kg m^{-3} or g dm^{-3}) of various thermal insulation materials. Dots shows an average value of the most commonly used product for industrial products and equipment, whereas lines (error bars) shows other variations of densities of insulation materials used for all possible purposes.

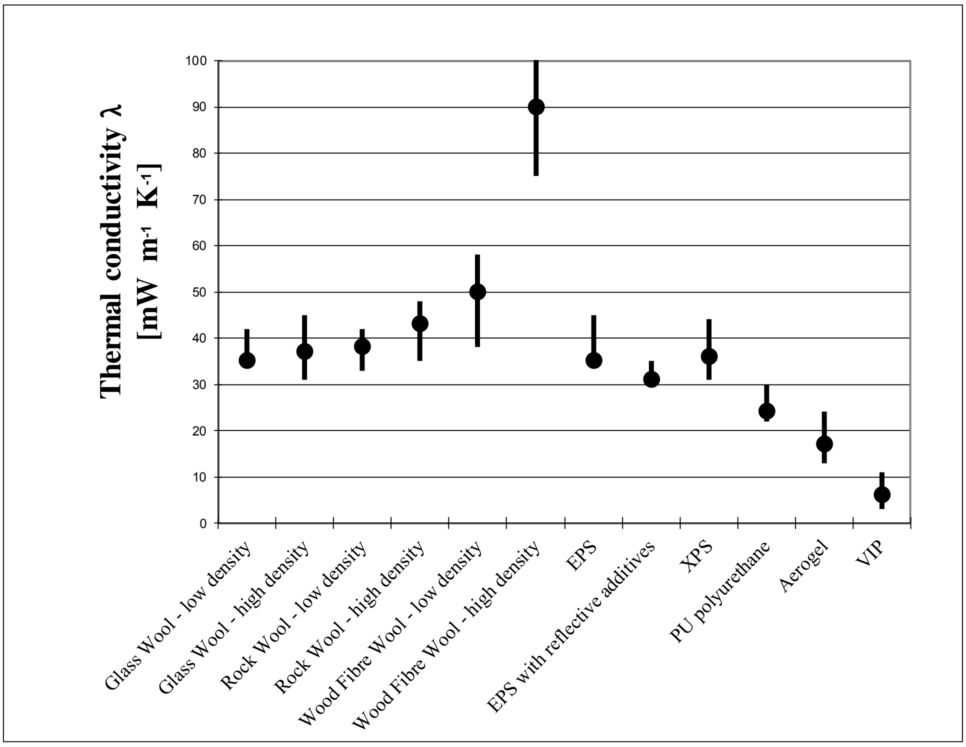

Figure-3. Thermal conductivity λ (mW m^{-1} K^{-1}) of various thermal insulations.

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Table-2. Thermal insulation materials with their physical properties and their embodied GWP (kg CO_2-eq. kg^{-1}).

TI material used for industrial products and equipment	**GWP per mass of most commonly used material for TI**	**Surface weight** (per 1 m^2) **of various TI for enabling thermal resistance of** R **= 1.0 m^2 K W^{-1}**	**GWP of TI materials per surface unit** (1m^2), **enabling various thermal resistances** R (m^2 K W^{-1})			
			***R* = 1.0**	***R* = 2.0**	***R* = 3.0**	***R* = 4.0**
	kg CO_2 eq. kg^{-1}	kg m^{-2}	kg CO_2 eq. kg^{-1}			
Glass Wool - low density	1.46	1.05	1.5	3.1	4.6	6.1
Glass Wool - high density	1.30	3.60	4.8	9.6	14.4	19.2
Rock Wool - low density	1.08	3.42	3.7	7.4	11.1	14.8
Rock Wool - high density	0.90	7.31	6.6	13.2	19.7	26.3
Wood fibre wool – low density	0.06	7.00	0.4	0.9	1.3	1.7
Wood fibre wool – high density	0.06	36.00	2.2	4.4	6.6	8.8
EPS	3.38	0.77	2.6	5.2	7.8	10.4
EPS with reflective additives	3.50	0.68	2.4	4.8	7.2	9.5
XPS	5.86	1.30	7.6	15.2	22.8	30.4
PU polyurethane	4.83	1.20	5.8	11.6	17.4	23.2
Aerogel	4.20	2.38	10.0	20.0	30.0	40.0
VIP	11.08	1.02	11.3	22.6	33.9	45.2

In Figure-4, the GWPof TI material for achieving R = 1.0per unit area of the barrier (1 m^2) is represented in bar chart for clearer visual comparison among the analysed TI materials. Comparison shows that wood-based TI materials, in this case low density wood fibre wool, causes the least environmental impact. A significant part of the embodied GWP in the wood wool TI materials is a consequence of using the additives for prevention of rot, decay and burning. Looking at the other analysed TI materials, also low density glass wool and EPS insulation materials have low embodied GHG emissions (up to 2.25 kg of CO_2-eq. for m^2), whereas others show significant higher values (up to 11 kg of CO_2-eq. for m^2).

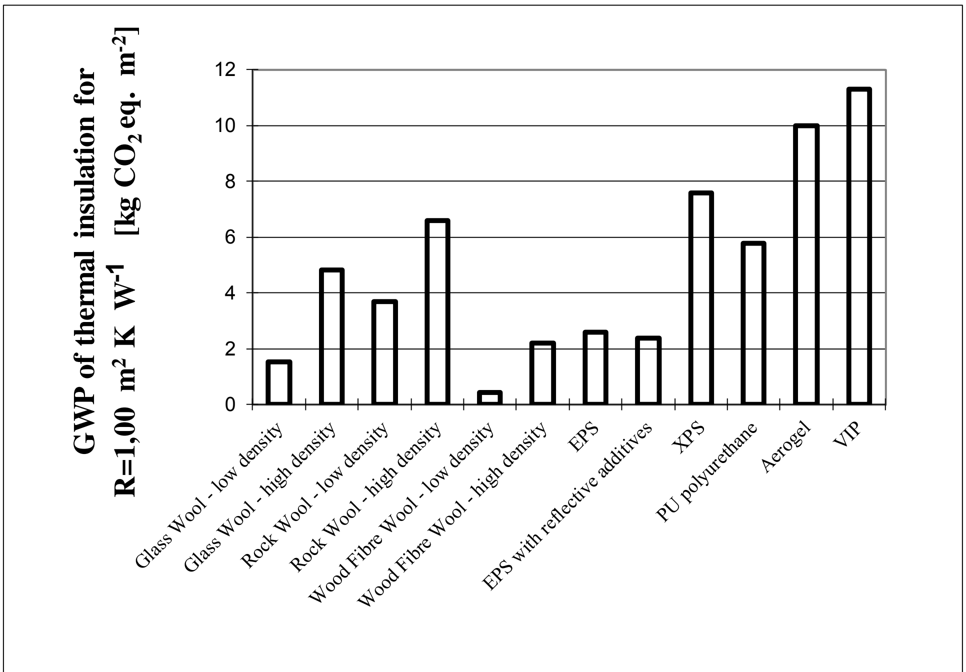

Figure-4. Embodied GWP of various TI materials needed to achieve the value of thermal resistance of the thermal barrier, R = 1.0 m^2 K W^{-1}.

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Comparing the analysed TI materials form the view of the embodied GWP synthetic or plastic materials have higher values, compared to natural materials (e.g. wood fibre wool). The embodied GWP of one kilogram EPS is 3.38 kg of CO_2-eq., which is much higher than the GWP of natural TI materials, which on average are ranging around 0.06 kg of CO_2-eq. per kilogram of the material (Table-2). On the other hand, plastic or synthetic materials are more robust, stable and compact, are easier for installation and require less maintenance. They are usually also more resistive to external influences and have lower thermal conductivity values, even though their densities are on average low (between 12-35 kgm^{-3}) (Table-1). All this influences that these, non-natural materials are very often used.

However, synthetic or plastic materials are extremely robust, compact, stable, more easily installable, 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 characteristics give them some competitive advantage in regard to other TI materials, even comparing to natural insulation in spite of the higher embodied GHG values (Figure-3). On average they still have higher values of thermal conductivity (Table-1). So called artificial TI materials are therefore seen as comparable with other insulation materials with similar TI efficiency looking at the value of *R* (Figure-4).

In this study it was shown that the TI materials with highest embodied GWP are mineral wool of high density, extruded polystyrene, polyurethane foam, aerogel and VIP (Figure-4). The cause of this is mainly in their higher density values. Consequently for achieving a certain level of TI, large mass of material are needed. This is connected also with the production process, which needs a higher amount of energy for manufacture; consequently also the emissions to the environment are higher.

The GWP impact caused by the use of insulation materials (1 m^2) in industrial products, with the aim to achieve *R* of the value 1.0 $m^2 K W^{-1}$, compared to the embodied GWP of other, in production industry highly used materials (glass, steel, aluminium and PVC)is shown in Table-3.

It is clearly presented that in relation to the GWP of TI; the same environmental impact is caused with very small quantities of other materials. This goes also for the analysed TI materials with highest embodied GWP values like PU foam (GWP of 5.80 kg CO_2-eq. m^{-2}, Table-2) with the weight of 1.20 kg m^{-2} for the thermal resistance of R=1.0 $m^2 K W^{-1}$. This footprint equates to embodied GWP footprint of 1.36 kg of PVC material and only 0.68 kg of aluminium. Naturally, it is very important to emphasize that only with applying TI materials energy consumption in use phase of appliances is reduced.

Table-3. Amount of GWPfor various TI materials needed to achieve heat resistance *R* of 1.0 m^2KW^{-1} in comparison with some non-insulation materials mostly used for industrial products and equipment.

	Required thicknesses of TI for thermal resistance *R*=1,0 m^2 K W^{-1}	**Surface weight** (per 1 m^2) **of TI for *R R*=1,0 m^2 K W^{-1}**	**Equivalent GWP as achieved with flat glass weight of**	**Equivalent GWP as achieved with polyvinylchloride** (PVC) **weight of**	**Equivalent GWP as achieved with steel weight of**	**Equivalent GWP as achieved with aluminium weight of**
	mm	**kg m^{-2}**	**kg**	**kg**	**kg**	**kg**
Glass Wool - low density	35	1.05	2.21	0.36	1.00	0.18
Glass Wool - high density	37	3.60	6.92	1.13	3.15	0.56
Rock Wool - low density	38	3.42	5.31	0.87	2.42	0.43
Rock Wool - high density	43	7.31	9.47	1.54	4.31	0.77
Wood fibre wool - low density	50	7.00	0.61	0.10	0.28	0.05
Wood fibre wool - high density	90	36.00	3.16	0.51	1.44	0.26
EPS	35	0.77	3.74	0.61	1.71	0.30
EPS with reflective additives	31	0.68	3.43	0.56	1.56	0.28
XPS	36	1.30	10.93	1.78	4.98	0.89
PU polyurethane	24	1.20	8.34	1.36	3.80	0.68
Aerogel	17	2.38	14.38	2.34	6.55	1.17
VIP	6	1.02	16.27	2.65	7.41	1.32

In addition to their relatively low embodied GWP, using TI materials in industrial products and appliances contribute significantly to energy savings of during their use in the whole life cycle. This puts them very high on the list of effective actions and decisions for improving the energy efficiency of the products in the phase of their use, as well as with their careful selection lowering their embodied GWP, which has been proved by this analysis and confirmed by the results of other studies [20-22].

CONCLUSIONS

Energy use during the production of whole carbon emissions per unit volume or mass of insulation material is inadequate as a functional unit, because equal volumes or masses of different materials do not fulfil the same function or effectiveness. We must therefore look at the values for achieving a certain amount of thermal insulation and the embodied GWP of different TI materials for achieving this. A decision in selection of a TI material based on actual values of embodied GWP considering also their effectiveness can further reduce the environmental impact in production of domestic appliances, refrigerators or other industrial products.

The paper clearly demonstrates that the choice of TI material based only on information of embodied GWP per unit weight is not appropriate, since it is not taking into account the differences of density of each material and also their thermal conductivity values. In our study of GWP of selected TI materials we have taken this into account (Figure-4). Results show that the TI materials with lowest embodied GWP are wood wool, low density glass wool and also EPS TI materials. TI materials with highest embodied GWP are mineral wool of high density, extruded polystyrene, polyurethane foam, aerogel and VIP. The cause of this is mainly in their higher density values.

Comparing the embodied GWP of the selected analysed TI materials with embodied GWP of other materials used in the industrial products or equipment (glass, steel, aluminium and PVC) (Table-3) we see that the prior represent a smaller environmental burden, but are nevertheless an important in ecodesign approach. Eco design in industrial products and appliances is an important factor and presents a crucial decision at the start to minimise the overall environmental impacts of the product without high additional costs.

Presented approach can be applicable to evaluate otherkind of products used industrial and building design, its` systems, traditional or new constructional materials [23-25]. In further studies, beside GWP also other environmental indicators, such as ozone depletion potential, photochemical ozone creation potential, acidification potential and eutrophication potential, could be taken into consideration.

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