Journal of Cleaner Production 154 (2017) 203–213

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life-cycle study on semi intensive green roofs

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A R T I C L E I N F O

Article history:
Received 8 October 2015
Received in revised form
11 January 2017
Accepted 27 March 2017
Available online 3 April 2017

Keywords:
Environmental impacts
Green roofs
Semi intensive greening
Life-cycle assessment

A B S T R A C T

Properly designed green roofs are environmentally-friendly type of roofing which attracts increasing attention of both general public and professionals. Their use brings many benefits to people and surrounding environment. But with (excessive) use of man-made materials, environmental impacts of green roofs may unnecessarily increase. This paper focuses on Life Cycle Assessment of four semi intensive green roof assemblies, i.e. common assembly, assembly with added extruded polystyrene providing increased thermal resistance and two assemblies with hydrophilic mineral wool. Apart from increasing thermal insulation, this material also partially substitutes plant substrate and fulfils role of a water reservoir. A 20-year cradle-to-grave model of these assemblies life cycle has been created. The main goal of the assessment is evaluation of influence of added man-made materials (e.g. hydrophilic mineral wool) on the assemblies' total environmental impacts. These materials significantly increase the environmental impacts of the first stages of the assemblies' life cycle. On the other hand, use of these materials reduces the environmental impact in following life cycle stages. According to our calculations, the lowest environmental impacts are related to common green roof assembly without any replacement of the substrate. Highest environmental impacts are related to assembly with added extruded polystyrene panels and assembly with 75% of the substrate replaced by the mineral wool. Proper use of the assessed hydrophilic mineral wool increases the environmental impacts by approximately 11%, compared to the common assembly. To sum up, irrespective of other advantages (e.g. water retention potential) we can conclude that this material is suitable for green roofs, almost comparable to natural substrates (from the defined cradle-to-grave perspective).

1. Introduction

The construction industry plays an important role in striving for sustainability (Spence and Mulligan, 1995; UNEP, 2003; Sev, 2009). In 2009, Frauhofer ISI published a study, which illustrates the fact that buildings account for approximately 40% of energy use in EU member states and represent EU's largest source of Green House Gas (GHG) emissions (Fraunhofer, 2009). Similarly Bianchini and Hewage (2012) claim that according to the United States Green Building Council residential and commercial buildings use up to 65% of produced energy and have a 35% share on USA's GHG emissions. Furthermore, new construction uses vast areas of "greenfield" land. This is especially true for developing countries where the construction industry is rapidly growing (Phuc et al., 2014).Densely populated developed countries, however, present a problem too. For example, in the Czech Republic new residential buildings covered approximately 250 km^2 of originally agricultural land or forests between 1997 and 2009. However insignificant this seems compared to global statistics (UNEP, 2003), it almost equals the area of the second largest city in the country (Struhala et al., 2012).

Disappearance of free space and vegetation in cities has many negative impacts – worse air quality, noise, storm-water overflows (Chenani et al., 2015), creation of heat islands (Coseo and Larsen, 2014), loss of biodiversity or shrinking of leisure and relaxation zones. These can be at least partially mitigated by implementing "green" concepts e.g. (Tzoulaset al., 2007, Shwartzet al., 2014) including the use of green roofs or facades (Getter and Rowe, 2006).

Existing works describe the positive effects of using green roofs from varying points of view. Baumann (2006) and Colla et al. (2009). describe the relation between green roofs and the survival and spreading of animal species (birds and bees respectively). Razzaghmanesh et al. (2016). evaluate green roofs' role in mitigating urban heat islands. Reducing of air pollution by specific

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http://dx.doi.org/10.1016/j.jclepro.2017.03.188

plants growing on green roofs is described by e.g. Speak et al. (Speak et al., 2012), while the effect of vegetation on the reduction of water run-off is described for example by Nagase and Dunnett (2012). The fact that such works are not only important for researchers can be seen at conferences such as the International Green Roof Congress 2015 (IGRA, 2015; held in Istanbul, Turkey). There the professionals from many worldwide-known corporations discuss with researchers about the latest trends in the field and their implementation to their respective portfolios – e.g. storm water management or environmental impacts already mentioned above (Appl et al., 2015).

This paper follows works of Bianchini and Hewage (2012), Chenani et al. (2015), Kosareo and Ries, (2007), Rincón et al., (2014) and Gargari et al., (2016) who evaluated benefits of green roofs using the Life Cycle Assessment (LCA) methodology defined in ISO standards ((ISO, 2006a), (ISO, 2006b), etc.). These authors focused on more common intensive or extensive green roof (IGR and EGR respectively) assemblies. This paper focuses on semi intensive green roofs (SIGRs), because the number of works describing them is much lower. It has two closely related goals. The first goal is the assessment of environmental impacts related with four selected SIGR assemblies: i. e. common assembly, assembly with added extruded polystyrene providing increased thermal resistance and two assemblies with hydrophilic mineral wool. The second, main goal is related to the contemporary intensive use of artificial (or man-made) materials. Original green roofs (e.g. pitched green roofs in Iceland (Nečadová and Selník, 2014)) had a rather simple composition. Nowadays the situation is different. Green roof assemblies include a multitude of built-in man-made materials such as waterproofing membranes or thermal insulation. Recycled waste materials (e.g. brick shards) are often included in the substrate mixtures (Vijayaraghavan, 2016). The substrate can even be replaced by materials such as mineral wool as described later. Thus the main goal of this paper is to answer the following questions: How does the in-building of the man-made materials (such as the mentioned mineral wool) influence the total environmental impacts of SIGRs? Are these replacements justifiable replacements of more "natural" materials from the environmental point of view?

1.1. SIGR – definition

Semi intensive (or simple intensive) green roofs are an intermediate stage between EGRs and IGRs. It is possible to implement almost any kind of garden vegetation on a green roof (Heim and Lundholm, 2014). From the modest plants, such as mosses, stonecrops or houseleeks, which are common for light-weight extensive green roofs, to trees that can be found on intensive green roofs with thick substrate layers (Nagase et al., 2013). Applicable vegetation for a SIGR includes ground covers, small herbaceous plants, grasses or small shrubs as illustrated in Fig. 1. Exact composition of the roofs vegetation can be adjusted to fit the local climate. In mild climate (e.g. in Central Europe) these plants require only moderate maintenance and occasional irrigation. Irrigation is needed mostly during prolonged periods without precipitation. The amount of supplied water depends on the demand of the specific plants. The recommended minimum substrate thickness varies between 12 cm (grass or herbaceous plants) and 20 cm (smaller shrubs and coppices – see Table 1), but can be adjusted. Increased substrate thickness is needed for more demanding vegetation. SIGRs also provide higher thermal resistance compared to EGRs (Zhao et al., 2014; Vacek and Matějka, 2014) which is one of the key characteristics of contemporary low-energy architecture. Thanks to the substrate layer thickness, the SIGR system can host a richer habitat (Czemiel Berndtsson, 2010). Therefore, it has bigger potential to serve as a replacement for built-up land than an extensive system. In addition, it can also retain more storm water and thus improves the urban water cycle (Lamera et al., 2014).

Fig. 1. SIGR on passive house in Buš, Czech Republic.

Another reason for assessing SIGRs is the potential for applying of multi-purpose hydrophilic mineral wool (HMW). This material is an alternative choice to traditional assemblies with a substrate (soil), drainage and water accumulation layer. Growing plants (exclusively) in HMW is not a brand new idea. It was originally patented in 1940 (Games and Thomas, 1940). The application on green roofs dates back to the 1990s (Kummermehr and Bihy, 1997) and is constantly tested and investigated. Similarly to hydroponics, it is important to choose plants that can tolerate higher water saturation levels (Vacek, 2016). Besides its good thermal insulation characteristics ($\lambda = 0.035–0.5129$ W m^{-1} K^{-1}, depending on water saturation rate (CSI a.s, 2014a)), HMW can hold more water for longer periods than a substrate with a standard dimple membrane. The water storage capacity of HMW can easily go up to 90% (Xiao et al., 2014), whereas standard soil reaches only about 65% (Kirkham, 2014). It is lightweight, so these compositions can be used even for roof renovations. Its density varies between 76 kg·m^{-3} and 1027 kg·m^{-3}, depending on water saturation and the type of panel (CSI a.s, 2014b). In comparison, a fully saturated substrate can weigh approximately 1300 kg·m^{-3}. The light weight of HMW is beneficial for roof statics as well as for its initial construction (better handling, ease of storage on roof and transport). Its considerable water permeability in both vertical and horizontal direction (CSI a.s, 2014b) guarantees possible eliminations of drainage dimple membranes in most cases. On the other hand, compared to natural soils and substrates, the production process of mineral wool is quite demanding and has higher environmental impacts. Fig. 2 shows the scheme of the production process. It also lacks nutrients contained in common soil. Thus in the case of higher vegetation (SIGRs and IGRs) nutrients have to be added artificially or the material has to be combined with a substrate layer.

This work assesses environmental impacts related to the life cycle of four SIGR assemblies further described in the following section: two common SIGR assemblies with intensive substrate (Assemblies 1 and 2) and two assemblies combining HMW with extensive substrate (Assemblies 3 and 4).

2. Materials and methodology

The presented LCA follows the whole life cycle of the assessed

Table 1
Vegetation forms and substrate depths for various types of green roofs and its greening according to (FLL, 2008).

	Necessary depth of the vegetation support [cm]	4	6	8	10	12	15	18	20	25	30	35	40	45	50	60	70	80	90	100
Extensive	Moss, sedum	■	■	■																
	Sedum, moss, herbaceous plants		■	■	■															
	Sedum, herbaceous, grass plants				■	■	■													
	Grass, herbaceous plants						■	■	■											
Semi intensive	Grass, herbaceous plants					■	■	■	■	■	■	■								
	Wild shrubs, coppices					■	■	■	■	■	■	■	■	■	■					
	Coppices and shrubs						■	■	■	■	■	■	■	■	■					
	Coppices								■	■	■	■	■	■	■	■	■	■	■	■
Intensive	Lawn						■	■	■	■	■	■								
	Low-lying shrubs, coppices						■	■	■	■	■	■	■	■	■					
	Medium-height shrubs								■	■	■	■	■	■	■					
	Medium-height coppices											■	■	■	■	■	■			
	Tall shrubs and coppices															■	■	■	■	■
	Large bushes, small trees																			■
	Medium-size trees																			

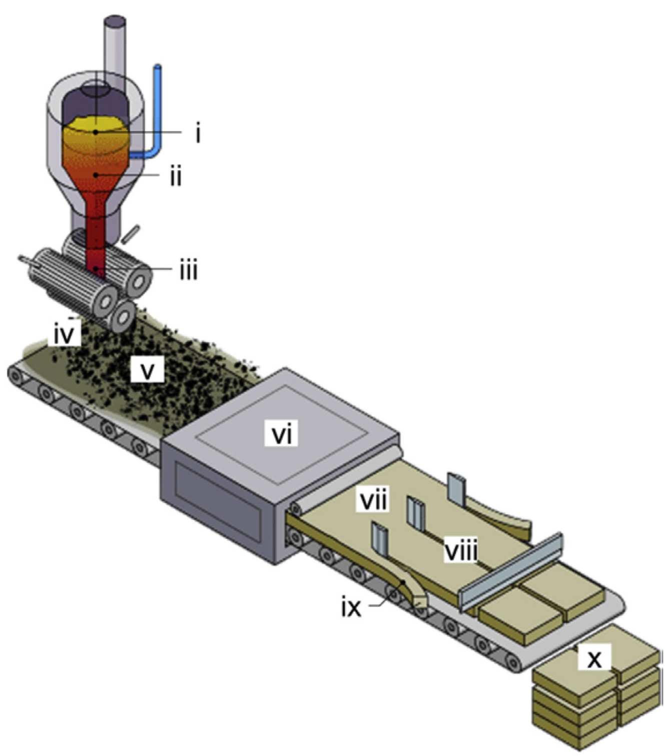

Fig. 2. Production of mineral wool. i – raw materials (e.g. slag and basalt) insertion; ii – melting; iii - fiberizing and injection of binders; iv – conveyor belt; v – uncured "grey" mineral wool; vi – curing at around 200 °C; vii – cured mineral wool; viii – longitudinal and transversal cutting; ix – cut waste to be recycled; x – finished mineral wool panels (Eurima, 2016).

roof assemblies in compliance with the following standards and literature. LCA framework is defined in international standards (especially ISO 14040, (ISO, 2006a),) or their national variants (e.g. Czech standards ČSN EN 15804 (UNMZ, 2014) and ČSN EN 15978 (UNMZ, 2012a) that have the same content and status as the originals) and Product Category Rules (PCRs, (Rossi, 2014),) for Environmental Product Declarations (EPDs) serve as the basis for this assessment. These standards define general guidelines for the LCA of building elements and materials (especially ČSN EN 15804) – e.g. they divide a building element's life cycle to stages and modules as shown in Fig. 3. The PCRs further specify the assessment methodology for building materials – they especially define recommended characterization models and impact categories. The following subsections define the system boundaries of the presented assessment, calculation methods, databases and software.

2.1. Scope and limitations of the assessment

The assessment is divided into two parts corresponding with the specified goals. In the first part the functional unit is 1 m^2 of the green roof assembly with a 200 mm thick layer of growing medium (substrate or substrate and HMW respectively). The thickness is selected based on information about demands of plants specified in Table 1. This part focuses on the evaluation and comparison of the environmental impacts of the individual roof assemblies with regard to the use of substrate or HMW as a substrate replacement. However in order to highlight the differences in results between individual materials the functional unit purposefully omits one significant factor: varying energy losses through the assessed roof assemblies. Adding more materials with higher-than-average thermal resistance (e.g. HMW) into the roof assemblies should

A1 to A3: Product stage	A4 to A5: Construction process stage	B1 to B7: Use stage	C1 to C4: End of life stage
A1: Raw material supply **A2: Transport** **A3: Manufacturing**	**A4: Transport** A5: Construction/Installation process	B1: Use **B2: Maintenance** B3: Repair **B4: Replacement** B5: Refurbishment B6: Operational energy use B7: Operational water use	C1: De-construction or Demolition **C2: Transport** C3: Water Processing **C4: Disposal**
D: Benefits and loads beyond the system boundary (Reuse, Recovery and Recycling potential)			

Fig. 3. Life cycle stages and modules according to ČSN EN 15978. Modules included in the presented assessment are highlighted in boldface.

reduce heat losses and related environmental impacts during the building's service life. This assumption leads to the second part of the assessment which tries to address the environmental impacts related with reducing heat losses through the roof assemblies. In our opinion the simplest way to do this is "enhancing" the functional unit with the U-value (or thermal transmittance, (ISO, 2007),). For the purpose of the presented assessment, a U-value of 0.24 $W \cdot m^{-2} \cdot K^{-1}$ is set. This U-value is specified in the Czech standard ČSN 73 0540-2 (UNMZ, 2012b) as sufficient for a flat roof. To reach this U-value a layer of EPS thermal insulation is added to each assembly. The boundary conditions considered in the assessment include:

- The impact of varying weight of the individual assemblies on the design of the load-bearing structure is not evaluated in the assessment. Based on weights of the individual assemblies (see section 2.2.1) we assume that all assemblies could share the same load-bearing structure.
- The mild climate of the Czech Republic (Central Europe) is considered in the assessment. This is reflected especially in the need of fertilizers for plants, lack of artificial irrigation and length of the green roof assemblies' service life – see section 2.2 for details. Expected service life used in this assessment is 20 years. This period is based on the materials' technical specifications and recommendations provided by the producers in the Czech Republic. Green roofs can serve for much longer periods. But it is assumed that after this period the assessed roof assemblies would require deep renovation and replacement of most layers. Any renovation in general is hard to predict. Its extent depends on many variables such as local climate and quality of the materials. In the authors' opinion such estimates would unnecessarily increase the uncertainty of the assessment's results.
- The life cycle of a product is divided into four stages and 16 modules shown in Fig. 3. Only the modules highlighted in boldface are included in this LCA. Modules A5 (Construction/Installation process) and C1 (De-construction or demolition) are omitted, because there will be minimal environmental impacts related with the construction and dismantling of the assessed green roof assemblies – e.g. small amount of energy used to power a crane. Other omitted modules are B1 (Use), B3 (Repair) and B5 (Refurbishment). There are no direct impacts related to the "use" of a green roof and no repairs or refurbishment is considered during the defined service life. Module B7 (Operational water) is omitted, because no additional irrigation is needed according to information in (FLL, 2008). The average precipitation in the Czech Republic is around 700 mm annually (CHMI, 2016). The design of the assessed green roofs does not consider specific plant species. In general the thickness of the substrate layer (200 mm) is suitable for plants specified in Table 1. The specified precipitation should be sufficient for representatives of the plants grown on SIGRs in the region (e.g. Sedum Floriferum, Festuca ovina, Euphorbia myrsinites) (SZÚS, 2016). Module C3 (Water processing) is omitted too – no waste water (which is not included in other modules) is expected. Module B6 (Operational Energy) is also omitted. This module can include the energy necessary to cover heat losses through the assessed roof assemblies. It is omitted in the first part of the assessment as it would overshadow the environmental impacts of the rest of the assemblies' life cycle – the differences between the results of the materials would be hard to see. It is omitted in the second part of the assessment as well because the environmental impacts related with it would be the same for all four assemblies due to a common U-value.

2.2. Inventory analysis

Generally, the inventory analysis (or Life Cycle Inventory, LCI) is the basis of any LCA. All the necessary data about an assessed material or system has to be gathered during this phase of the assessment. This sub-section describes the inputs and outputs considered in the presented LCA.

Various literature of green roof designing is taken into account for the calculated assemblies. Although the core document for assemblies' setting was German Green Roofing Guidelines (FLL, 2008), Austrian (AS, 2010), Swiss (Beuth Verlag GmbH, 2013) or English (Groundwork Sheffield, 2011) standards were also considered. Furthermore, topical research papers (e.g (DIBt, 2013). and the works cited above), other literature (Xiao et al., 2014) and results of measurements (CSI a.s, 2014a; CSI a.s, 2014b) guarantee the paper is up to date. All SIGR assemblies described below are designed to have the same thickness of vegetation layer for comparison purposes and follow the recommendation of Green Roofing Guidelines. Physical parameters of described materials are adopted from their respective data sheets. The assessed assemblies are shown in Fig. 4. The amounts of built-in materials are listed in Tables 2–5. Both types of substrate in the assemblies (intensive and extensive) are represented by a mixture of expanded clay, waste brick shards, waste slag, peat and compost in the assessment. Densities and volume ratios of these materials used in the assessment are specified in Table 6. Data in this table are based on consultations with Czech professionals in the field.

- **Assembly 1** is specified in Table 2. It is a common SIGR assembly based on a green roof substrate and dimple membrane. This assembly is accepted in many European countries, as the aforementioned literature and national standards suggest. It can be used for EGR as well as for IGR assemblies with minor modifications. Intensive substrate is chosen because it can easily supply plants with necessary nutrients and artificial fertilization can be reduced to extensive roof standards. The maximum weight of this assembly in wet state (with maximum water saturation of the growing medium and accumulation layer) is 290 $kg \cdot m^{-2}$.

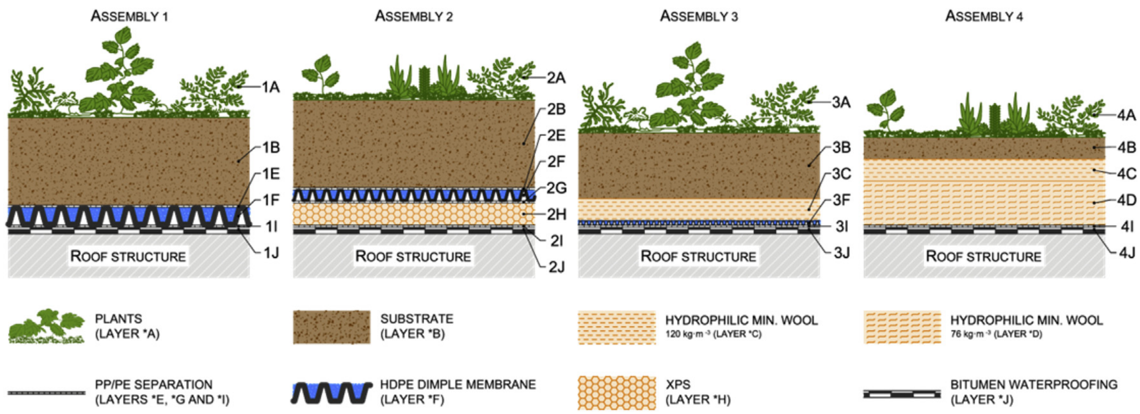

Fig. 4. All assessed SIGR assemblies. The asterisk before a letter in the legend represents assembly number (one to four) shown in the schemes above and in Tables 2–5 – e.g. *A represents layers 1A, 2A, 3A and 4A.

Table 2
Assembly 1: Common SIGR assembly with substrate and dimple membrane. Layers are numbered according to Fig. 4. Weights given in dry state.

Layer			Thickness	Used amount
No.	Function	Material specification	[mm]	[$kg \cdot m^{-2}$]
1A	Greenings	Semi intensive plants	100 - 300 mm	–
1B	Growing medium	Intensive substrate	200 mm	136
1E	Separation and filtration	PP geotextile	1 mm	0.13
1F	Drainage and accumulation	HDPE dimple membrane	40 mm	1.60
1I	Protection and separation	PP geotextile	2 mm	0.30
1J	Waterproofing and root barrier	Bitumen top-layer membrane with Al reinforcement	2 mm	2.40
		Bitumen base membrane	4 mm	5.00

- **Assembly 2** is specified in Table 3. It is a modification of Assembly 1. A thermal insulation panel made of extruded polystyrene (XPS) is added. This can reduce heat losses and improve thermal comfort of spaces directly under the roof structure, but only at the cost of increased environmental impacts related to the use of XPS. Such a solution (waterproofing layer under thermal insulation) is also called "inverted" roof assembly and is well known to material manufactures (ZinCo, 2012) and green roof designers, too. The maximum weight of this assembly in wet state is 290 $kg \cdot m^{-2}$. It coincidentally equals the weight of Assembly 1. The added weight of the XPS insulation is compensated by lower water capacity of the designed dimple membrane.

Table 3
Assembly 2: SIGR assembly with substrate, dimple membrane and additional XPS thermal insulation. Layers are numbered according to Fig. 4. Weights given in dry state.

Layer			Thickness	Used amount
No.	Function	Material specification	[mm]	[$kg \cdot m^{-2}$]
2A	Greenings	Semi intensive plants	100–300	–
2B	Growing medium	Intensive substrate	200	136
2E	Separation and filtration	PP geotextile	1	0.13
2F	Drainage and accumulation	HDPE dimple membrane	25	1.35
2G	Water repellent separation	WSL PE foil	1	0.10
2H	Additional thermal insulation	XPS 30 L	50	2.70
2I	Separation and protection	PP geotextile	2	0.30
2J	Waterproofing and root barrier	Bitumen top-layer membrane with Al reinforcement	2	2.40
		Bitumen base membrane	4	5.00

Table 4
Assembly 3: SIGR assembly with substrate, basic water-reservoir HMW panel and safety drainage dimple membrane. Layers are numbered according to Fig. 4. Weights given in dry state.

Layer			Thickness	Used amount
No.	Function	Material specification	[mm]	[$kg \cdot m^{-2}$]
3A	Greenings	Semi intensive plants	100–300	–
3B	Growing medium	Extensive substrate	150	98.25
3C	Growing medium	HMW, 120 $kg \cdot m^{-3}$	50	6.00
3F	Drainage	Turned-up HDPE dimple membrane	8	0.55
3I	Separation and protection	PP geotextile	2	0.30
3J	Waterproofing and root barrier	Bitumen top-layer membrane with Al reinforcement	2	2.40
		Bitumen base membrane	4	5.00

Table 5
SIGR assembly with substrate and HMW panels. Layers are numbered according to Fig. 4. Weights given in dry state.

Layer			Thickness	Used amount
No.	Function	Material specification	[mm]	[$kg \cdot m^{-2}$]
4A	Greenings	Semi intensive plants	100–300	–
4B	Growing medium	Extensive substrate	50	32.75
4C	Growing medium	HMW, 120 $kg \cdot m^{-3}$	50	6.00
4D	Growing medium	HMW, 76 $kg \cdot m^{-3}$	100	7.60
4I	Separation and protection	PP geotextile	2	0.30
4J	Waterproofing and root barrier	Bitumen top-layer membrane with Al reinforcement	2	2.40
		Bitumen base membrane	4	5.00

Table 6
Composition of assessed substrates.

Material	Density	Volume ratio	
	[$kg \cdot m^{-3}$]	Intensive	Extensive
Expanded clay	450	60%	70%
Brick shards	1800	10%	10%
Slag	900	10%	10%
Peat	500	10%	5%
Compost	500	10%	5%

- While Assembly 2 improves the roof's thermal properties, Assembly 3 (see Table 4) increases its water storage potential. The layer of the HMW works as an excellent water absorber. The water storage capacity of this material greatly exceeds standard dimple membranes. Only a drainage membrane with turned-up dimples and lower height (8 mm vs. 40 or 25 mm in Assemblies 1 and 2 respectively) is therefore included. Due to the fibrous structure, the panels also provide space for the plants' root system. Extensive substrate is chosen for this assembly. HMW panels contain no nutrients, so larger doses of nutrients (in form of fertilizers) would be required nonetheless. The maximum weight of this assembly in wet state is 280 $kg \cdot m^{-2}$.
- **Assembly 4** is specified in Table 5. It contains considerable amount of HMW that serves as a near-total substrate substitution. Only a thin layer (50 mm) of extensive substrate helps to cover the HMW panels. The main reason for this is easier rooting of plant cuttings. It also improves the visual perception of the roof assembly as it gives it a natural look. Two layers of HMW panels are under the extensive substrate. The upper layer serves as a spread footing and solidifying substrate layer. The bottom layer serves as a substrate layer and it can also drain excessive water from the green roof assembly without using a dimple membrane. The drainage capacity required in (FLL, 2008) is fulfilled according to tests described in (CSI a.s, 2014a; CSI a.s, 2014b). The maximum weight of this assembly in wet state is 237 $kg \cdot m^{-2}$.

The amount of EPS necessary to achieve the same U-values of the roof assemblies in the second part of the assessment depends on thermal conductivity of individual materials. Thermal conductivity of HMW and roof substrate depends on their water saturation (see Table 7). The applied water saturation rate is based on measurement results (CSI a.s, 2014a) and information in another Czech standard ČSN 73 0540-3 (UNMZ, 2012c). Thermal conductivity of other materials is taken from the producers' data sheets. To achieve the required U-value, it would be necessary to add an extra 130 mm EPS ($\lambda = 0.034\ W \cdot m^{-1} \cdot K^{-1}$ and $\rho = 25\ kg \cdot m^{-3}$) layer to Assembly 1, 80 mm to Assembly 2, 110 mm to Assembly 3 and 90 mm to Assembly 4.

Transport is an integral part of a material's life cycle. In our assessment it is represented by modules A2, A4 and C2. Transport of raw materials (module A2) is already included in the LCI database entries specified in sub-section 2.2.1, therefore it is not addressed in the inventory analysis. A diesel truck and 100 km transport distance are presumed for transport of materials between production facilities and construction site (module A4). The same diesel truck and transport distance of 20 km are used when modelling transport between construction (demolition) site and waste treatment facilities.

The use stage of the assemblies' life cycle is represented by modules B2 (Maintenance) and B4 (Replacement). It is assumed that during the short life span maintenance would consist only of regular fertilizing of the substrate, visual checks and weeding. The recommended annual dosage of fertilizers is specified in literature (FLL, 2008; AS, 2010). It varies between 5 and 8 $g \cdot m^{-2}$ twice a year – spring and autumn dose. The dosage depends on the content of nutrients in the substrate. Generally speaking, intensive substrates contain more organic compounds (20% vs. 10% respectively, see Table 6) which also serves as nutrition for growing plants. The presented assessment includes 5 $g \cdot m^{-2}$ doses for Assemblies 1 and 2 (intensive green roof substrate) and 8 $g \cdot m^{-2}$ doses for Assemblies 3 and 4 (mineral wool and extensive substrate). Spring and autumn doses contain different amounts of nutrients depending on the plants' needs. This is represented by the NPK ratio – the ratio between three main components of the fertilizer: nitrogen (N), phosphorous (P) and potassium (K). The presented assessment includes an NPK ratio 19:06:12 in the spring dose and 10:09:19 in the autumn dose recommended by (FLL, 2008). For the purpose of this assessment it was also necessary to specify the amounts of waste created during weeding. Thus, it is estimated that 0.1 kg of plants (in dry state) is weeded annually from 1 m^2 of each assessed roof assembly. Weeding is also connected with the loss of substrate which is entangled within the weeds' roots. 0.5% annual loss of substrate is estimated in the assessment. Assumingly (due to relatively small volume), this waste is added to common municipal

Table 7
Dependance of thermal conductivity coefficient λ on water saturation rate (CSI a.s, 2014a; UNMZ, 2012c).

Water saturation level	Thermal conductivity coefficient λ [$W \cdot m^{-1} \cdot K^{-1}$]		
	Substrate	HMW 76 $kg \cdot m^{-3}$	HMW 120 $kg \cdot m^{-3}$
Dry state (minimum moisture)	0.700	0.037	0.035
Wet state (maximum moisture)	2.300	0.513	0.320
Average moisture (design value)	1.100	0.156	0.106

waste. Based on the information about waste management in the Czech Republic we assume that this municipal waste is subsequently landfilled (CENIA, 2015). The area of the roof is an influencing factor for this decision. If the green roof area would be under 100 m^2, annual amounts of waste will be rather small. Adding it to municipal waste would be the easiest option in most Czech cities. If the green roof had an area of hundreds or thousands of square meters, other waste management scenarios could become feasible. However, such assumptions are out of scope of this paper. Gradual loss of substrate would be harmful to the plants. Thus, replacement of the lost substrate in five-year periods is also included in the assessment.

It is presumed that only modules C2 (Transport) and C4 (Disposal) have a measurable impact during the End of life stage. Only one End of life scenario is assessed: landfilling of all materials. This decision is based on information in (CENIA, 2015). It states that most of the waste produced in the Czech Republic is re-used (e.g. for landscaping) or landfilled. The substrate would contain organic loads (roots, decomposed plants, etc.) and residual fertilizers at the end of the assemblies' service life. Determining the amount of these residuals is out of the scope of this paper as it depends on many variables (e.g. weather). Inorganic parts (brick shards, burned clay and slag) of the substrate as well as the rest of the green roof assemblies would be considerably degraded by weather and ingrowing plant roots. Such degraded materials would be unsuitable for recycling or re-use, inter alia because of the content of organic matter.

2.3. Specification of the LCI database

A computer model of each roof assembly's life cycle was prepared, before calculating the environmental impacts. Data gathered during LCI were assigned to processes in the ecoinvent 2.0 database developed by the Swiss Centre for Life Cycle Inventories. This database includes approximately 4000 datasets representing products, services and processes (Frischknecht et al., 2007). However, not all processes, materials or technologies necessary for the presented assessment are defined in this database. This means that several simplifications were necessary:

- There is no single process suitable to represent a dimple membrane or separation foil in the database. The processes *RER: polyethylene, HDPE, granulate, at plant* (dimple membrane and PE foils) and *RER: polypropylene, granulate, at plant* (geotextile) therefore represent the materials and process *RER: extrusion, plastic film* describes their processing.
- Brick shards and slag are waste from the production of bricks or (for example) metal. To represent this, an approach similar to that of Chenani et al. (2015). is applied. Processes *CH: disposal, building, brick, to final disposal* and *CH: disposal, slag, unalloyed electr. steel, 0% water, to residual material landfill*, in negative quantities represent environmental impacts of prevented landfilling. As both materials have to be crushed to gravel before mixing with other substrate components, the process *RER: crushing rock* is also included.
- The producer of the HMW gave the authors access to results of an LCA study of this material. The results of the study are used to represent this material in the presented assessment. In the authors' opinion, the use of this data brings more precise total results than the use of generic data from the ecoinvent database.

2.4. Impact assessment

According to ISO 14040 (ISO, 2006a) the impact assessment (or Life Cycle Impact Assessment, LCIA) is the next step of any LCA. It is aimed at evaluating the significance of potential environmental impacts using the LCI results. The data gathered during LCI are associated with specific environmental impact categories. Various LCIA methods exist – see (Barnthouse et al., 1998) or (Hauschild et al., 2013) for more information. The presented assessment uses the CML2001 method developed by the Institute of Environmental Sciences, University of Leuven, Netherlands (Barnthouse et al., 1998) with impact categories and characterization factors in version Nov. 10. Only seven out of all impact categories within the characterization model – those required by PCRs mentioned above (see Table 8, (AS, 2010),) – are taken into account for the presentation of results in the following sections. This is due to the fact that the LCA study of HMW used as one of the data sources (see subsection 2.3) includes results only in these impact categories. Normalization CML2001 Nov. 10, EU25 is also applied in general comparisons of all four assessed assemblies to improve clarity of the results. It enables an easy way to summarise the results from multiple categories, their joint presentation and interpretation. The GaBi 4 software tool is used as a main tool during the LCIA.

3. Results and discussion

3.1. SIGR LCA – the first goal of the presented research

The overall results of the first part of the assessment are summarized in Table 9, while Fig. 5 shows the comparison of all assessed variants in the individual impact categories. It can be seen that under specified boundary conditions Assembly 2 has the highest environmental impacts in four categories (ADP elements, GWP100, ODP, POCP) and Assembly 4 in the remaining three (ADP fossil, AP, EP). These results are caused by the use of man-made materials with an energetically demanding production process (mineral wool) or high demand on non-renewable raw materials, such as oil (XPS). Assembly 2 has a clear disadvantage. The XPS doesn't have another function other than increasing thermal insulation, which is not taken into account in this part of the assessment.

Direct interpretation of the results in the individual impact categories may seem difficult at first sight. Thus, normalized results of the assessment are also presented. Fig. 6 illustrates shares of individual impact categories on the total normalized results. AP, EP

Table 8
List of assessed impact categories and normalization references.

Impact category	Unit	Normal. ref.
Abiotic Depletion Potential (ADP, elements)	[kg Sb-Eq.]	8.46E+07
Abiotic Depletion Potential (ADP, fossil)	[MJ]	3.15E+13
Acidification Potential (AP)	[kg SO_2-Eq.]	2.81E+10
Eutrophication Potential (EP)	[kg Phosp.-Eq.]	1.32E+10
Global Warming Potential, 100 years (GWP100)	[kg CO_2-Eq.]	5.02E+12
Ozone Layer Depletion Potential, steady state (ODP)	[kg R11-Eq.]	8.94E+07
Photochem. Ozone Creation Potential (POCP)	[kg Ethene-Eq.]	8.48E+09

Table 9
Environmental impacts of the assessed SIGR assemblies in chosen impact categories.

Impact category	Unit	Assembly 1	Assembly 2	Assembly 3	Assembly 4
ADP, elements	[kg Sb-Eq.]	8.41E-05	9.78E−05	8.09E−05	7.18E−05
ADP, fossil	[MJ]	5.99E−01	7.58E−01	8.35E−01	1.07E+00
AP	[kg SO_2-Eq.]	2.95E−01	3.35E−01	4.00E−01	4.62E−01
EP	[kg Phosp.-Eq.]	1.30E−01	1.33E−01	1.32E−01	1.95E−01
GWP100	[kg CO_2-Eq.]	6.21E+01	8.92E+01	7.25E+01	7.94E+01
ODP	[kg R11-Eq.]	4.94E−06	4.95E−04	2.42E−05	4.34E−05
POCP	[kg Ethene-Eq.]	3.02E−02	3.76E−02	2.66E−02	2.32E−02

and GWP100 categories have the greatest share on the total normalized results, i.e. up to 30.99%, 29.03% and 32.16% respectively in the case of Assembly 4. Importantly enough, this represents a 92.18% share in its total normalized result. This is also the reason why Assembly 4 has the same total normalized environmental impacts as Assembly 3 which scored worse in more impact categories. Assembly 4 has worse environmental impacts in two out of three most important impact categories (AP and EP).

Fig. 7 shows normalized results in yet another perspective. It presents the distribution of environmental impacts between the life cycle stages according to ČSN EN 15978 (UNMZ, 2012a). It is clear that the highest environmental impacts are related with Product and Construction process stages (modules A1 to A4) – the building materials. Their share on total results ranges from 63.53% in Assembly 1 up to 88.37% in Assembly 4. These results also explain why Assembly 4 has such high total environmental impacts. It is due to the fact that it includes the most man-made materials (e.g. mineral wool replacing the substrate). Even significant reduction (55.69% compared to Assemblies 1 and 2) of environmental impacts related with the Use stage (regular maintenance – modules B2 and B4) of the Assembly 4's life cycle is unable to balance such an increase. The effect of End of Life stage on the results of the assessment is negligible (max. 1.13% share on results). The results of the Product, Construction process and Use stage are further discussed in the following sections.

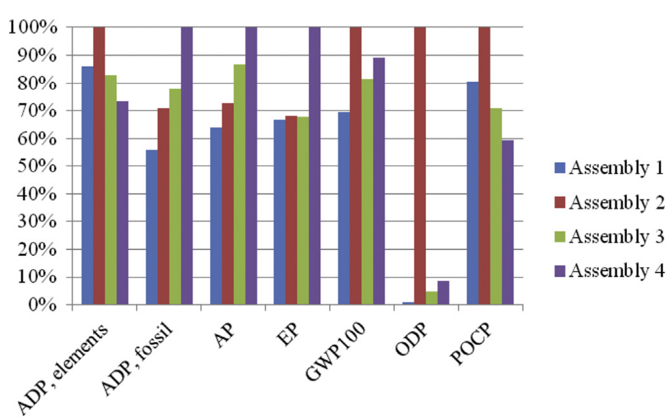

Fig. 5. Comparison of environmental impacts of the assessed SIGR assemblies in chosen impact categories.

3.1.1. Building materials – modules A1 to A4

As previously mentioned, the Product stage (modules A1 – A3) and Construction process stage (only module A4 in this paper) significantly influence overall the environmental impacts of all assessed roof assemblies. Hence, their detailed analysis seems appropriate. Results of the calculations show that module A4 (Transport) has less than a 1% share in the total results of the Product stage and Construction process stage in this LCA. Thus this sub-section focuses only on the Product stage.

Fig. 8 shows the distribution of the environmental impacts (normalized totals) among the materials. It is clear that the intensive substrate mixture has a dominant share in the environmental impacts of Assemblies 1 and 2–65.68% and 41.64% respectively. In comparison, shares of all other materials on environmental impacts of Assemblies 3 and 4 are overshadowed by the environmental impacts of the HMW. This material is responsible for 49.80% and 79.98% of both assemblies' environmental impacts respectively. These results are partially compensated by the lower environmental impacts related to the extensive substrate. Still, Assembly 4 has the highest environmental impacts of all the assessed assemblies in modules A1 to A3 of their life cycle. It is also worth mentioning that normalized environmental impacts of 76 $kg \cdot m^{-3}$ and 120 $kg \cdot m^{-3}$ HMW in Assembly 4 are almost the same, despite different volumes of these materials (50 mm vs. 100 mm respectively). The reason for this is that the environmental impacts related to the production process (stone melting, baking or transforming, see Fig. 2) are much higher than the environmental impacts related to the raw materials. Thus, doubling the density (or thickness) of the HMW certainly does not mean doubling of the related environmental impacts.

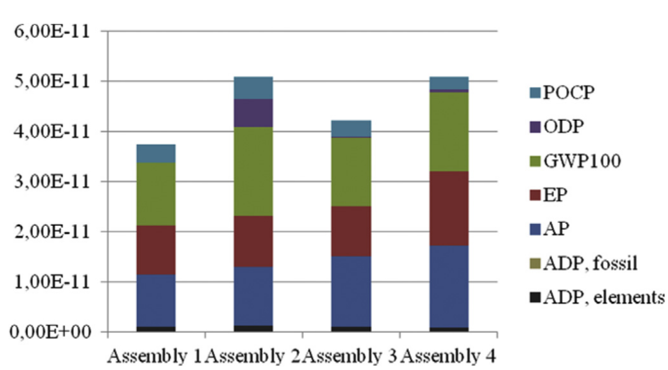

Fig. 6. Sums of normalized results of the assessed SIGR assemblies.

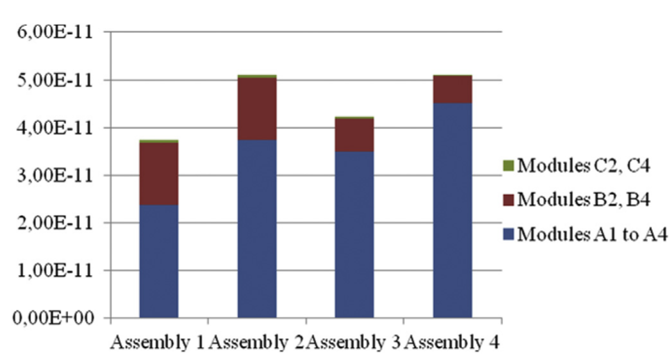

Fig. 7. Sums of normalized results of the assessed SIGR assemblies.

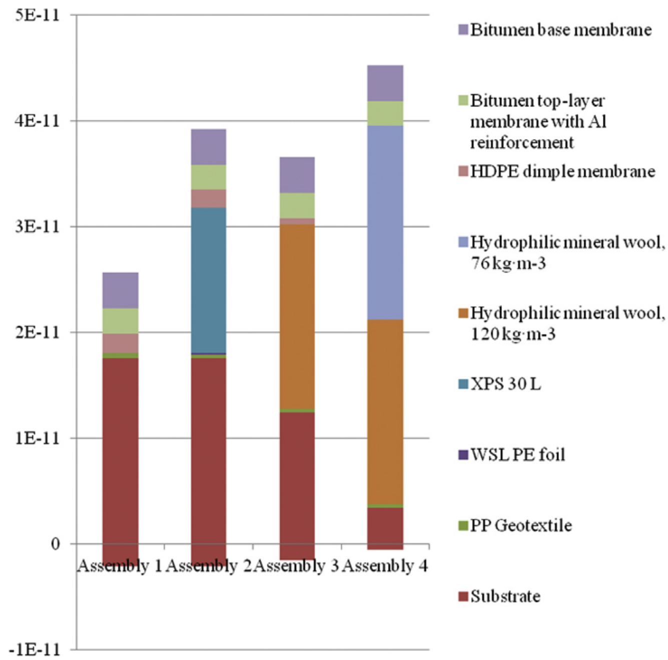

Fig. 8. Shares of used materials on normalized environmental impacts of modules A1 to A3 of the assessed SIGR assemblies' life cycle.

Negative values of normalized environmental impacts related to the substrate are the result of avoided landfilling of brick shards and slag. Out of all materials making up the substrate, expanded clay has the largest share in the calculated environmental impacts – 59% in the case of the intensive substrate (Assemblies 1 and 2) and 73% in the case of the extensive substrate (Assemblies 3 and 4).

3.1.2. Maintenance and replacement – modules B2 and B4

According to Fig. 7, modules B2 and B4 have a significant impact on the normalized results of the presented LCA. As mentioned in section 2.2, these modules include fertilizing, weeding and replacements of substrate. Fig. 9 shows the distribution of environmental impacts (normalized totals) between the inputs and outputs related to these processes. Weeding has the dominant share in these environmental impacts. The explanation is simple. Large quantities of substrate and plants weeded during the expected 20-year service life of the assessed SIGR assemblies and their subsequent landfilling are included in the module B2. In the case of Assemblies 1 and 2, it means approximately 15 kg of landfilled waste – almost one eighth of the assemblies' original weight. This is the reason why the Use stage has a significant share on environmental impacts of these assemblies – 34.82% in Assembly 1 and 25.51% in Assembly 2. Assembly 4 only has a thin layer of substrate, which is reflected by the relatively low environmental impacts of the Use stage.

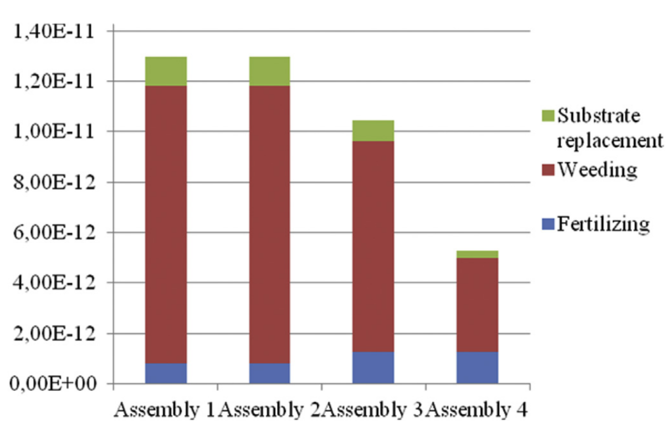

Fig. 9. Shares of all inputs and outputs on normalized environmental impacts of modules B2 and B4 of the assessed SIGR assemblies' life cycle.

3.2. Evaluation of the impact of adding U-value to the functional unit – the second goal of the presented assessment

The results presented in sub-section 3.1 show that the environmental impacts of the assessed green roof assemblies are significantly influenced by the added built-in man-made materials – XPS and HMW in particular. The results presented in this section take into account the main advantage of these materials: their thermal properties. A layer of EPS is added to the assemblies to equalize their U-value. Presumably the difference between environmental impacts of individual assemblies should even out or the results may turn in favour of the assemblies with more built-in man-made materials. The total normalized environmental impacts of all assessed green roof assemblies with added EPS are summarized in Fig. 10. It shows that equalizing their U-values by adding EPS only has a minor effect on the mutual ratios between their environmental impacts. Assembly 4 retains the highest total normalized environmental impacts. It is closely followed by Assembly 2 with 0.30% difference between them. Assembly 1 is still the most environmentally-friendly. The difference between Assembly 1 (based on substrate) and Assembly 4 (based on HMW) decreased from 26.71% (see Table 9) to 19.64%. The difference between Assembly 1 and Assembly 3 also decreased, from 11.51% to 7.54%. Additions of even more EPS would further reduce the differences between assemblies, but at the cost of an unnecessary increase of the total environmental impacts.

3.3. Comparability of the results with other LCA studies

There aren't many works using LCA to evaluate the environmental impacts of SIGRs or even green roofs in general. Existing studies use varying methodologies, characterization models and impact categories. Out of the cited works only Chenani et al. (2015) and Gargari et al., (2016) use the CML characterization model, although in different versions. And only Chenani et al. have published enough information to make even a partial comparison possible. They evaluate environmental impacts of two EGR (100 mm of substrate) assemblies with thermal insulation. The methodology differs, but at least partial comparison of the

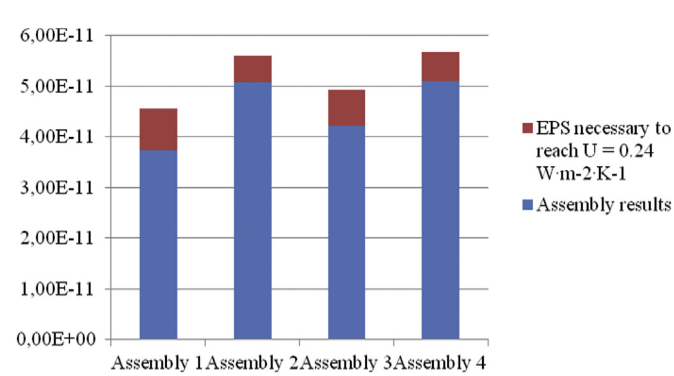

Fig. 10. Normalized environmental impacts of the assessed SIGR assemblies with added EPS insulation.

environmental impacts during the Product stage is possible. For example the GWP100 of the assemblies assessed by Chenani et al. is 26.4 and 32.23 kg CO_2-Eq. respectively in the Product stage. Assembly 1 presented in this paper is the most similar to assemblies evaluated by Chenani et al. Its GWP100 is 46.7 kg CO_2-Eq. in the Product stage. If the thickness of the substrate in Assembly 1 would be reduced to 100 mm, it would have GWP100 of 29.7 kg CO_2-Eq. in the Product stage, which is just between Chenani et al.'s results. Given the differences in assemblies' composition and boundary conditions we find the result of the comparison satisfactory. In our opinion it indicates that from the LCA point of view the SIGRs are comparable with other types of green roofs.

4. Conclusions

This paper shows the readers environmental impacts related to the life cycle of a specific type of green roofs: semi intensive green roofs. The goal of the paper was to investigate the suitability (and tenability) of individual materials in context of assessed SIGR assemblies' total environmental impacts. Based on the results we can conclude that the lowest environmental impacts are related with Assembly 1 – the simplest assessed assembly with no substrate replacement or added thermal insulation. This is mostly due to high environmental impacts related to the production of the assessed insulation materials – XPS and HMW. From the environmental point of view, it seems that the addition of XPS thermal insulation to a green roof assembly is not justifiable at all. Differences between substrate-based Assembly 1 and Assemblies 3 and 4 using the HMW substrate also favour the more "natural" Assembly 1. Production of built-in HMW significantly increases environmental impacts of Assemblies 3 and 4. However, the replacement of substrate mixture by HMW (inter alia) reduces environmental impacts related with the use of these assemblies. Total differences are not insurmountable and there are ways for further improvements, e.g.: modifications of the production process (out of the scope of this paper) or implementation of environmentally-friendly energy sources during the production of the necessary building materials. It was already mentioned that the production of XPS and HMW consumes relatively high amounts of energy. Electricity production in the Czech Republic has rather high environmental impacts, due to the high share of coal power plants. According to the ecoinvent 2.0 database, these environmental impacts are almost three times higher than those of the electricity production in Austria. Or seven times higher than those of the electricity production in France. The Czech energy mix was used in the LCA of the HMW. This material has major share in the environmental impacts of Assemblies 3 and 4. Thus, a simple change of the energy mix could significantly influence the results in favour of the assemblies with a substrate replaced by HMW. Based on these facts we conclude that the overuse of man-made thermal insulation in green roofs should always be carefully considered. On the other hand, man-made substrate replacements such as HMW can have environmental impacts comparable to "natural" substrate mixtures. With environmentally-friendly production technologies they can possibly be a better choice than "natural" substrates. Not to mention other positives, such as lower weight or increased water retention potential of the roof assemblies.

Acknowledgements

This paper has been prepared under project No. LO1408 "AdMaS UP - Advanced Materials, Structures and Technologies", supported by the Ministry of Education, Youth and Sports under the „National Sustainability Programme I".

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