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A comparison of the environmental impacts of different categories of insulation materials

Callum Hill [a,b,*], Andrew Norton [c,d], Janka Dibdiakova [a]

[a] Norwegian Institute of Bioeconomy Research (NIBIO), PO Box 115, NO-1431, Ås, Norway
[b] JCH Industrial Ecology Ltd, Bangor, Gwynedd, LL57 1LJ, UK
[c] School of the Environment, Natural Resources and Geography, Bangor University, Bangor, Gwynedd, LL57 2DG, UK
[d] Renuables, 41 High Street, Menai Bridge, Isle of Anglesey, LL59 5EF, UK

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ABSTRACT

More than sixty environmental product declarations of insulation materials (glass wool, mineral wool, expanded polystyrene, extruded polystyrene, polyurethane, foam glass and cellulose) have been examined and the published information for global warming potential (GWP) and for embodied energy (EE) has been analysed and is presented. A peer-review literature survey of the data for GWP and EE associated with the different insulation products is also included. The data for GWP (kg carbon dioxide equivalents) and EE (megajoules) is reported in terms of product mass or as a functional unit (FU) (1 m^2 of insulation with R = 1 m^2 K/W). Data for some classes of insulation material (such as glass wool) exhibit a relatively narrow range of values when reported in terms of weight of product or as a functional unit. Other classes of insulation material exhibit much wider distributions of values (e.g., expanded polystyrene). When reported per weight of product, the hydrocarbon-based insulation materials exhibit higher GWP and EE values compared to inorganic or cellulosic equivalents. However, when compared on an FU basis this distinction is no longer apparent and some of the cellulosic based materials (obtained by refining of wood chips) show some of the highest EE values. The relationship between the EE and GWP per kg of insulation product has also been determined as being 15.8 MJ per kg CO_2 equivalents.

1. Introduction

According to statistics supplied by the European Commission (EC) Directorate General of Energy, the built environment is responsible for 40% of energy consumption and 36% of carbon emissions in the European Union (EU) [1]. As part of a commitment to reduce greenhouse gas emissions by 20% below 1990 levels, the EC introduced the Energy Performance Buildings Directive (2010/31/EU) in 2010, which states that all new buildings must be ‘nearly zero energy buildings’ by 31 December 2020 (public buildings by 31 December 2018) and that EU countries must set minimum energy performance standards for new buildings. Under the Energy Efficiency Directive (2012/27/EU) EU countries must draw up building renovation strategies under their National Energy Efficiency Action Plans.

As the insulation performance of buildings improves, more attention must be given to the embodied energy and associated carbon emissions attributable to the insulation and other building products [2,3]. Until recently, such comparisons have been made in an essentially ad-hoc fashion, but the methodology used is being increasingly regulated. In March 2011, the Construction Products Regulation (CPR) (EU regulation 305/2011) was introduced, replacing the Construction Products Directive (89/106/EEC). The CPR lays down harmonised rules for the marketing of construction products in the EU and states that where a European standard exists then this has to be used. It further states that ‘For the assessment of the sustainable use of resources and of the impact of construction works on environment Environmental Product Declarations should be used when available’. There have been standards issued that apply to the construction sector in order to ensure greater comparability of the environmental performance of products. The

Abbreviations: CEL, cellulose; CO_2eq, carbon dioxide equivalents; CPR, Construction Products Regulation; CTGA, cradle to gate; CTGR, cradle to grave; EC, European Commission; EE, embodied energy; EPD, environmental product declaration; EPS, expanded polystyrene; EU, European Union; GW, glass wool; GWP, global warming potential; LCA, life cycle assessment; LCIA, life cycle impact assessment; MW, mineral wool; PCR, product category rules; PEF, product environmental footprint; PU, polyurethane; XPS, extruded polystyrene.

* Corresponding author at: Bangor Business Centre, 2 Farrar Road, Bangor, Gwynedd, LL57 1LJ, UK.
E-mail address: enquiries@jchindustrial.co.uk (C. Hill).

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standard ISO 21930 gave some guidance on both product category rule (PCR) and Environmental Product Declaration (EPD) development [4], but this was recently replaced in the EU by EN 15804 [5], which is a core PCR for building products and it is therefore considerably more detailed and prescriptive. Sitting below this core PCR are more product specific PCRs (e.g., for insulation) which are currently developed by EPD Program Operators, although these will increasingly be the subject of international standards in the future. According to ISO 14025 [6] different EPD Program Operators are encouraged to harmonise their PCRs to allow for better comparability of EPDs. These standards are increasingly removing the flexibility that was once available when determining the environmental performance of products and services, thereby increasing confidence when making comparisons between different products in a specific product category. At the time of writing this submission over 60 published EPDs on insulation products have been published, which represents a rich source of data for determining the environmental impacts of different materials within the thermal insulation product category. The gain in acceptance of EPDs as the "environmental yardstick" means that this number is anticipated to rise with an approximately 20% increase in newly registered construction EPDs being published each year, meaning more data will become available for study in the future. The advent of machine readable EPDs, which input their results directly into databases, (such as IBU.data, from Institut Bauen und Umwelt.Data), as well as databases of EPD and LCA results becoming established (such as the work of the International open Data Network for Sustainable Building in creating InData) [7] means that it will be even easier to compare EPD results. There is consequently a potential risk of future EPD (and PEF) results to be compared without critical examination of descriptions of the calculations or understanding of potential discrepancies between the use of secondary datasets or revisions in LCIA methodologies. It has been shown that published building product EPDs do contain discrepancies and inaccuracies, even when performed according to the PCRs specified in EN 15804 [8]. Gelowitz and McArthur [8] conducted a review of published EPDs for building products and came to the following conclusions:

- Discrepancies between life cycle inventory methodology, environmental indicators and life cycle inventory databases were a barrier to making comparisons between EPDs.
- There was a high level of incomparability between EPDs using the same PCR, which was unexpected and should not occur.
- There was evidence of poor verification practices, demonstrated by a high proportion of EPDs containing contradictory data.
- The EN 15804 harmonisation standard has not been entirely successful. The proportion of valid comparisons was much higher with EN 15804-compliant EPDs, but the overall level of comparability was still low.

Passer et al. [9] described the experiences of different European countries with regards to built environment EPDs, examining the differences between EPD's, PEF's and the CPR. This study concludes that harmonisation is needed on the impact categories and assessment models/indicators, as we move towards PEF as well as the system boundaries and life cycle scenarios, biogenic carbon emissions, and data quality requirements.

This means that it is important to discus and understand the level of impact such discrepancies may have in order to harmonise the development of future revisions in standards and PCRs. An analysis of published EPDs may also be used to reveal if there are typical values for environmental impacts that can be assigned to specific product categories, or if the spread of data is too wide to allow for comparisons to be made. In addition, there is also academic work that has been performed to determine the environmental burdens associated with the production of different insulation materials and a comparison between this data and EPD data is required to see if there is any agreement. An analysis of this type is currently absent in the scientific literature.

Lasvaux et al. [10] studied generic and product specific construction material LCA results and reported that GWP and Cumulative Energy Demand (CED) were the most reliable LCIA indicators studied when using and comparing LCA data originating from differing data sets. There was between 26% and 33% relative deviation (respectively) between a generic materials database (Ecoinvent) and the EPD data studied, across a wide range of building materials. Even less deviation was found at a full building level, with differences in final building LCA results less than 20% and sometimes closed to 0%, due to compensations among the materials' percentage of relative deviation in CED and GWP, whereas other less reliable indicators confirmed the deviations found at the database scale. The environmental impacts of 28 building materials were compared using the Life Cycle Impact Assessment Indicators (LCIA) of EN 15804, for the cradle to gate part of the life cycle. They concluded that for some impact categories mixing LCA databases is not appropriate, but that for the main indicators used by the building sector (GWP and embodied energy) the information was reasonably comparable between the two sets of data.

Biswas et al. [11] presented a study of the environmental impacts of insulation materials in a North American context where the embodied energy (EE) and global warming potential (GWP) of polyisocyanurate foam, extruded polystyrene (XPS), expanded polystyrene (EPS) and aerogel were reported. The study investigated the whole life cycle from cradle to grave, but this was broken down into different life cycle stages, giving separate information on the raw material acquisition and manufacturing stages. A functional unit (FU) of 1 m^2 of insulation with a thermal resistance (R) = 1 m^2 K/W was used for comparison purposes. They employed a sign convention where energy consumed and environmental impacts were reported as negative quantities, whereas energy saved or impacts avoided were reported as positive quantities. Su et al. [12] modelled the production of eight different types of insulation: EPS, XPS, polystyrene, PU, mineral wool (MW), glass wool (GW), foam glass (FG) and phenol-formaldehdye (PF) in a Chinese context. The life cycle boundary was cradle to grave, but did not include any transportation of insulation to building site, or transport associated with disposal. The model also included a component to account for uncertainty. Comparison was made using a FU of 1 m^2 of insulation material with an R = 1 m^2 K/W. Embodied energy data was also presented in terms of unit mass (MJ/kg) and was compared with that reported by Anastaselos et al. [13], Zabalza et al. [14] and Gu et al. [15]. Anastaselos et al. [13] quoted embodied energy values per kg of insulation and also in terms of a FU, which was defined as 1 m^2 of load-bearing wall element with a U value of 0.48–0.5 W/m^2 K. The environmental impacts in the latter case included the materials used to construct the wall. In a study of the effects of different insulation materials on the energy consumption and CO_2 emissions associated with a building, Tettey et al. [16] reported on the embodied energies in kWh per kg associated with the production and transport to site of a range of insulation materials, including rock wool (MW), GW, foam glass (FG), cellulose (CEL) and EPS. Papadopoulos and Giama [17] undertook a comparative study of stone wool and XPS, reporting GWP on a per kg basis and for 1 m^2 of insulation with a U = 0.8 W/m^2 K. The impacts were considered for the manufacture stage of the life cycle and included transport to the building site (distance not stated). Energy consumption for producing 1 kg of insulation was also quoted (0.3 kWh/kg for stone wool and 0.86 kWh/kg for XPS). These values are very low (by a factor of 10x) compared to what is commonly reported in the literature. Schmidt et al. [18,19] reported on an investigation of stone wool, paper wool and flax insulation, using a FU of 1 m^2 of insulation with a R = 1 m^2 K/W, giving embodied

Table 1
Embodied energy for different insulation materials in MJ/kg. Glass wool (GW), mineral wool (MW), extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PU), foam glass (FG) and cellulose (CEL). System boundary is for cradle to gate except where indicated.

Reference	GW	MW	EPS	XPS	PU	FG	CEL
11	–	–	112.1	105.2	93.5	–	–
12	–	22.2c	102.9c	85.4c	87.3c	158.8c	–
12,15	–	–	117.0	–	74.0	–	–
12,13	–	24.6	80.8	87.1	92.2	–	–
12,14	–	26.4	105.5	–	103.8	–	–
16	19.5b	10.0b	30.7b	–	–	13.3b	2.7b
17	–	1.1	–	3.1	–	–	–
18,19	–	17.5c	–	–	–	–	20.5c
20,21	–	26.4	105.5	–	103.8	–	10.5
21	28.6	–	159.1	72.8	140.4	–	8.3
22	–	–	125.8	93.9a	106.2	–	–
23,24	14.0	–	105.0	–	–	–	3.3
23,27	–	19.2	106.7	–	–	–	–
23,26	–	18.0	127.0	–	137.0	–	0.9
29	28.0	16.8b	–	–	–	–	20.2c

a average of two thicknesses, b cradle to site, c cradle to grave.

energy and GWP values for a cradle to grave system boundary. They quoted an EE of 17.52 MJ per kg and a GWP of 1.223 kg CO_2eq per kg for rockwool (MW) and an EE of 20.5 MJ/kg and GWP of 0.645–2.221 kg CO_2eq per kg for paper wool (CEL), depending upon the end of life scenario. Bribián et al. [20] reviewed the LCAs of a range of building materials, giving data for some insulation materials (EPS, rock wool, PU, cork, cellulose fibre and wood wool). The LCA data were reported for a FU of 1 kg, but little detail was given on how the LCAs were performed. The system boundary included material manufacture, transport to site (100 km), construction and demolition of building and final disposal of product. A comprehensive review of insulation materials has appeared recently [21]. This includes a study of some comparative analyses of embodied energy and GWP of insulation materials divided into cradle to gate (CTGA) and cradle to grave (CTGR) analyses, taking data from manufacturers and the scientific literature including data from [19,20]. The data were reported for a functional unit of a mass of material required to produce 1m^2 of insulation with a thermal resistance (R) of 1 m^2 K/W. Pargana et al. [22] reported on the cradle to gate LCAs of XPS, EPS, PU, cork and expanded clay, using a functional unit of the weight in kg required to produce 1 m^2 of insulation with R = 1 (m^2 K)/W. The environmental impacts were assigned to different stages of the life cycle defined according to EN 15804:2012 (A1, A2, A3). This paper also reported on previous LCA studies of insulation materials, listing the impact categories reported. Harvey [23] conducted a study of the effect of different blowing agents on the environmental impact of foam insulation materials, and included a table showing the EE associated with the production of various insulation materials, using data from [24–27]. This has been incorporated into Table 1, with the exception of the data of Lenzen and Treloar [25], who quote several widely different EE values for mineral wool and glass wool combined and included several other materials in the data. Harvey [23] also quoted a study by Petersdorff et al. [26]. This was a study prepared for the European Insulation Manufacturers Association by Ecofys which used EE data obtained from Bauhaus Universität Weimar, Institut für Industrielle Bauproduktion [28]. The Bath Inventory of Carbon and Energy [29] quotes an embodied energy value of 28 MJ/kg for GW (cradle to site), with an associated carbon footprint of 1.35 kg CO_2eq per kg; rockwool (MW) is assigned an EE of 16.8 MJ/kg and 1.12 kg CO_2eq per kg (cradle to gate). It is not clear how the GW or MW values are derived. They also quote a EE value of 20.2 MJ/kg and GWP of 0.63 kg CO_2eq per kg for paper wool (CEL) (cradle to grave) taken from the work of Schmidt et al. [18,19]. Tingley et al. (2015) [30] reported on cradle to gate LCA studies of insulation materials which were based upon a previous study (PF) [31] the Ecoinvent database (EPS, MW) or the Bath ICE database poly(isocyanurate foam) (PIR). They quoted GWP values (kg CO_2eq) of 7.02 (PF), 4.21 (EPS), 1.13 (MW) and 4.26 (PIR) per kg of product and also for a functional unit (in their paper quoted as 1 m^2 of insulation with an R = 3 m^2 K/W, but which has been converted to the FU used in this paper to give GWP values of 6.3 (PF), 4.8 (EPS), 5.2 (MW) and 4.3 kg CO_2 eq. (PIR). The EE data per kg of insulation product taken from all of the above cradle to factory gate studies (modules A1-A3 in EN 15804) are summarised in Table 1.

The published EPDs of insulation products, many of which have been produced according to the same or similar PCRs, have been used to calculate the embodied energy and GWP burdens associated with the manufacture of these materials. This study was conducted in order to survey the currently published data set and collate the information, which is reported herein. A comparison of this data is made with the already published information in the peer review literature.

2. Methodology

EPDs were obtained from the available and open access websites of EPD program operators. The majority were published by the Institute Bauen und Umwelt (IBU) of Germany, with some published by the Building Research Establishment (UK), the International EPD System (Sweden), Underwriters Laboratories (USA), Norge EPD, or EPD Danmark. In making a comparison of the various published EPDs it is crucial to understand the background and calculation methods used. The most recent European EPDs now follow the EN 15804 core PCR. This divides up the life cycle of a product into different stages. For the purposes of this study, only life cycle stages A1 (raw material supply), A2 (transport) and A3 (manufacturing) have been compared (i.e., cradle to factory gate). This represents, potentially, the most accurate LCA data and does not involve assumptions regarding service life, maintenance and disposal, etc., which can increase the uncertainties when comparisons are made. For the purposes of this analysis, only GWP (embodied carbon dioxide emissions) and embodied energy associated with the manufacture (cradle to factory gate) of the products are considered, along with the quantity of atmospheric carbon dioxide sequestered in the product (embedded carbon) in biogenic materials. Not all the published EPDs follow the EN15804 standard, e.g. those published outside of Europe and those published prior to 2013. Even where EN15804 is followed, there may be differences in the methodologies, databases and assumptions. In order to make valid comparisons between materials or products, it is necessary to decide upon the appropriate criteria to make these comparisons. It was decided to use weight as one comparator and a FU based upon thermal performance as another. In order to perform the calculations, it was necessary to gather the following information about the insulation materials/products: environmental impact, thermal conductivity, area of product, thickness of product, weight of product (or density). Thermal conductivity of a material is reported as a lamda (λ) value (units: W/m K), which is defined as the heat flow (in Watts) through 1 m^2 of material of thickness 1 m when there is a temperature difference of 1 K. Insulation performance in a building is usually reported as an R (thermal resistance) value (units: m^2 K/W), or as the reciprocal, U (thermal transmittance) value (units: W/m^2 K). A higher R value or lower U value corresponds to better insulation effectiveness. The relationship between these different parameters is as follows: R = t/λ, where t is the thickness of the material in m, and R = 1/U. In order to make a comparison, it is also necessary to define a quantity of material which gives a specified insulation performance. For this study, the functional unit of comparison was defined as: 1 m^2 of a material or product with an R value of 1 m^2 K/W and U value of 1 W/m^2 K. In all EPDs, the GWP was reported as kg CO_2eq per declared unit, but the reporting of embodied energy was more complex. In some cases, the embodied energy was explicitly stated, but where the EPD followed EN 15804 (the majority of EPDs) then the embodied energy was obtained by summation of the two impact categories (use of renewable primary energy excluding renewable primary energy resources used as raw materials, use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials). Shreshta et al. [32] note that there are varying definitions of embodied energy which depend upon the context of the study. For the purposes of this study, embodied energy is defined as the primary energy used for the production of the insulation material from cradle to factory gate (modules A1-A3) (including both renewable and non-renewable primary energy). Transport to installation site, maintenance and disposal are all excluded from this study. Embodied energy is also referred to as indirect, or grey, energy and it is one contribution to the cumulative energy demand (CED) associated with the use of a product. The CED is defined as the total primary energy used during the lifetime of a product and since only the cradle to factory gate phase of the life cycle is being considered in this paper, the CED and EE are identical.

3. Results and discussion

Environmental data of insulation materials is reported in a variety of ways, usually as a given weight, or volume or square meterage. In order to allow for a meaningful evaluation and comparison of the published data it is necessary to know the volume, density and thermal performance (λ) of the material. For the purpose of this study the insulation products were grouped into different categories: glass wool (GW), mineral wool (MW), expanded polystyrene (XPS), extruded polystyrene (EPS), polyurethane foam (PU) (polyisocyanurate was also included), foam glass (FG) and cellulose (CEL). Glass wool (sometimes confusingly referred to as glass mineral wool) is produced by heating sand and glass at 1300–1450 °C. The glass is often sourced from recycled material. Blown glass wool insulation is not mixed with resin, but if glass wool batts or blankets are made, a resin is added to bond the fibres. Mineral wool (also called rock mineral wool, rock wool, stone wool) is made by a similar process to glass wool, but the source material is rock (basalt, dolomite, slag, diabase) rather than glass and a higher processing temperature of 1600 °C is used. Expanded polystyrene is manufactured by adding pentane to polystyrene beads, which is then evaporated off to foam the beads. Extruded polystyrene is made by melting polystyrene beads and passing the melt through an extruder with the addition of a blowing agent. Polyurethane foam is produced by a reaction between a polyisocyanate and a polyether backbone polyol. Polyisocyanurate foam is made by a reaction between polyester backbone derived polyol and a polyisocyanate. Phenol formaldehyde foam is a thermoset resin produced by a reaction between phenol and formaldehyde. The cellulosic fibres in this study were either derived from recycled paper, or using fibres obtained from wood chips by a chemical or mechanical separation technique.

The EPDs used in this analysis are listed in Table 2, along with which product sub-category they are assigned to.

The embodied energies (EEs) for the insulation materials are shown in Fig. 1 as MJ per kg. The lowest EEs are generally associated with the some of the cellulose (CEL) materials and two of the foam glass (FG) products, when reported as MJ/kg. One of the EE/kg values for foam glass is approximately10 x higher than the other three (this is for the manufacture of a foam glass slab whereas the others are for the manufacture of foam glass pellets). In terms of EE per kg, glass (GW) and mineral wool (MW) show the next highest

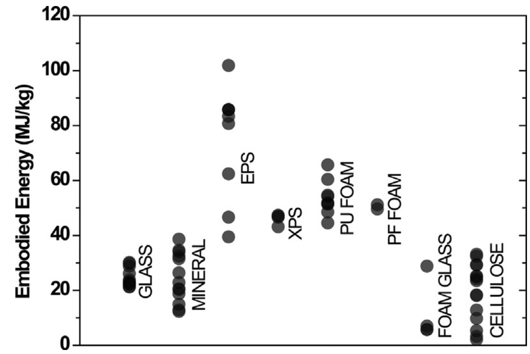

Fig. 1. The embodied energy values associated with the different classes of insulation material on a weight basis. The data are taken from the published EPDs only.

impact after CEL and FG, with the MW exhibiting a greater spread of values (12.3–38.6 MJ/kg) compared with GW (21.2–30.1 MJ/kg). Inspection of the literature data reproduced in Table 1, shows that the values fall within the range given in the EPDs, with the exception of that reported by Papadopoulos and Giama [17] for MW (0.3 kWh/kg = 1.08 MJ/kg), which is a factor 10 x smaller than the lowest value found in any other study. The EE/kg values for EPS are generally the highest of those recorded for all the insulation materials, with a few exceptions. The literature data tends towards the upper end of the spread of values shown by the EPDs. The lowest value (40 MJ/kg) reported is that for generic EPS (EPS2) conducted for EUMPS (European Association of EPS) for the Scandinavian region. A more representative value for the product is in the region of 82 MJ/kg, being the highest EE per unit mass of all the products compared in this study. XPS generally shows a lower EE/kg and a narrower spread of values (43–47 MJ/kg). The literature values are 30–40 MJ/kg higher than those obtained from the EPDs, with the exception of the study of Papadopoulos and Giama [17] (0.86 kWh/kg = 3.1 MJ/kg), which can only be considered anomalous and was not used in this study any further. PU foam insulation exhibits a range of values from 37.1-60.4 MJ/kg, which are all considerably lower than the embodied energy values quoted in the literature and reproduced in Table 1. Some of the PU insulation materials are faced with aluminium foil (e.g., PU1, PU2), mineral material (e.g., PU5) or steel sheeting (PU8), which tend to have higher EE's, but this is not universally observed. It is not possible to comment on the PF insulation, given the small sample set from the same manufacturer. The foam glass gives data that is among the lowest EE/kg of all the materials studied, but one product gives much higher values. The higher value is for the production of a glass foam board and the lower values for the production of foam glass granules. The data for CEL has a very wide range of values of embodied energy (2.1-32.4 MJ/kg), with recycled cellulose insulation falling in the lower part of the range, but virgin wood fibre-based insulation produced by mechanical processing giving much higher values.

Fig. 2 shows a box and whisker plot of the EE/kg data from the published EPDs and also all of the literature data included in Table 1, with the exception of that reported by Papadopoulos and Giama [17]. The box represents the interquartile range between the 25th and 75th percentile, the open square inside the box is the mean and the line is the median. The whiskers represent the standard deviation and the open circles the maximum and minimum values. This shows very clearly that the mean and median values for GW (mean 24.8 MJ/kg, median 23.4 MJ/kg) and for MW 23.5 and 22.8 MJ/kg) are close and that there is no significant statistical difference in the EE/kg values between GW and MW. However, the spread of data for MW is considerably larger than that for GW, but the product descriptions in the EPDs do not give any indication why this should be the case. The EE/kg values for all of the hydrocarbon-

Table 2
List of EDPs evaluated for this study.

Cat.	EPD reg	Operator	Dec. Unit	λ (W/m k)	GWP kg CO_2eq	EE (MJ)
GW1	50	BRE Global	1 m^3	0.0425	16.0	318.8
GW2	51	BRE Global	1 m^3	0.0395	20.3	403.9
GW3	52	BRE Global	1 m^3	0.035	27.8	552.4
GW4	53	BRE Global	1 m^3	0.033	33.1	658.3
GW5	59	BRE Global	1 m^3	0.044	12.2	254.8
GW6	EPD-SDT-2012112-D	IBU	1 kg	0.037	1.5	29.8
GW7	EPD-KIN-20140161-CBB1-EN	IBU	1 m^3	0.032	30.2	707.4
GW8	EPD-KIN-20140160-CBB1-EN	IBU	1 m^3	0.035	19.0	438.0
GW9	EPD-KIN-20140162-CBB1-EN	IBU	1 m^3	0.04	11.4	253.7
GW10	EPD-KNA-20140052-CBC1-EN	IBU	1 m^3	0.035	28.5	521.2
GW11	EPD-GHI-2011212-D	IBU	1 kg	0.0365	1.8	30.1
MW1	9	BRE Global	1 m^2	0.35	15.7	474.1
MW2	532	Int EPD Sys	1 m^2	0.03676	1.2	49.0
MW3	Generic mineral wool (Europe)	eurima	1 m^2	0.035	4.4	81.5
MW4	EPD-KIN-20130163-CBC1-EN	IBU	1 m^3	0.039	53.7	668.7
MW5	EPD-KIN-20140242-CBD1-EN	IBU	1 m^3	0.04	95.8	1746.0
MW6	EPD-KNA-20140053-CBC1-EN	IBU	1 m^3	0.035	76.7	937.8
MW7	EPD-GHI-2011112-D	IBU	1 kg	0.0375	1.6	26.4
MW8	00131E rev1	EPD NORGE	1 m^2	0.037	1.3	13.5
MW9	EPD-DRW-2012111-EN	IBU	1 m^3	0.04	34.4	609.7
MW10	EPD-DRW-2012121-EN	IBU	1 m^3	0.04	82.6	1213.0
MW11	EPD-DRW-2012131-EN	IBU	1 m^3	0.04	141.0	1941.4
MW12	NEPD 131E	EPD NORGE	1 m^2	0.037	1.5	20.8
MW13	EPD-URS-2012121-D	IBU	1 m^3	0.036	25.4	465.5
MW14	EPD-URS-2012131-D	IBU	1 m^3	0.0335	42.6	762.6
MW15	EPD-URS-2012211-D	IBU	1 m^3	0.0335	41.4	758.4
MW16	EPD-URS-2012111-D	IBU	1 m^3	0.04	25.4	465.5
MW17	EPD-URS-2012221-D	IBU	1 m^3	0.04	28.8	578.9
EPS1	EPD-DAW-2011421-D	IBU	1 m^3	0.035	46.34	1329.6
EPS2	EPD-EPS-20130078-CBG1-EN	IBU	1 m^2	0.034	2.0	33.5
EPS3	EPD-DAW-2011411-D	IBU	1 m^3	0.035	46.3	1329.6
EPS4	EPD-DAW-2011431-D	IBU	1 m^3	0.035	46.3	1327.9
EPS5	MR_ENV_EPD_ICF_20140003_IT	IBU	1 m^2	0.036	2.3	26.0
EPS6	MR_ENV_EPD_ICF_20140003_IT	IBU	1 m^2	0.031	2.0	30.0
EPS7	EPD-IVH-2009111-D	IBU	1 m^3	0.035	79.0	2291.9
EPS8	EPD-IVH-2009211-D	IBU	1 m^3	0.035	48.0	1383.8
EPS9	EPD-IVH-2009311-D	IBU	1 m^3	0.035	62.0	1847.5
XPS1	EPD-DOW-2013111-D	IBU	1 m^2	0.031	10.2	151.1
XPS2	EPD-EXI-20140154-IBE1-EN	IBU	1 m^2	0.035	9.4	158.6
XPS3	EPD-FPX-20140156-IBE1-DE	IBU	1 m^2	0.035	9.5	161.2
XPS4	EPD-EXI-20140155-IBE1-EN	IBU	1 m^2	0.035	9.4	159.4
PU1	EPD-IVP-20140207-IBE1-DE	IBU	1 m^2	0.023	15.0	241.4
PU2	EPD-IVP-20140208-IBE1-DE	IBU	1 m^2	0.023	12.9	216.6
PU3	EPD-IVP-20140206-IBE1-DE	IBU	1 m^2	0.026	13.1	209.4
PU4	EPD-PUE-20130285-CBE-EN	IBU	1 m^2	0.023	12.0	202.6
PU5	EPD-PUE-20130286-CBE1-EN	IBU	1 m^2	0.026	12.9	204.9
PU6	EPD-PUE-20140017-CBE1-EN	IBU	1 m^2	0.026	16.6	267.4
PU7	EPD-PUE-20140018-CBE1-EN	IBU	1 m^2	0.026	24.9	401.2
PU8	EPD-PUE-201400121-CBE1-EN	IBU	1 m^2	0.023	37.5	512.2
PU9	EPD-UNI-20140123-IBA1-EN	IBU	1 m^2	0.023	12.2	173.5
PF1	EPD-KSI-20130227-IAC1-EN	IBU	1 m^2	0.021	9.9	173.7
PF2	EPD-KSI-20130228-IAC1-EN	IBU	1 m^2	0.021	10.2	178.9
FG1	EPD-MIS-20150020-IAA1-DE	IBU	1 m^3	0.103	19.2	937.0
FG2	EPD-MIS-20150019-IAA1-DE	IBU	1 m^3	0.082	15.2	738.9
FG3	EPD-TPH-2010111-E	IBU	1 kg		0.2	7.0
FG4	EPD-PCE-2013256-IAA1-EN	IBU	1 kg	0.041	1.3	28.8
CEL1	EPD-ISOCELL-2014-1-ECOINVENT	Bau EPD	1 m^3	0.039	3.7	89.7
CEL2	EPD-ISOCELL-2014-1-GaBi	Bau EPD	1 m^3	0.039	2.8	100
CEL3	135E	EPD Norge	1000 kg	–	1189.0	9768.0
CEL4	VTT-CR-01200-14catenate	VTT	1 kg	0.039	0.2	5.3
CEL5	MD-14002-DA	EPD Danmark	1 kg	–	0.1	2.1
CEL6	4787319688.101.1	UL Environmental	1 m^3	–	295.0	6148.0
CEL7	EPD-GTX-2011211-E	IBU	1m^3	0.049	214.1	8263.5
CEL8	EPD-GTX-2011211-E	IBU	1m^3	0.040	102.6	4006.9
CEL9	EPD-GTX-2011211-E	IBU	1m^3	0.042	100.6	4037.2
CEL10	EPD-GTX-2011211-E	IBU	1m^3	0.050	182.5	7589.4
CEL11	EPD-PAV-2013254-CBG1-EN	IBU	1m^3	0.038	59.9	2560.0
CEL12	EPD-PAV-2013255-CBG1-EN	IBU	1m^3	0.047	105.4	4337.0
CEL13	EPD-PAV-2014197-CBG1-EN	IBU	1m^3	0.044	82.1	4936.2

based insulation materials are considerably higher than GW or MW. EPS exhibits the widest range out of all the insulation materials studied and the highest average (and median) magnitude for EE per unit weight of 85.8 MJ/kg. The median values for XPS are 47.3, PU 63.1, PF 50.4, FG 9.4 and CEL 18.2 MJ/kg. However, the CEL category should be split into products made from recycled paper, which has a median EE of 4.3 MJ/kg (average 5.1 MJ/kg) and from fibreboard (median 25.1 MJ/kg, average 25.0 MJ/kg).

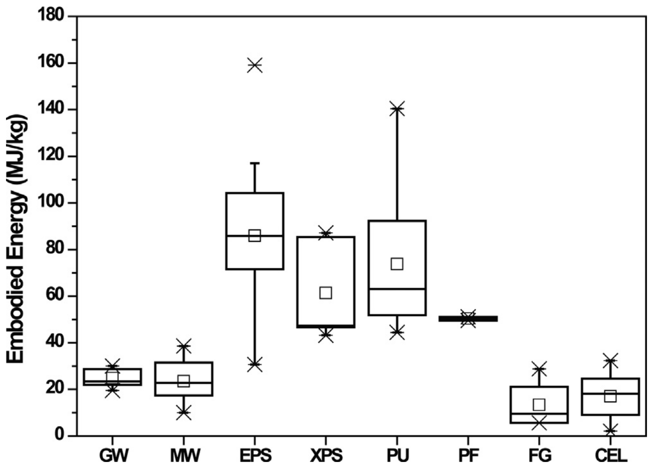

Fig. 2. Box and whisker plot of the embodied energy per kg of the insulation materials. The open square is the average value, the line in the box is the median value, the whiskers represent the standard deviation, the limits of the box are the 25 and 75 percentile and open circles are the maximum and minimum values. The data includes the published EPDs and embodied energy values reported in the peer review literature.

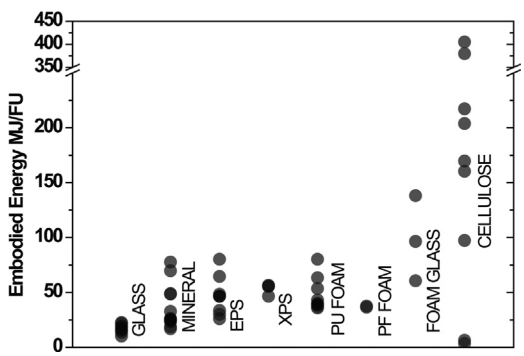

Fig. 3. Embodied energy data reported for the functional unit (1 m^2 with R = 1 m^2 K/W). Data are taken from published EPDs only.

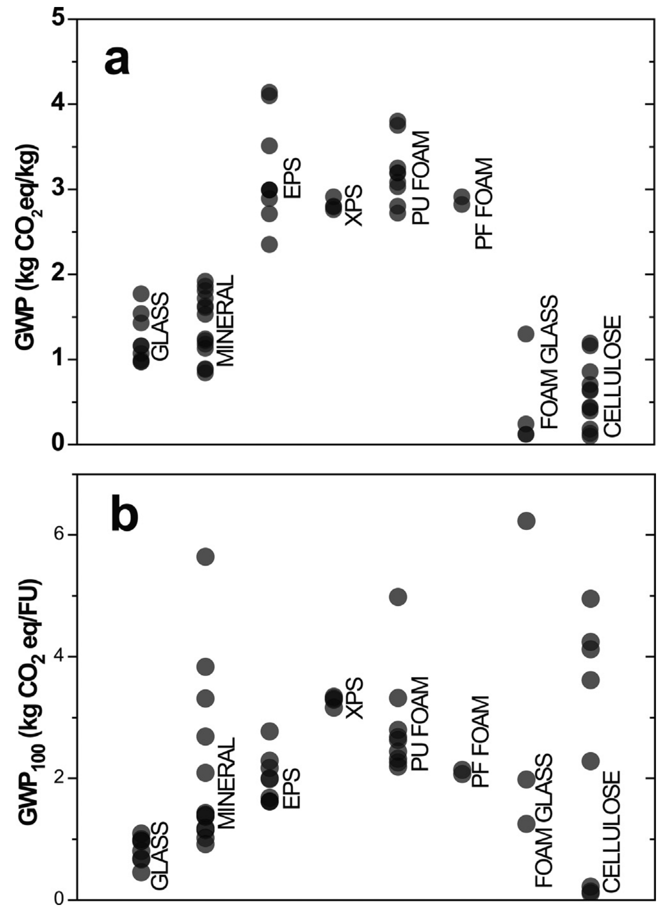

Fig. 4. Global warming potential data reported per kg of insulation (a) and for the functional unit (1 m^2 with R = 1 m^2 K/W). Data are taken from the EPDs only.

The embodied energy data are also compared in terms of the FU in Fig. 3, although in some cases the necessary information was not available in the EPDs to make the calculations. The range of EE values for MW becomes considerably larger when this is calculated in terms of the FU (16.8-77.7 MJ/FU), whereas the spread of EE values for GW remains relatively narrow (10.1-22.6 MJ/FU). The EE values quoted for glass fibre and glass wool in the review of Schiavoni et al. [21] (134.2 and 229.0 MJ/FU, respectively) are considerably higher by a factor of 10x, whereas those for rockwool (20.8, 53.1, 63.3 MJ/FU) fall within the range for MW reported here. There was little data available for PF insulation, but it is interesting to note that the average value of 37 MJ/FU obtained from the EPDs is considerably lower than that reported by Su et al. [12] (52 MJ/FU). The performance of the XPS, EPS, PU and PF products is competitive with many of the MW materials, although somewhat higher than the GW products. CEL now shows the highest of all the EE/FU values and in some cases CEL also exhibits the lowest values (CEL1/2, CEL4), with a considerable spread of data in between. The highest values are exhibited by products made by refining of virgin wood chips as a source of fibre for wet-formed boards and the lowest from blown recycled cellulosic products, such as waste paper. The remarkable difference in environmental performance of the wood fibreboard insulation products when embodied energy is calculated in terms of the FU, rather than unit weight of product, is noteworthy. However, it should also be noted that the use of regenerative primary energy (such as hydro or wind) in the production process was not considered, nor was energy recovered at the end of the life cycle (e.g., by incineration of biogenic material with energy recovery) taken into account in this study, which is only a cradle to factory gate analysis. The high EE values associated with the fibreboard products arise from the electricity consumption of the refiners and from the energy involved in drying the wet-formed fibreboards. Harvey et al. [23] listed EE values of 1.6-2.8 MJ for cellulose and 113–127 MJ for fibreboard for the same functional unit as used herein. Although fibreboard and cellulose insulation have been included in the same category in this paper, this is in reality two different product types and this should be taken into account when interpreting these results.

The GWP/kg data are presented in Fig. 4a. Visually, both GW and MW exhibit very similar values and a spread of data. The hydrocarbon-based insulation shows higher GWP/kg values and the FG and CEL products the lowest in some cases. However, when the same data are presented in terms of the FU (Fig. 4b), then some substantial differences are observed. In particular, the MW data shows a much greater spread of data compared with GW. The EPS material also appears to be more competitive with the MW. CEL still gives the lowest GWP per FU for the recycled cellulose products, even without including the sequestered atmospheric carbon, whereas examples of the cellulosic products made from virgin wood fibres give some of the highest GWP values (again, without taking into account sequestered carbon in the biogenic material). This large change in performance emphasises the need for the comparison of products to be made on the basis of an appropriate functional unit, rather than a declared unit and also shows the need

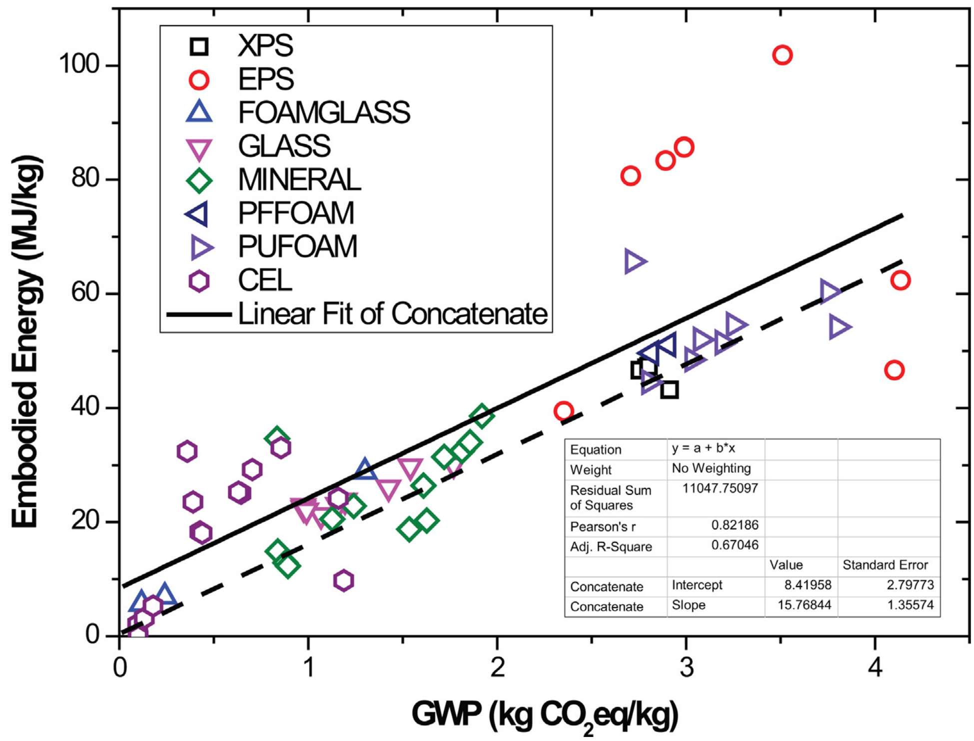

Fig. 5. Relationship between embodied energy per kg of insulation and GWP per kg of insulation. The solid line represents the best linear fit through all the data points. The dotted line is an offset of the best fit line through the origin. Data are taken from the EPDs only.

to treat insulation made from recovered cellulose fibres differently from virgin wood fibre products.

An analysis of the relationship between embodied energy (MJ/kg) and GWP (kg CO_2eq/kg) is shown in Fig. 5. Also shown is a linear fit through all of the data points (solid line) along with the associated fitting parameters. Also shown is a fit through the data which was obtained by subtracting the intercept from the best fit line (8.4 MJ/kg). Most of the embodied energy data falls within a band +/− 8.4 MJ/kg above and below this line, with a few exceptions. Several of the EPS data points show much higher EE/kg values, but the corresponding GWP/kg values are relatively much lower compared with the main dataset. Inspection of the text of the EPDs does not reveal any reason for this difference with these materials. With the cellulosic insulation materials exhibiting higher EEs, these are all associated with the production of fibres from virgin wood chips with wet-forming, whereas the products with low embodied energies are those manufactured from recycled paper. The influence of the grid energy mix on the relationship between embodied carbon dioxide equivalent emissions and embodied energy is an important consideration. Huijbregts et al. [33] found a good correlation between fossil CED and GWP and resource depletion, but the correlations of fossil CED with acidification, eutrophication, tropospheric ozone formation, stratospheric ozone depletion and human toxicity were much lower and for land-use they were absent. Cabeza et al. [34] and Jiao et al. [35] note that there is a relationship between embodied energy and GWP for primary production, for some building components and that there is also a link between embodied energy and cost of buildings, which is related to the energy intensity per unit GDP for that country.

The CEL materials are distinguished from all other insulation materials in that they are largely composed of atmospheric carbon dioxide, since the biogenic material content is obtained from photosynthesis. When this is taken into account, the GWP plots of Fig. 6 are obtained, where the GWP for the cellulosic materials is obtained by subtracting the sequestered atmospheric carbon from

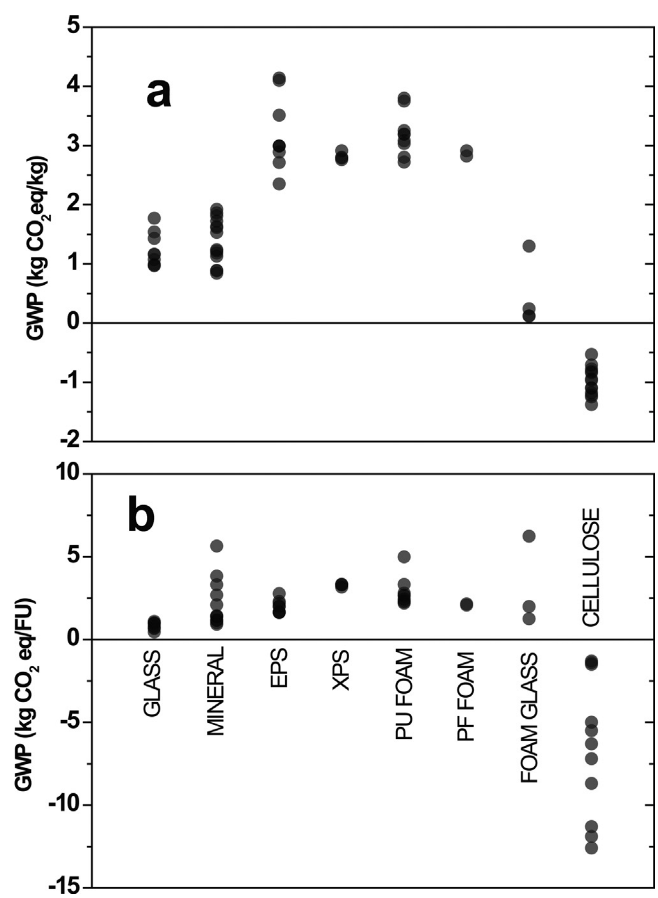

Fig. 6. Global warming potential of the insulation materials excluding (a) and including (b) the sequestered carbon in the cellulosic insulation materials. Data are taken from the EPDs only.

the embodied carbon dioxide equivalent emissions. These show that all of the cellulose-based insulation materials act as stores for atmospheric carbon dioxide (negative CO_2eq values), even when the embodied carbon dioxide emissions associated with the product manufacture are taken into account. In Fig. 6a there is a spread in data for CEL centred around −1 kg CO_2eq/kg, with the value dependent upon the biogenic content, composition (lignin to cellulose proportion), moisture content and embodied GWP emissions. A much larger range of GWP values (between −1.3 and −12.6 kg CO_2eq/FU) is obtained when the GWP is determined based upon the functional unit, since this depends upon the amount of material used in the insulation product (better insulating products use less biogenic material and have a smaller negative GWP value as a consequence). It should be noted that the actual benefit of the Sequestered CO_2 is dependent on the length of time it is stored in the product and there is currently much debate over how this is potentially included in a product carbon footprint [36].

The low variance in the glass wool data might be attributable to large economies of scale and production optimisation. The skew of mean averages of PU, GF and possibly MW towards the lower end of impacts may indicate a trend towards more efficient methods of production – with some less optimised products still in the market place? Other sources in variation include the use of different databases for secondary data, although most of the data examined in this study used the GaBi data base, with most of the remainder using Ecoinvent. A recent study was conducted by Herrmann and Moltesen [37] on the LCA calculation tools SimaPro (which uses the Ecoinvent database) and GaBi, to determine what effect this had upon the outcomes. They found that in many cases the answers from these two databases were the same or closely similar. One of the cellulose products examined in our study has two EPDs, one of which was generated using the Ecoinvent database (CEL1) and the other using the GaBi database (CEL2). The GWP values in these EPDs differ by approximately 30% and the EE by about 15% due to the use of different databases.

4. Conclusions

Many product sub-categories exhibit a large range of values of both EE and GWP and in most cases it is possible to select a particular product from a sub-category with a lower EE or GWP compared with a product from another sub-category, even when the median or mean value may be higher for all the products in that sub-category. This emphasises the need to consider specific LCA/EPD data when this is available. When such information is not available then it is suggested that the median values reproduced in this paper be used as being the most representative for each product sub-category at this stage. The EE and GWP impact values for the cellulose-based insulation materials should clearly differentiate between products made from wood fibres using a wet forming method and insulation products that are obtained from recycled paper, since products obtained from these two sources have very different environmental profiles. Materials selection for building projects should be made giving due consideration to the environmental impacts, but the reliance on data that does not take into account the inherent uncertainties should be avoided unless product-specific data are used. The environmental data should be based on an appropriate functional unit and must take account of the whole life cycle impacts, not just the cradle to factory gate stage.

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References

[1] https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (last accessed 16/10/2017).
[2] C. Thormark, A low energy building in a life cycle –its embodied energy, energy need for operation and recycling potential, Build. Environ. 37 (2002) 429–435, http://dx.doi.org/10.1016/S0360-1323(01)00033-6.
[3] I. Sartori, A. Hestnes, Energy use in the life cycle of conventional and low energy buildings: a review article, Energy Build. 39 (2007) 249–257, http://dx.doi.org/10.1016/j.enbuild.2006.07.001.
[4] ISO 21930. 2007. Sustainability in building construction – Environmental declaration of building products.
[5] EN 15804. 2012. + A1. 2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products.
[6] ISO 14025. 2006. Environmental labels and declarations – Type III environmental declarations – Principles and procedures.
[7] http://www.oekobaudat.de/en/info/working-group-indata.html (last accessed 16/10/2017).
[8] M. Gelowitz, J. McArthur, Comparison of type III environmental product declarations for construction products: material sourcing and harmonization evaluation, J. Cleaner Prod. 157 (2017) 125–133, http://dx.doi.org/10.1016/j.jclepro.2017.04.133.
[9] A. Passer, S. Lasvaux, K. Allacker, D. De Lathauwer, C. Spirinckx, B. Wittstock, D. Kellenberger, F. Gschösser, J. Wall, H. Wallbaum, Environmental product declarations entering the building sector: critical reflections based on 5–10 years experience in different European countries, Int. J. LCA 20 (2015) 1199–1212, http://dx.doi.org/10.1007/s11367-015-0926-3.
[10] S. Lasvaux, G. Habert, B. Peuportier, J. Chevalier, Comparison of generic and product-specific life cycle assessment databases: application to construction materials used in building LCA studies, Int. J. LCA 20 (2015) 1473–1490, http://dx.doi.org/10.1007/s11367-015-0938-z.
[11] K. Biswas, S. Shrestha, M. Bhandari, A. Desjarlais, Insulation materials for commercial buildings in North America: an assessment of lifetime energy and environmental impacts, Energy Build. 112 (2016) 256–269, http://dx.doi.org/10.1016/j.enbuild.2015.12.013.
[12] X. Su, Z. Luo, Y. Li, C. Huang, Life cycle inventory comparison of different building insulation materials and sensitivity analysis, J. Cleaner Prod. 112 (2016) 275–281, http://dx.doi.org/10.1016/j.jclepro.2015.08.113.
[13] D. Anastaselos, E. Giama, A. Papadopoulos, An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions, Energy Build. 41 (2009) 1165–1171, http://dx.doi.org/10.1016/j.enbuild.2009.06.003.
[14] I. Zabalza, A. Aranda, S. Scarpellini, S. Diaz, Life cycle assessment in building sector: state of the art and assessment of environmental impact for building materials, 1st International Exergy Life Cycle Assessment and Sustainability Workshop and Symposium (ELCAS) (2009) 4–6.
[15] D. Gu, Y. Zhu, L. Gu, Life cycle assessment for China building environmental impacts, Journal of Tsinghua University 46 (2006) 1553–1956.
[16] U. Tettey, A. Dodoo, L. Gustavsson, Effects of different insulation materials on primary energy and CO_2 emission of a multi-storey residential building, Energy Build. 82 (2014) 369–377, http://dx.doi.org/10.1016/j.enbuild.2014.07.009.
[17] A. Papadopoulos, E. Giama, Environmental performance evaluation of thermal insulation materials and its impact on the building, Build. Environ. 42 (2007) 2178–2187, http://dx.doi.org/10.1016/j.buildenv.2006.04.012.
[18] A. Schmidt, A. Jensen, A. Clausen, O. Kamstrup, D. Postlethwaite, A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Part 1: Background, goal and scope, life cycle inventory, impact assessment and interpretation, Int. J. LCA 9 (2004) 53–66, http://dx.doi.org/10.1065/lca2003.12.144.1.
[19] A. Schmidt, A. Jensen, A. Clausen, O. Kamstrup, D. Postlethwaite, A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Part 2: comparative assessment, Int. J. LCA 9 (2004) 122–129, http://dx.doi.org/10.1065/lca2003.12.144.2.
[20] I. Bribián, A. Capilla, A. Usón, Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential, Build. Environ. 46 (2011) 1133–1140, http://dx.doi.org/10.1016/j.buildenv.2010.12.002.
[21] S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: a review and comparative analysis, Renew. Sust. Energy Rev. 62 (2016) 988–1011, http://dx.doi.org/10.1016/j.rser.2016.05.045.
[22] N. Pargana, M. Pinheiro, J. Silvestre, J. de Brito, Comparative environmental life cycle assessment of thermal insulation materials of buildings, Energy Build. 82 (2014) 466–481, http://dx.doi.org/10.1016/j.enbuild.2014.05.057.
[23] L. Harvey, Net climatic impact of solid foam insulation produced with halocarbon and non-halocarbon blowing agents, Build. Environ. 42 (2007) 2860–2879, http://dx.doi.org/10.1016/j.buildenv.2006.10.028.
[24] T. Chen, J. Burnett, C. Chau, Analysis of embodied energy use in the residential building of Hong Kong, Energy 26 (2001) 323–340, http://dx.doi.org/10.1016/S0360-5442(01)00006-8.
[25] M. Lenzen, G. Treloar, Embodied energy in buildings: wood versus concrete –reply to Borjesson and Gustavsson, Energy Policy 30 (2002) 249–255, http://dx.doi.org/10.1016/S0301-4215(01)00142-2.
[26] C. Petersdorff, T., Boermans, J., Harnsich, S., Joosen, F. Wouters, The contribution of mineral wool and other thermal insulation materials to

energy saving and climate protection in Europe. Cologne, ECOFYS, 2002. (available from www.eurima.org).
[27] K. Adalberth, Energy use during the life cycle of single-unit dwellings: examples, Building and Environment 32 (1997) 321–329, http://dx.doi.org/10.1016/S0360-1323(96)00069-8.
[28] Ökoinstitut, Bauhaus Universität Weimar, Institut für Industrielle Bauproduktion: Der Kumulierte Energieaufwand (KEA) im Baubereich – Erarbeitung von Basisdaten zum Energieaufwand und der Umweltbelastung von energieintensiven Produkten und Dienstleistungen für Ökobilanzen und Öko-Audits, Darmstadt, Karlsruhe, Weimar, for the German Umweltbundesamt (UBA), 1999.
[29] G. Hammond, C. Jones Bath Inventory of Carbon and Energy (ICE) database, version 2.
[30] D. Tingley, A. Hathaway, B. Davison, An environmental impact comparison of external wall insulation types, Build. Environ. 85 (2015) 182–189, http://dx.doi.org/10.1016/j.buildenv.2014.11.021.
[31] D. Tingley, A. Hathaway, B. Davison, D. Allwood, The environmental impact of phenolic foam insulation boards, Proc. ICE Constr. Mater. 170 (2017) 91–103, http://dx.doi.org/10.1680/coma.14.00022.
[32] S. Shreshta, K. Biswas, A. Desjarlais, A protocol for lifetime energy and environmental impact assessment of building insulation materials, Environ. Impact Assess. Rev. 46 (2014) 25–31, http://dx.doi.org/10.1016/j.eiar.2014.01.002.
[33] M. Huijbregts, L. Rombouts, S. Hellweg, A. Frischknecht, D. Van de Meent, A. Ragas, L. Reijnders, J. Struijs, Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. 40 (2006) 641–648, http://dx.doi.org/10.1021/es051689g.
[34] L. Cabeza, C. Barrenesche, L. Miro, J. Morera, E. Bartoli, I. Fernández, Low carbon and low embodied energy materials in buildings: a review, Renew. Sust. Energy Rev. 23 (2013) 536–542, http://dx.doi.org/10.1016/j.rser.2013.03.017.
[35] Y. Jiao, C. Lloyd, S. Wakes, The relationship between total embodied energy and cost of commercial buildings, Energy Build. 52 (2012) 20–27, http://dx.doi.org/10.1016/j.enbuild.2012.05.028.
[36] L. Tellnes, C. Ganne-Chedeville, A. Dias, F. Dolezal, C. Hill, E. Escamilla, Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: a review study for construction materials based on forest products, iForest 10 (2017) 815–823, http://dx.doi.org/10.3832/ifor2386-010.
[37] I. Herrmann, A. Moltesen, Does it matter which life cycle assessment tool you choose? –a comparative assessment of SimaPro and GaBi, J. Cleaner Prod. 86 (2014) 163–169, http://dx.doi.org/10.1016/j.jclepro.2014.08.004.