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Embodied energy and carbon of building insulating materials: A critical review

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ABSTRACT

An extensive and updated review of 223 values about the embodied energy and carbon of building insulation materials, mainly retrieved from 156 Environmental Product Declarations, is proposed with attention to innovative and emerging insulation materials. Comparative analyses were carried out thanks to the adoption of the same functional unit (1 m^2 with a thermal resistance of 1m^2K/W and a design life span of 50 years) to assess the consistence of reference values and the main sources of variability. The comparison suffers from many uncertainties and variance decomposition was employed to verify the main drivers of variability in the dataset elaborated. Data about traditional insulation materials show the lowest ranges of variation when reported per functional unit while the definition of reference values for innovative and unconventional insulation materials was quite difficult due to the low values found and their high variance. Traditional inorganic insulation materials exhibit competitive embodied impacts (glass wool: 16–31 MJ/FU and 0.6–1.2 kg CO_2eq/FU; stone wool: 21–66 MJ/FU and 1.4–4.2 kg CO_2eq/FU) if compared with fossil fuel derived (EPS: 44–78 MJ/FU and 1.9–3.5 kg CO_2eq/FU) or many emerging super-insulating solutions (aerogel: 251–372 MJ/FU and 11.6–18.7 kg CO_2eq/FU). Density is an important variability carrier for glass wool, stone wool, and EPS.

1. Introduction

The building sector is responsible for a significant share of the energy consumptions and carbon emissions in Europe. The European Commission, Directorate General for Energy, performing some statistical analysis, attributed to the built environment 40% of the energy consumptions and 36% of the carbon emissions of the entire Union (European Commission Directorate General of Energy, 2020). The 2030 climate and energy framework set by the European Commission foresees a 40% reduction of greenhouse gas emissions (referring to the levels of 1990), a share of renewable energy production of minimum 32% and an improvement of the energy efficiency of at least 32.5%. Looking at the buildings, the Energy Performance of Buildings Directive (European Parliament and Council, 2010) imposes the nearly Zero Energy Standard for all new constructions by the end of 2020. Following the European law, member states promoted different national regulations, plans and actions to improve the efficiency of their building stock. Generally, the best strategy in the design nearly Zero Energy Buildings or energy retrofits is to act both on the envelope and on the energy systems to reduce the energy demand of the building before the installation of renewable energy systems (Cellura et al., 2017). As regards the envelope, the installation of insulation materials proved to be very effective in the reduction of the energy consumptions of buildings, particularly if the opaque surface is preponderant (Fang et al., 2014). Low-energy buildings and passive-houses are today the reference for many building designers, and they are characterized by reduced energy requirements and high envelope insulation levels.

As new constructions are characterized by reduced operational energy consumptions, more and more attention should be given to the embodied components such as the Embodied Energy (EE) and Global Warming Potential (GWP) due to building materials and systems (Asdrubali et al., 2019; Dodoo et al., 2010). Embodied impacts represent the environmental burdens generated from the acquisition of raw materials, their processing, manufacturing, transportation to site and construction throughout the whole life cycle. Embodied components are relevant in energy efficient buildings as shown by different

Abbreviations: EE, embodied energy; EPS, Expanded Polystyrene; FU, reference mass flow to provide one unit of Functional Unit (kg); PIR, Polyisocyanurate; PUR, Polyurethane; R, Thermal Resistance (m^2K/W); VIP, Vacuum Insulation Panels; XPS, Extruded Polystyrene.

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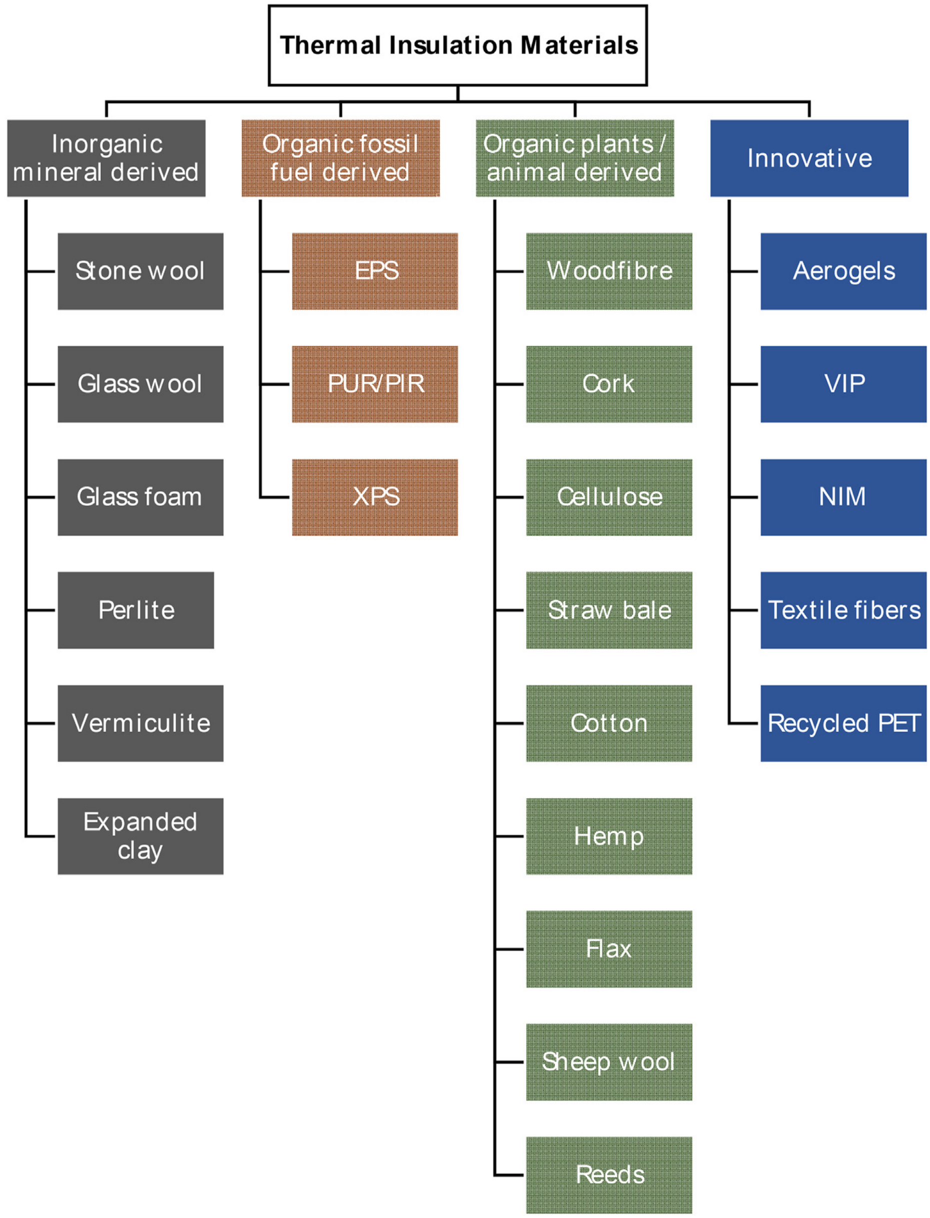


Fig. 1. A classification for building insulation materials (Blagoeva and Pavel, 2018).

Table 1
Literature reference values of EE and GWP (cradle-to-gate) for the most common insulation materials.

Reference	FU	Stone wool	glass wool	EPS	PUR/PIR	XPS
Casini (2020)[a]	Kg $R = 2$ m^{2}K/W	63 MJ	37 MJ	147 MJ	147 MJ	144 MJ
		3.62 kg CO_2eq	1.62 kg CO_2eq	4.52 kg CO_2eq	10.4 kg CO_2eq	5.52 kg CO_2eq
Hill et al. (2018)	Kg	23.5 MJ	24.8 MJ	85.8 MJ	63.1 MJ	47.3 MJ
Su et al. (2016)	Kg $R = 1$ m^{2}K/W	64 MJ	90 MJ	85 MJ	81 MJ	75 MJ
		5.85 kg CO_2eq	8.63 kg CO_2eq	6.25 kg CO_2eq	5.83 kg CO_2eq	5.45 kg CO_2eq
Schiavoni et al. (2016)	Kg $R = 1$ m^{2}K/W	53.09 MJ	134.17 MJ	127.31 MJ	99.63 MJ	127.31 MJ
		2.77 kg CO_2eq	7.70 kg CO_2eq	5.05 kg CO_2eq	6.51 kg CO_2eq	13.22 kg CO_2eq
Biswas et al. (2016)	Kg $R = 1$ m^{2}K/W	-	-	100.87 MJ	63.61 MJ	100.97 MJ
				4.18 kg CO_2eq	2.63 kg CO_2eq	6.11 kg CO_2eq
Pargana et al. (2014)	Kg $R = 1$ m^{2}K/W	-	-	74.31 MJ	85.97 MJ	98.11 MJ
				3.25 kg CO_2eq	3.33 kg CO_2eq	5.21 kg CO_2eq

[a] Only the non-renewable primary energy is accounted.

authors: incorporated impacts represent a percentage of the total equal to 45% for (Thormark, 2002), 50% for (Blengini and Di Carlo, 2010), 57–74% for (Chastas et al., 2016). In some cases, also a burden shifting can be verified and, to avoid it, life cycle methodologies are effective tools of analysis (Cellura et al., 2014; Weißenberger et al., 2014).

Applying Life Cycle Assessment (LCA) methods, different authors

Table 2
Number of values gathered for every material and for each impact indicator; the reference database/literature source is reported in brackets.

Material	Values for each impact (reference database)	Total n.
Fossil fuel derived		
EPS	13 (Ire), 11 (Env), 9 (Bau), 7 (Ibu), 3 (Ita), 2 (OcL), 1 (Ini), 1 (Öko), 1 (EcI)	48
PUR	8 (Ibu), 4 (Bau), 4 (Ire), 1 (Ini), 1 (Öko), 1 (OcL), 1 (Dapc)	20
XPS	5 (Bau), 2 (EcI), 1 (Env), 1 (Ini), 1 (Öko), 1 (OcL), 1 (Dapc), 1 (Ibu)	13
Mineral derived		
Stone wool	13 (Env), 4 (Bau), 6 (Ibu), 2 (OcL), 1 (Ini), 1 (Öko), 1 (EcI), 1 (Ire), 1 (Nor)	30
Glass wool	14 (Env), 3 (Bau), 2 (OcL), 1 (Ini), 1 (Öko), 1 (EcI), 1 (Ibu), 1 (Bre)	24
Expanded clay	3 (Nor), 2 (Ita), 1 (Bau), 1 (Daph)	7
Glass foam	1 (Bau), 1 (Öko), 1 (OcL)	3
Perlite	1 (Bau), 1 (Öko), 1 (OcL)	3
Vermiculite	1 (Ini)	1
Natural derived		
Cellulose	7 (Ire), 7 (Ibu), 2 (Bau), 1 (Ini), 1 (Öko), 1 (OcL), 1 (EcI), 1 (Env)	21
Cork	3 (Daph), 1 (Bau), 1 (Öko), 1 (OcL), 1 (Silvestre et al., 2016)	7
Wood fibers	4 (Ibu), 1 (Öko), 1 (OcL)	6
Wood fibers	2 (Nor), 1 (Bau), 1 (Ini), 1 (OcL)	5
Mineralized wood fibers	3 (Env), 1 (Mil)	4
Straw bale	1 (Bau), 1 (Ini), 1 (Öko), 1 (OcL)	4
Hemp	1 (Bau), 1(Env), 1 (Öko), 1 (OcL)	4
Flax	3 (Bau), 1 (Öko)	4
Cotton	1 (Ini), 1 (Öko)	2
Reeds	1 (Bau)	1
Sheep wool	1 (Bau)	1
Innovative		
Recycled PET	5 (Env), 1 (Bau)	6
VIP	3 (Karami et al., 2015; Schonhardt et al., 2003), 1 (Bau), 1 (Öko)	5
Aerogel	1 (Env), 1 (Sáez de Guinoa et al., 2017), 1 (Biswas et al., 2016)	3
Textile fibers	1 (Ini)	1

showed that the vertical walls and roofs, in particular with high levels of insulation, represent a very important component in the total EE and GWP of high efficient buildings (Asdrubali et al., 2020; Thormark, 2002). The energy and environmental impacts attributed to buildings insulation materials can be distinguished in direct embodied burdens and avoided impacts due to their capacity of energy consumption reduction. Usually, the operational energy savings dominate the embodied burdens, especially for low thickness of insulation material applied in the retrofit of old and poorly designed buildings (Biswas et al., 2016). The environmental competitiveness of the application of building insulation materials can be expressed as the ratio between their embodied burdens and the total amount of impacts saved per year of useful life of the material. Different authors (Abd Alla et al., 2020; Marrone et al., 2021) have already shown that this ratio can be lower than the useful life of the insulation material applied making the solution environmentally friendly within its life cycle. The calculation methodologies for both embodied impacts and operational savings are however subjected to a lot of uncertainties and variability issues. That is why some standardization methodologies are proposed by some literature works (Gelowitz and McArthur, 2017; Shrestha et al., 2014) to effectively allow the comparability between different insulation materials. The main object of this study is to compare the embodied environmental impact of different insulation materials, including conventional, natural and innovative ones, and considering a uniform functional unit able also to describe their operational performance; the consistence in the definition of reference values was verified, and the main drivers of variability were assessed.

The work is organized as follows: section 2 gives an overview of the state of the art, section 3 describes the methodology adopted and describes the dataset, section 4 shows the results obtained and the main drivers of their variability, and finally, section 5 draws the conclusions.

2. State of the art

Building thermal insulation materials can be classified considering their origin (Blagoeva and Pavel, 2018): inorganic mineral, organic fossil fuels, organic plants and animal derived or deriving from innovative engineered processes using biopolymers, nano technologies, high reflective coatings, vacuum panels or phase change materials. Fig. 1 shows a schematic representation of the proposed classification.

The European market of building insulation materials is dominated by mineral and fossil fuel derived insulation materials that offer the best performance in term of unit cost. Glass (36%) and stone wool (22%) represent the 58% of the market in Europe, followed by EPS (27%), PUR/PIR (8%) and XPS (6%) that are expected to increase their market diffusion due to their better insulation properties (Blagoeva and Pavel, 2018).

As the use of insulation materials in the building sector grows, a higher attention should be given to their EE and emissions. The goal is to define a uniform, comparable, LCA based manner of assessing and reporting the sustainability of insulation and, more in general, of construction products. The EN 15804 (CEN, 2012) gave the main rules to establish Product Category Rules (PCR) for the elaboration of Environmental Product Declarations (EPDs, type III of ISO 14025) related to buildings products and services. The PCR are rules set by the EPD program operators to conduct a detailed LCA for specific products, such as insulation materials.

The literature reviewed in this section (Shrestha et al., 2014) shows that the environmental properties of insulation materials vary depending on different issues:

- Typology of the insulation materials (blown/expanding/loose material, panel, …)
- Manufacturing methods and technologies
- Energy mix of the countries where manufacturing processes happen
- Percentage of recycled material introduced in the production chain
- Origin of the raw material and distance from the manufacturing site

One of the main issues that remains still vague to permit a good comparability regards the energy mix that should be considered in the LCA calculations of embodied impacts. Industrial factories apply different strategies to cover their energy load curve balancing power demand and supply. The active participation of industrial consumers in energy production, especially in case of renewable energy generation, and the implementation of demand-response programs can create opportunities to increase efficiency and profitability (Gerami et al., 2021). In this way the local energy mix employed in the production chain can be very variable and dependent on the energy management performed by every single factory. A day ahead scheduling of production activities can furthermore optimize the load profile and change the typology of energy carrier to cover it. The use of national energy mix and annual average values is often recommended (Shrestha et al., 2014) for an adequate comparability in results about the environmental impacts of construction materials.

Despite these important variation parameters, the comparison of the environmental properties of insulation materials is requested and standardized methodologies have been developed since the beginning of the new millennial. The harmonization of the PCR of different program operators is desired to guarantee a good comparability among the declarations: the ISO 14025 (ISO, 2006) and the Guidance for PCR development (Allacker et al., 2013) recommends global harmonization efforts in PCR development. The scientific literature has already underlined the differences between programs comparing PCR and EPDs (Ibáñez-Forés et al., 2016) for the same category of products: in

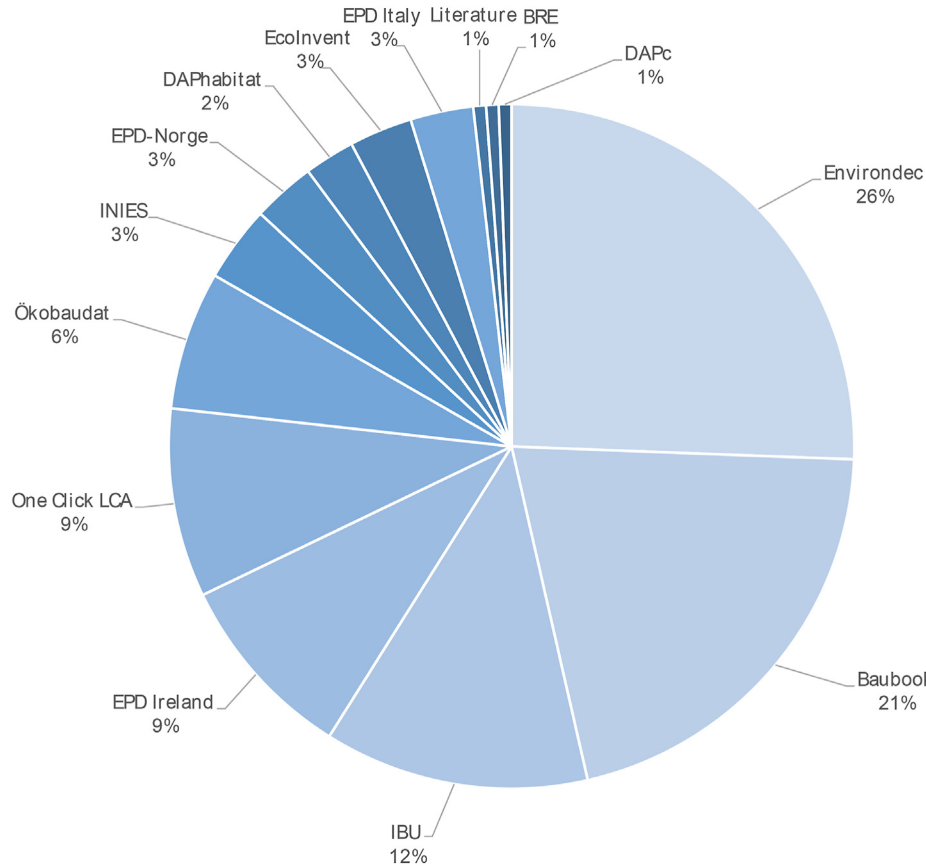


Fig. 2. Incidence of every database in the total number of the data analyzed.

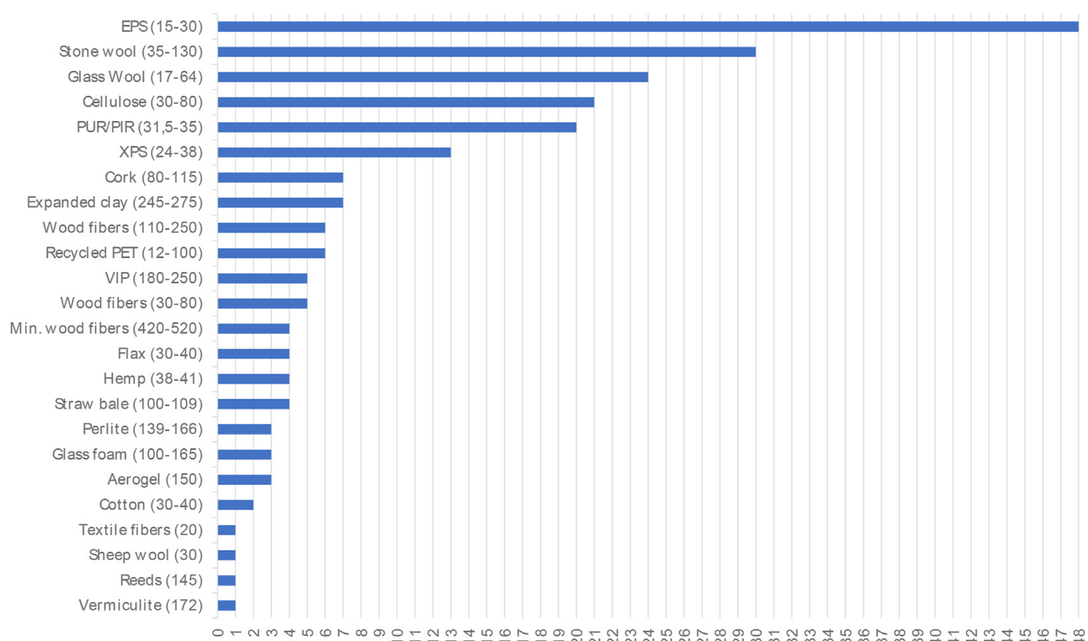


Fig. 3. Number of PENR/PER or GWP values considered for every insulation material.

particular, in 2016, the construction sector was the second for number of EPDs (about eighty registered by the International EPD system), with the presence of about twenty PCR and resulting between the two categories in the highest growth rate in the publications during the period 2009–2014.

Even if these standards are devoted to provide a consistent, transparent and trustworthy framework, (Gelowitz and McArthur, 2017) showed that EPDs are usually characterized by omissions, incomplete information and errors that undermine every harmonization effort. Some methodological limitations and the necessity of a higher harmonization

Table 3
Thermo-physical, fire resistance, water related and durability properties of the insulation materials.

Material	Density [kg/m^3]	Thermal conductivity [W/m K]	Avg. reference flow (FU) [kg]	Specific heat [kJ/kg K]	Fire class	Water resistance	Compression resistance [kPa]	Durability [years]
Stone wool	35–130	0.33–0.40	2.44	0.85–1.0	A1	Good	50	50
Glass wool	12–64	0.31–0.45	0.91	≈0.85	A1	Good	50	50
Expanded clay	245–275	0.095–0.12	35.75	≈1.0	A1	-	50	50
Vermiculite	170	0.062–0.090	12.92	0.8–1.0	A1	-	-	-
Perlite	139–166	0.040–0.055	11.31	0.9–1.0	A1	Good	-	-
EPS	15–30	0.031–0.037	0.72	1.25	E	Good	-	50
XPS	24–38	0.031–0.036	1.16	1.3–1.7	E	Good	250–500	50
PUR	31.5–35	0.022–0.040	0.87	1.3–1.45	F-E	Good	150	50
Wood fibers	30–60	0.037–0.038	2.80	1.9–2.1	E	Scarce	-	-
Wood fibers	110–250	0.047–0.08	9.80	2.1	E-D	Scarce	40–300	-
Mineralized Wood Fibers	420–520	0.070–0.10	39.20	1.8–2.1	A2-B	-	> 200	50
Cork	80–115	0.04–0.050	3.93	1.5–1.7	E	Scarce	-	50
Cellulose	30–80	0.037–0.042	1.75	1.3–2.0	E	Vulnerable	-	50[a]
Straw bale	100–109	0.038–0.067	5.55	0.6	E	Vulnerable	-	-
Hemp	38–41	0.038–0.060	2.25	1.6–1.7	E	Vulnerable	-	-
Flax	30–40	0.038–0.042	2.45	1.4–1.6	E	Vulnerable	-	-
Sheep Wool	30	0.033	0.96	1.9–2.0	E	Vulnerable	-	50[a]
Recycled PET	12–100	0.039	1.03	0.24	B	-	-	50
Aerogel	150–220	0.015–0.028	2.37	1.05	C	Hydrophobic	-	50
VIPs	180–250	0.02	5.00	-	-	Hydrophobic	-	50

[a] If protected from water.

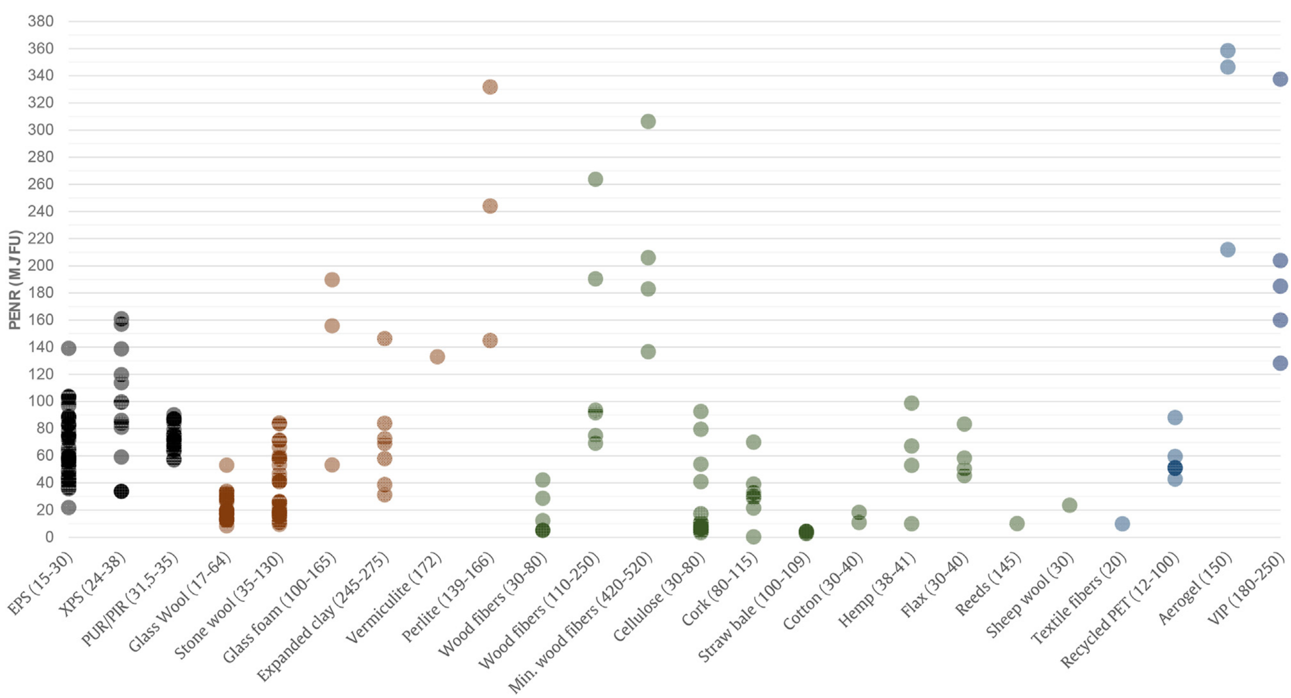


Fig. 4. Results of PENR/FU: fossil (grey), mineral (brown), natural (green) and innovative (blue) materials. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of PCR were mentioned by Galindro et al. (2020) as the limiting factors for the comparisons between studies and for the definition of benchmarks.

Different authors have already checked the comparability between the environmental properties of insulation materials. Hill et al. (2018) proposed a comparison of the values of GWP and EE of building insulating materials obtained from sixty environmental product declarations. Eight widely used insulation materials were considered by Su et al. (2016) for a comparison of their life cycle performance. Pargana et al. (2014) reviewed the potential impacts deriving from the fabrication of the most common insulation materials in Europe: they included EPS, XPS, PUR, cork and expanded clay lightweight aggregates. Biswas et al. (2016) showed the embodied environmental impacts for PIR, EPS, XPS and aerogel. The reference values found by the different authors are reported in Table 1: the data can refer to different functional units (kg of material, amount of material necessary to obtain a $\boldsymbol{R} = 1$ m^{2}K/W). Casini (2020) performed a comparative analysis of the main insulation materials on the market also including aerogels: if the FU considered is the mass of materials to obtain a $\boldsymbol{R} = 2$ m^{2}K/W, they are characterized by a PENR of 242 MJ/m^2 and a GWP of 12.50 kg CO_2eq/m^2.

Some research works are focused on the evaluation of the potential of some alternative insulation materials, even if their use is still scarce. The attention is given to natural derived materials, usually obtained from agricultural residues (Barreca et al., 2019) or waste recycling

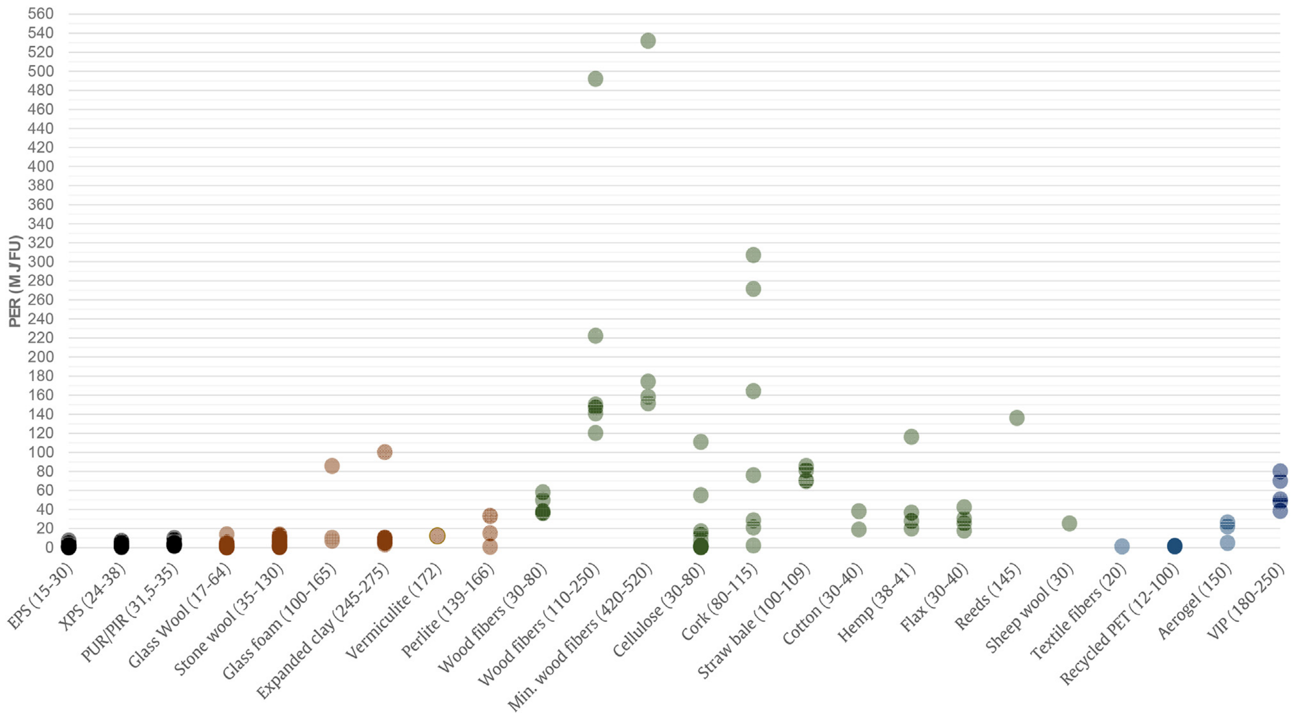


Fig. 5. Results of PER/FU: fossil (grey), mineral (brown), natural (green) and innovative (blue) materials. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

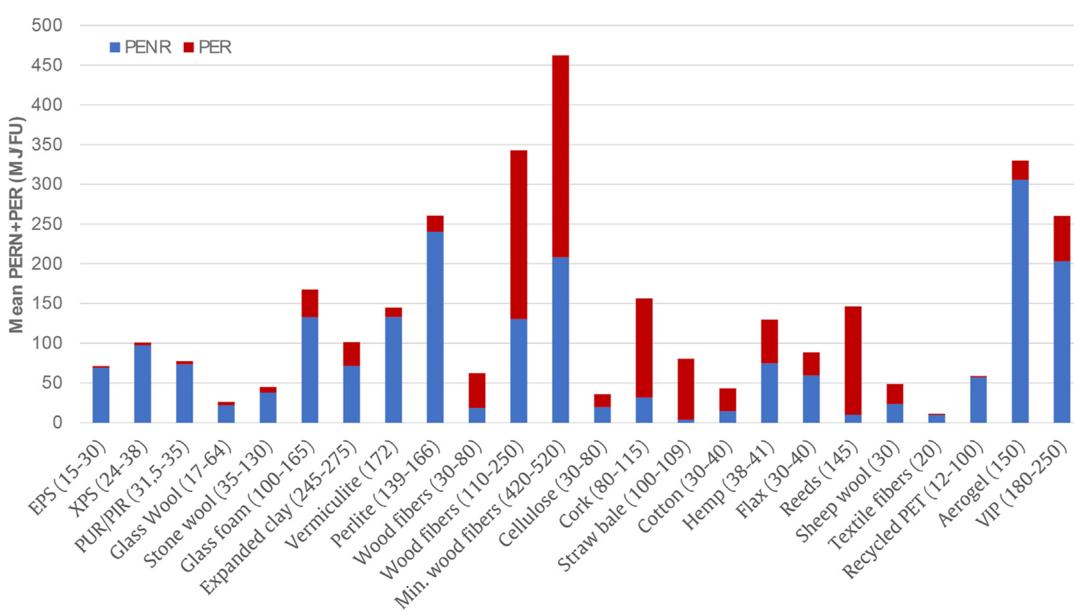


Fig. 6. Results about the EE, renewable and non-renewable part (using average values).

(Wiprächtiger et al., 2020). Other literature works have already found some literature data about EE and GWP of plants or animal derived insulation panels: (Asdrubali et al., 2015), for example, proposed a review of the acoustic, thermal and environmental properties of unconventional natural insulation materials; Schiavoni et al. (2016) reviewed the thermal, acoustics, environmental, fire and water vapor resistance of traditional, natural derived and innovative insulation materials. It was shown that some natural derived materials, such as cork, have high EE and GWP values while some commercialized materials, such as stone wool, presented very good environmental properties with low EE and GWP.

Innovative materials with very high insulation properties are also emerging. Examples are aerogels, Vacuum Insulation Panels (VIP), Phase Change Materials (PCM), Nano Insulation Materials (NIM) or materials derived from the recycling of polyethylene terephthalate (PET) or textile fibers. Few literature studies, however, reported standardized data about the EE and GWP of innovative insulation materials. The data about the environmental impacts of innovative insulation materials are still scarce and this work tries to integrate the information already published.

3. Materials and methods

This study was based on the European standard related to the sustainability evaluation of construction works (CEN, 2012). A Cradle to

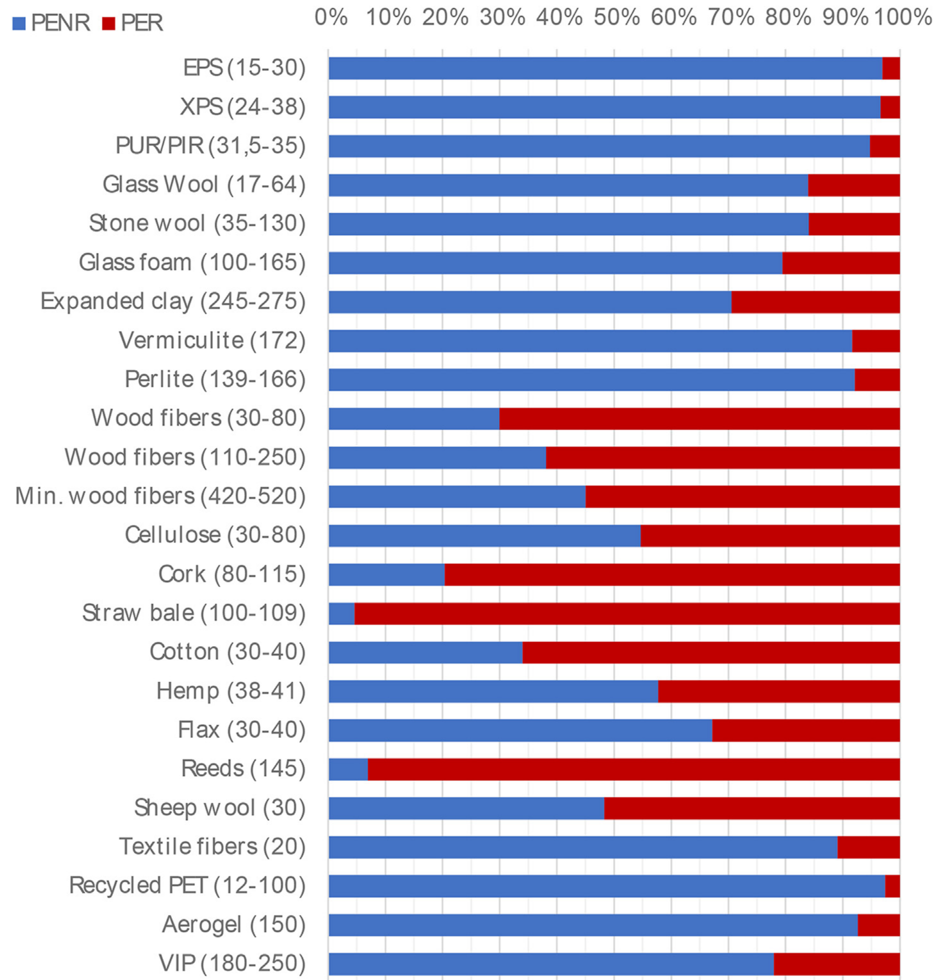


Fig. 7. Results about the incidence (%) of PERN and PER for every considered material.

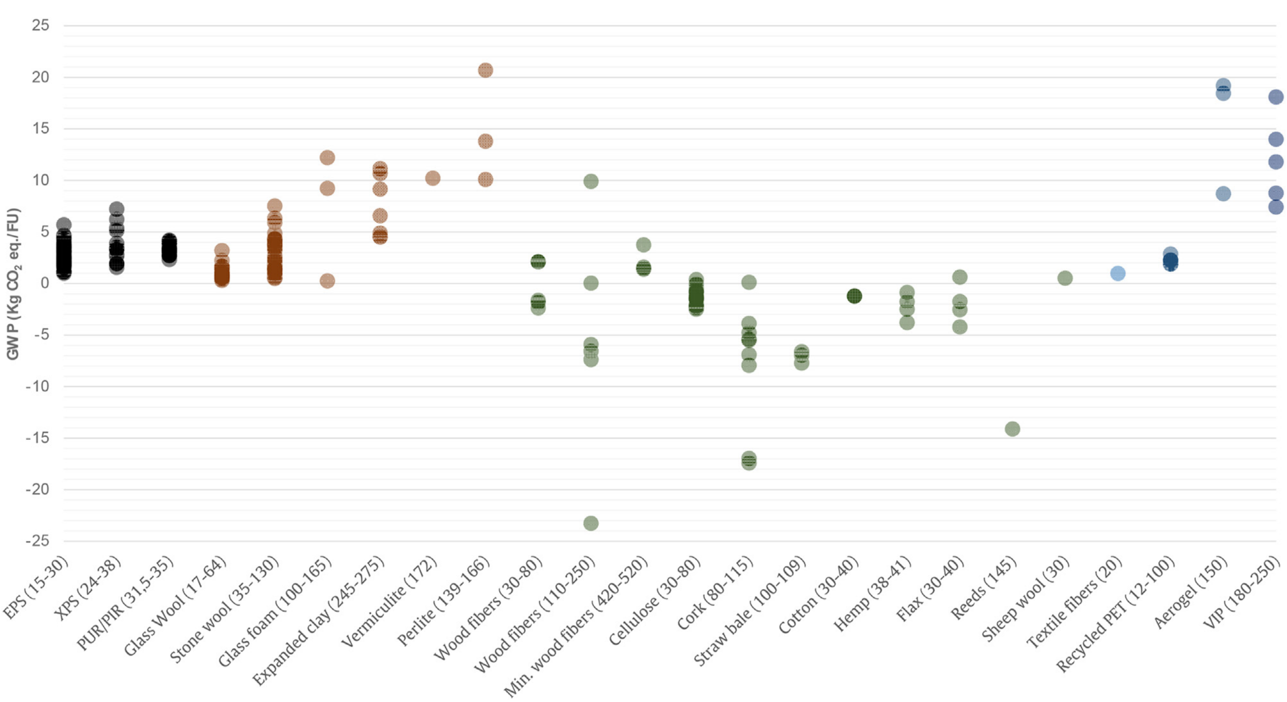


Fig. 8. Results of GWP/FU: fossil (grey), mineral (brown), natural (green) and innovative (blue) materials. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

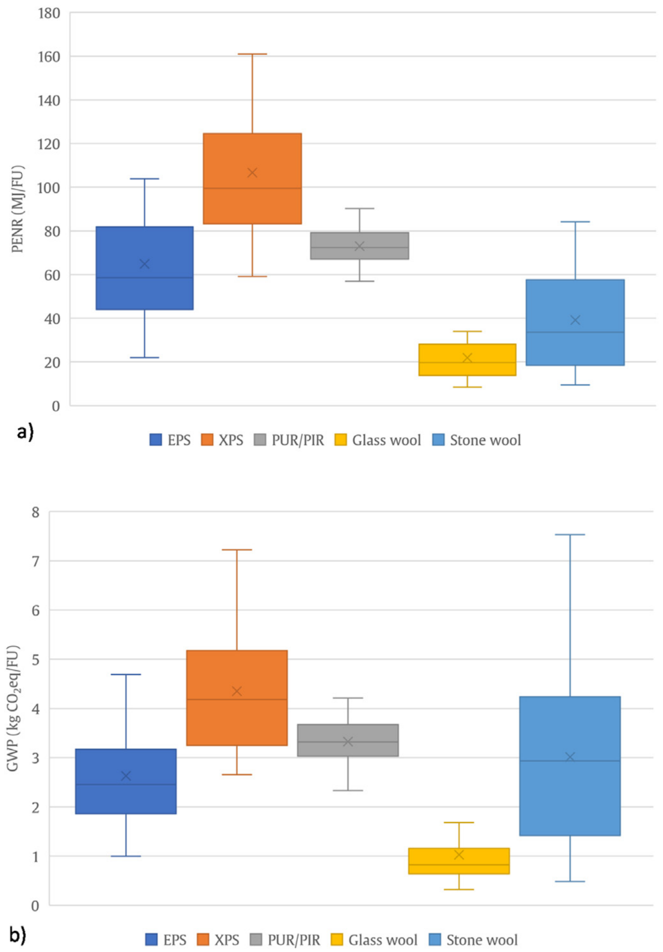


Fig. 9. Box plot for the PENR/FU (a) and GWP/FU (b) of market leaders insulation materials.

Table 4
Results of the variance decomposition analysis.

Material	Variability sources	Explained variance		
		PER	PENR	GWP
EPS	Program operator	85% (p = 0.0000)	41% (p = 0.0050)	45% (p = 0.0014)
	Density	9% (p = 0.3979)	70% (p = 0.0000)	55% (p = 0.0000)
XPS	Program operator	99% (p = 0.0008)	50% (p = 0.7543)	50% (p = 0.7632)
	Density	58% (p = 0.2727)	89% (p = 0.0071)	62% (p = 0.2205)
PUR/PIR	Program operator	63% (p = 0.0096)	71% (p = 0.0022)	71% (p = 0.0021)
	Density	2% (p = 0.9437)	49% (p = 0.0140)	52% (p = 0.0077)
Stone wool	Program operator	76% (p = 0.0014)	42% (p = 0.2990)	48% (p = 0.1702)
	Density	64% (p = 0.0027)	84% (p = 0.0000)	83% (p = 0.0000)
Glass wool	Program operator	14% (p = 0.9127)	32% (p = 0.4311)	26% (p = 0.5922)
	Density	83% (p = 0.0000)	78% (p = 0.0001)	76% (p = 0.0002)

Gate approach was employed: the phases considered are the extraction of the raw material (stage A1), the transportation to the manufacturing site (stage A2), and the manufacturing of the material into the commercial product (stage A3).

To achieve this study, we looked for values of:

- GWP: it is an indicator expressed in kg CO_2eq/FU, evaluated for 100 years horizon, which includes the effect of all the substances contributing to the greenhouse effect. Following the EN 15804 standard, the GWP includes emissions and removals of both fossil and biogenic carbon.
- EE: it is the energy (in MJ) required to produce one unit of functional unit of the material. In the present study, we considered the total Renewable Primary Energy (PER) and the total non-Renewable Primary Energy (PENR). These indicators can be calculated using the single issues method called Cumulative Energy Demand (Hischier et al., 2010).

In order to make a comparison between the different insulation materials, we chose as a functional unit 1 m^2 of an insulation panel with a thickness that gives a thermal resistance $\boldsymbol{R} = 1\ m^2K/W$, and with a design life span of 50 years as suggested by European Commission (2019). This choice permits to compare the insulation materials considering quite a uniform operational performance. Eq. (1) defines mathematically the reference flow of mass necessary to provide one unit of functional unit adopted in this work.

$$FU = R \cdot \lambda \cdot \rho \cdot A \tag{1}$$

where ***FU*** is the reference flow of mass in kg necessary to provide one unit of the functional unit chosen; ***R*** is the thermal resistance equal to 1 (m^2K/W); $\boldsymbol{\lambda}$ is the thermal conductivity of the panel in W/mK; $\boldsymbol{\rho}$ is the density of the panel in kg/m^3; ***A*** is the area equal to 1 m^2.

The choice of the right functional unit is fundamental in a comparative LCA study. When insulation materials are considered, it is very important to select a functional unit that is able to define a uniform insulation behavior. The compared materials should have equivalent performances and, since thermal insulation materials are demanded to reduce the thermal transmittance, various researchers adopted the amount of material to cover 1 m^2 and to provide a $\boldsymbol{R} = 1\ m^2K/W$ (Hill et al., 2018; Pargana et al., 2014; Schiavoni et al., 2016; Su et al., 2016). By using this unit, we can compare their environmental impact for the same given thermal performance. A similar approach was also employed by Densley Tingley et al. (2015) who used 1 m^2 of insulation with a ***R*** of 3 m^2K/W: it is the value to be applied in the retrofit of a poor existing wall to meet the English regulations for thermal transmittance of walls in dwellings.

As the chosen unit (1 m^2 with a $\boldsymbol{R} = 1\ m^2K/W$) is specific, very few databases use this unit and some conversions had to be made. Most databases use 1 kg or 1 m^3 as a reference, so it is quite simple to go back to the defined FU, as long as data for thermal conductivity and density are given.

It should be noted that the use of this kind of functional unit does not imply a strong equivalence of the performance of the insulating materials: the durability, for example, should be considered with a particular attention, because natural materials might not be performant for the same duration as conventional ones. In case the reference service life was not declared in the EPDs consulted, we however supposed a 50 years design life span. Similarly, also the performance related to mechanical and fire resistance, acoustics, water absorption and the impacts on human health are different. In order to underline this limitation, all performance parameters obtained from the consulted EPDs, technical sheets and literature works were however reported in the results section.

3.1. Sources of data

To find values for the GWP and the EE, we went through some literature works and some databases of EPD program operators. The data sets gathered were derived from Environmental Product Declarations or scientific studies realized in compliance with the standard EN

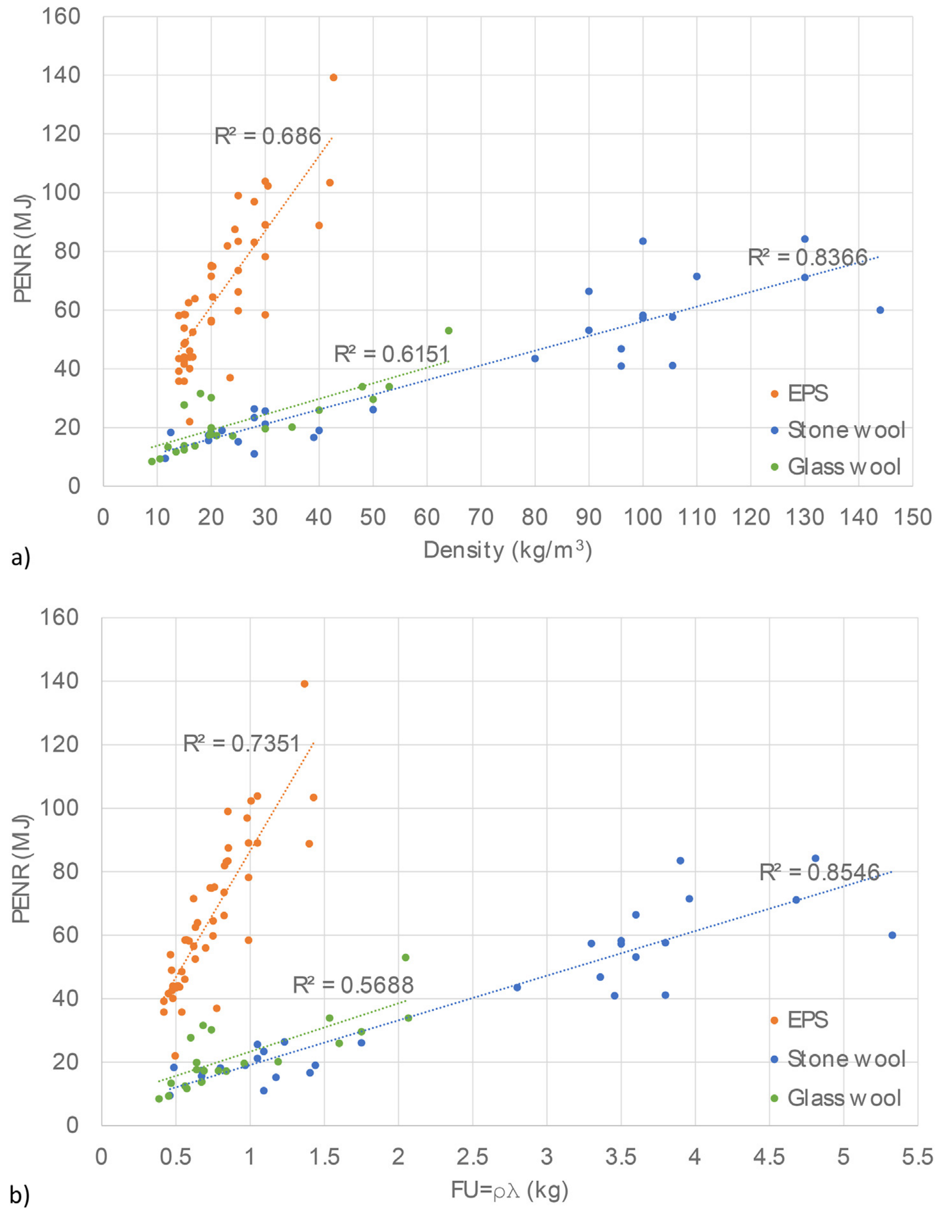
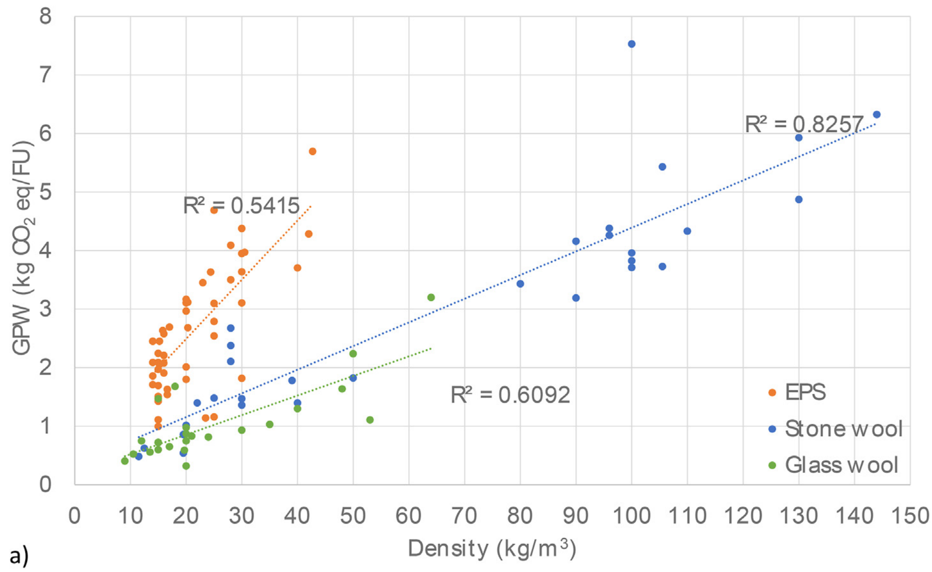


Fig. 10. Results about PENR/FU versus density (a) and FU (b).

15804:2012 (CEN, 2012) or its updates. All the EPDs selected were not expired. The following databases were consulted:

– **Baubook (Bau)** (Baubook GmbH, 2020): it is an Austrian database for building materials.
– **EcoInvent (EcI)** (Wernet et al., 2016): it is the one of the world's largest transparent life cycle inventory database.
– **INIES (Ini)** (Association HQE, 2020): it is a French database containing LCA information provided voluntarily by manufacturers and trade associations.
– **Ökobaudat (Öko)** (German Federal Ministry of the Interior Building and Community, 2020): it is a database used for ecological evaluations for buildings, handled by the German Federal Ministry of the Interior, Building and Community. Most datasets in Ökobaudat are imported from EPDs which were generated in the framework of an EPD programme.
– **One Click LCA (OcL)** (Bionova ltd, 2020)**:** this website managed by a Finnish group gathers many verified data from public and private sources.
– **EPD Ireland database (Ire):** this database is an Irish platform that collects products with EPDs.
– **EPD Italy database (Ita)** (EPDItaly, 2020)**:** it is a collection of EPDs of Italian manufactured materials.
– **Environdec database (Env)** (EPD International AB, 2020): it is a collection of EPDs of a wide range of products from all over the world managed by the International EPD System, settled in Sweden.
– **IBU (Ibu)** (Institut Bauen und Umwelt, 2020)**:** it is the abbreviation of Institut Bauen und Umwelt e.V., a German holder of an EPDs database.
– **EPD-Norge (Nor)** (The Norwegian EPD Foundation, 2020)**:** this Norwegian database contains more than 350 EPDs from over 100 companies published online.
– **Nationale Milieudatabase (Mil)** (Nieman et al., 2020)**:** it is the Dutch national database for EPDs.
– **BRE (Bre)** (BRE Centre for Sustainable Products, 2020)**:** it is the abbreviation of Building Research Establishment that is the owner of a UK based database for EPDs.



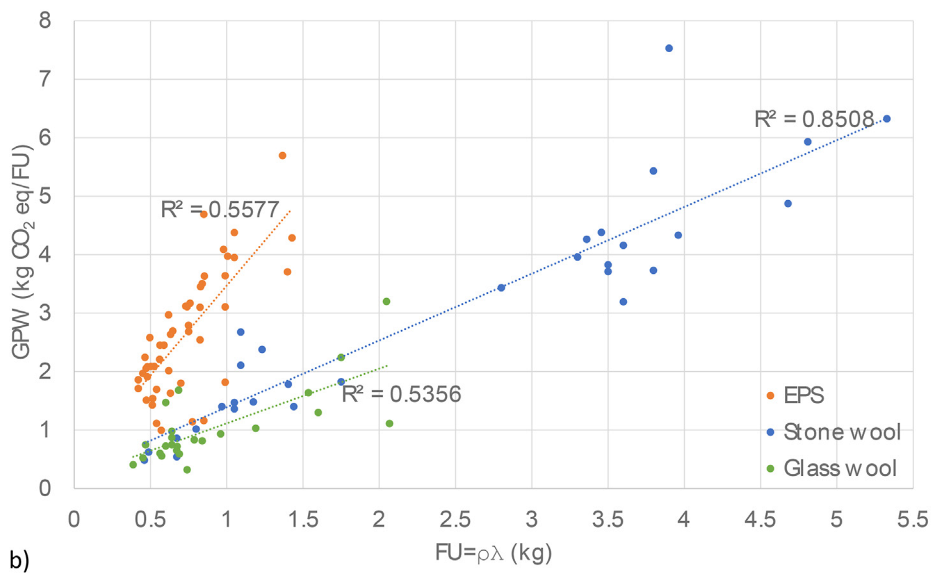


Fig. 11. Results about GWP/FU versus density (a) and FU (b).

- **DAPc (Dapc)** (Agenda de la Construcció Sostenible, 2020)**:** it is the national database of Spain for the EPDs about construction products.
- **DAPhabitat (Daph)** (Centrohabitat and Departamento de Engenharia Civil Universidade de Aveiro, 2020)**:** it is a Portuguese EPDs database managed by the Department of Civil Engineering of the University of Aveiro.
- **Literature:** the data derived from literature was obtained following the methodology necessary to produce an EPD.

3.2. Sample description and limitations

The data about the insulation materials were grouped following the classification already introduced in Fig. 1. Table 2 lists the number of PENR, PER or GWP values downloaded from the different sources considered in this work reporting, for every insulation material, the reference database or the literature work from which data are gathered.

223 values were obtained for the PENR, PER or for the GWP analyzing 156 EPDs and literature sources. Fig. 2 shows the share of every database considered in the total values analyzed. Environdec (26%), Baubook (21%), IBU (12%), EPD Ireland (9%), One Click LCA (9%) and Ökobaudat (6%) represent the most important sources of environmental declarations of this work; they together account for 83% of the data sample. The total amount of data for each insulation material is reported in Fig. 3: a higher number of values (concerning PER, PENR or GWP) was obtained for commercial insulation materials while lower datasets were found for innovative and low employed thermal insulators.

Some limitations should be highlighted before drawing some conclusions. Some insulation materials, that were however considered, are characterized by only few EPDs and that did not allow deriving significant conclusions. They are still not largely diffused in the market and few environmental certifications and information were found in the databases consulted.

Innovative super-insulating materials are worth of a particular attention: an important limitation is that the newest and most innovative insulation materials are still in early stages of development, meaning that the production process is not industrialized. One way to deal with this issue is to apply a scale up model in order to predict an industrialized production for these new materials. Pinto et al. (2020) published one of the first literature studies evaluating the environmental impacts of three different syntheses of subcritical silica aerogels. A very high variability in results was detected, also among different typologies of aerogel. The most environmental intensive typology was inorganic aerogel with

PENR = 7860 MJ/kg and a GWP = 454 kg/CO_2eq. High discrepancies between laboratory and industrial scale manufactured products were found by Dowson et al. (2012); Schlanbusch et al. (2014): some scaling assumptions can, however, reduce the gap between the laboratory and industrial results. Since it was demonstrated the difficulty in comparing the environmental performances of materials that are in very different development stages, only data referring to commercialized products were considered.

Different authors reported EPDs and academic analyses about the environmental performance of VIPs (Karami et al., 2015; Schonhardt et al., 2003). Also in this case, only data about panels already in the market were selected.

No EPDs were found for NIM. Schlanbusch et al. (2014) performed a cradle to gate LCA of a new nano insulation material composed of hollow silica nanospheres: the study didn't follow the EN 15804 rules and calculated an EE ranging between 920 and 1400 MJ/kg and a GWP between 60 and 40 kg CO_2eq/kg; more than the 65% of the EE was non-renewable. Gao et al. (2013) studied the environmental performances of a NIM with thermal conductivity equal to 0.026 W/mK and having an inner pore diameter of about 150 nm along with a shell thickness of about 10–15 nm: the cradle to gate analysis gave a higher value for the EE equal to 2650 MJ/kg. These results, however, did not permit a comparative LCA since the values of density and thermal conductivity of the material studied were not reported.

3.3. Variance decomposition

The main drivers of this variability in results were searched employing variance decomposition methods. Two sources of variability were checked: a material extrinsic source attributable to the EPD program operator, and a material intrinsic property such as its density (the data were grouped for similar density range). Different groups of data were created based on the variability carrier considered to decompose the variance in variance between groups and variance within groups. Fisher test was applied to check the consistence of the grouping in explaining the total variability of data.

4. Results and discussion

The thermo-physical, fire resistance, water related, durability and environmental performance are reported in Table 3 for the insulation materials of which we got relevant results.

As shown in Table 3 the environmental certifications found always report information about density, thermal conductivity of the insulation materials; they less frequently contain information about the specific heat, the fire behavior, acoustic properties, the water or compression resistance. As regards the reaction to fire, the fire class is often reported (CEN, 2018). The water resistance is important to avoid the necessity of additives to protect the material from moisture, rodents, and insects. Little or generic information is generally given about the compression resistance and the durability of the insulation materials certified. Durability expresses the declared expected service life of the material for building applications without a significant decay in thermal performance.

The normalization of the data in terms of functional unit allowed to perform a comparison among the various materials.

The EE energy values are reported in Fig. 4 and Fig. 5. Few data were found for some insulation materials such as glass foam, vermiculite, perlite, straw bale, cotton, hemp, flax, reeds, sheep wool, textile fibers, recycled PET and aerogels. They are not very common insulation materials and their scarce diffusion in the market can explain the lack of environmental declarations about them.

Considering the PENR, a wide variation range was found for the largest part of the materials analyzed. The spread is particularly large for glass foam, perlite, wood fibers, mineralized wood fibers, and VIP. Glass foam and perlite are uncommon insulation materials and the few data found do not permit to draw significant conclusions. However, their PENR content is surely dependent on their density as the one of fibrous and cellular insulation materials: this is particularly clear for stone wool that is characterized by lower values at lower densities (35–60 kg/m^3). The high variation of data about wood fibers might depend on different causes: first of all, on the density of the material since a relatively narrowed spread of values is observed for low density products (30–80 kg/m^3); then it might depend on the fabrication process that is very complex, variable, energy consuming: wood chips can be derived from virgin timber material or from recycled wooden waste, different additive can be added into wood fibers pulp (paraffine, latex), different drying methods can be employed, different treatments can be provided for the external surface of the final panel. The dispersion of the results about VIP is also linked to the variable typologies of panels (fumed silica core panels, perlite or glass fiber) and to the relative new technology that implies a scarce consolidation of the fabrication process and, consequently, of the related environmental performances.

Looking at the PER values reported in Fig. 5, it is possible to observe that natural derived insulation materials are characterized by a high PER value. The high dispersion of data does not permit to gather more detailed conclusions: the highest ranges of variation are found for wood fibers, cork, cellulose and VIP.

Considering the sum of the average values of the PENR and PER for every insulation material considered (see Fig. 6), it is possible to observe that natural insulation materials are not always a competitive alternative to traditional mineral or fossil thermal insulation panels. Excluding textile fibers since only one value can't be considered representative of the average, low density stone wool (35–60 kg/m^3) results the best solution with the lowest mean EE (about 17 MJ/FU) followed by glass wool (30 MJ/FU) and EPS (45 MJ/FU). Innovative insulation materials such as VIP and aerogels are characterized by a very high EE that is manly non-renewable (the PERN is on average the 78% of the total in VIP and 94% for aerogels). Considering aerogel, the EE results to be 125–203 MJ/kg while the embodied GWP is 6.5–10.7 kg CO_2eq. These values are much lower than the ones reported by literature works (Dowson et al., 2012; Pinto et al., 2020; Schlanbusch et al., 2014).

As displayed in Fig. 7, natural and recycled materials tend to use a higher portion of renewable energy for their manufacture, even if some of them still use more overall energy in the production process than conventional insulating materials. The percentage of PER in the average EE of the material can reach relevant percentages (see Fig. 7). On the contrary the PENR content is always over the 95% for organic fossil derived insulation materials.

Fig. 8 shows the data about the embodied GWP in kg CO_2eq/FU. Excluding the contribution in the results of materials characterized by less than four values, a very wide range of variation is found for wood fibers, cork, VIP. As already stated, the high variation of data about wood fibers can be linked to the high differences in the typologies of panels, densities, thermal properties, and fabrication processes. Similar considerations can be performed for cork insulation panels and for the VIP, that are also a relatively new technology with a not standardized production process. On the contrary, the most diffused insulation materials such as EPS, XPS, PUR/PIR, glass wool, stone wool and cellulose display low variation ranges and more standardized values.

The inclusion of biogenic carbon makes the natural insulation materials very competitive in comparison with the traditional fossil or mineral derived ones because their GWP is mostly lower and can sometimes be negative considering the carbon dioxide caught during the growth of the virgin materials. The inclusion of biogenic carbon is however debated since it is released into the atmosphere by the wooden material when burned or disposed during its end-of-life stage.

4.1. Uncertainty evaluation

This section discusses the main drivers of the variance in the results obtained. The analysis is performed only for some traditional insulation materials for which we have got a high amount of data: EPS, XPS, stone wool, glass wool and PUR. These materials are already very diffused in the market and their fabrication processes can be considered standardized. Fig. 9 shows the mean value, the median (the central line), the values of first and third quartiles (the limits of the box) and the minimum and maximum values (the whiskers) for the PENR and GWP of the market leaders insulation materials. Some of them (e.g. glass wool, PUR/PIR) exhibit a relatively narrow range of values while others (e.g. EPS, XPS and stone wool) show a wider range of variability. The results about variance decomposition are shown in Table 4.

As it can be noted, the variance due to the program operator is almost always lower than the one linked to the density and it is not very significant in explaining the total variability in results. This result is probably linked to the harmonization efforts in the calculation methodologies and PCR that has permitted to define valid reference values for the most diffused materials in the market. Moreover, the presence of a high number of declarations permits to define more reliable benchmarks. Some more transparency in the calculation methodologies is however required: not all the EPDs analyzed show the same typology and amount of information conveyed about the methodology employed, the country energy mix adopted, the percentage of recycled or virgin material characterizing the production process, the quality of data used. This kind of information is essential to understand and punctually compare the environmental performances of every type of commercialized product.

On the contrary, the grouping based on density similarity (intervals of 5 or 10 kg/m^3 were considered) can explain a significant amount of the variance of the considered environmental performances for the most diffused insulation materials, especially for EPS, stone wool and glass wool. The values of PENR/FU or GWP/FU of these kinds of fibrous or cellular insulation materials principally depend on their density: a higher air content per unit of volume implies a lower density and a lower EE and GWP. A significant linear regression fitting was obtained for PENR and GWP both against the density and the product between density and thermal conductivity (see Fig. 10 and Fig. 11).

5. Conclusions

Insulation materials are effective solutions to reduce operational energy consumptions in buildings and improve their environmental profile. The environmental properties gathered from EPDs and literature of a wide range of insulation materials were compared by means of a "cradle to gate" approach.

Even if the chosen functional unit guarantees quite an equivalent base for the comparison of the environmental performance of insulating materials (in terms of operating thermal performance and design life span), they still have different specific heat capacities, phase shift/attenuation performance and waterproofing/fire/acoustic properties. Considering comprehensively all these aspects, however, traditional insulation materials, such as stone wool and glass wool, turned to be still very competitive in comparison with natural and innovative ones. They have a good fire resistance performance, good water proofing properties that avoid the formation of mold, less restricted durability conditions, low values of EE (in the range of 16–31 MJ/FU for glass wool and 21–66 MJ/FU for stone wool) and very competitive values of GWP (in the range of 0.6–1.2 kg CO_2eq/FU for glass wool and 1.4–4.2 kg CO_2eq/FU for stone wool).

The competitiveness of natural insulation materials derives from their higher percentage of renewable embodied energy (that can easily overcome the 50%) and from their carbon sink properties.

On the other hand, the environmental impacts of innovative high-performance insulation materials (for example aerogel, in the range of 251–372 MJ/FU and 11.6–18.7 kg CO_2eq/FU) are still very high if compared with market leader panels having the same insulation potential; this contributes to hinder their application in the buildings sector.

The high variance in the results obtained is a strong limit for the definition of reliable reference values, particularly for unconventional materials of which low certifications and dispersed data were found. We can assume that the high differences among the values obtained for unconventional materials are linked to their manufacturing process that may not be standardized and still very different from one manufacturer to another. For the market leader materials, it was possible to perform a variance decomposition analysis grouping EPDs data by density similarity and program operator. Density was able to explain a significant percentage of the total variance while the program operator had a lower influence. More transparency and standardization in the information conveyed by the program operators is however desirable especially about the energy mixes adopted and about the amount of recycle-reused material input into the production chain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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