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Life cycle analysis of a novel thermal insulator obtained from recycled glass waste

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ABSTRACT

This paper focused on the application of the Life Cycle Analysis methodology to a novel thermal insulator by means of comparison with traditional materials widely used in the building sector. This innovative insulating foam was produced from recycled glass powder and green-chemistry reagents via a freeze-drying process. The materials inventory for this insulator was built from primary laboratory data, while energy flows were estimated according to available secondary sources. Materials inventory, energy flow and emission data for traditional insulators were obtained and averaged from literature and relevant environmental product declarations. Global warming, acidification, eutrophication and abiotic resource depletion potentials were evaluated as environmental impact factors to assess the environmental performances of the innovative insulator respect to the available materials. The benefits of the novel material in terms of these indexes were then highlighted taking into account also different local energetic sources.

1. Introduction

The building sector accounts nowadays for 40% of energy consumption and 36% of carbon emission in the European Union (EU Commission, 2018), making it the largest energy-consuming sector. Similar values are reported for the U.S. (US Dept. of Energy, 2012) and worldwide (UN Environ. Program, 2013). An improvement in energy efficiency is therefore essential to reduce energy use and related emissions. Consistently with this commitment, the European Commission introduced the Energy Performance Buildings Directive (EU Commission, 2010), which states that all new buildings must be “nearly zero building” by the end of 2020. Proper building insulation is a critical issue that permits to minimize the transmitted heat flow, save heating energy and thereby contributing to lower the associated emissions from fossil fuel combustion (Schiavoni et al., 2016; Schmidt et al., 2004a; Asdrubali et al., 2015; Intini and Kühtz, 2011; Densley Tingley et al., 2015). The insulating materials market is dominated by inorganic fibrous materials such as mineral wool (MW) and organic foamy materials, for instance expanded or extruded polystyrene (EPS) and polyurethane foams (PU) (Schmidt et al., 2004a; Asdrubali et al., 2015; Intini and Kühtz, 2011; Cabeza et al., 2010). These traditional insulators are produced starting from primary raw materials, such as minerals or rocks (MW) and fossil fuels (organic foams). The use of secondary or renewable raw materials is nowadays of paramount importance to comply with ecological and sustainability requirements, and the production of insulating materials from natural sources or recycled post-consuming objects is being increasingly evaluated (Asdrubali et al., 2015). Some works showed the possibility to recycle polyethylene terephthalate (PET) or textile fibers to obtain insulating panels (Intini and Kühtz, 2011; Ingrao et al., 2014; Patnaik et al., 2015), whereas others focused on the use of bio-based or natural raw materials (Shinoj et al., 2011; Binici et al., 2014; Tangjuank, 2011). Other works focused specifically on the production of foamy materials from glass recycling (Blengini et al., 2012; Fernandes et al., 2014; Andreola et al., 2016; Bernardo et al., 2007), but require high-temperature processes and the use of blowing agents. To the best of our knowledge, low-temperature foaming methods without blowing agents are not currently available. The successful production of an open-cell foam produced from recycled glass powder and natural alginate biopolymer was reported in our previous works (Kyaw Oo D'Amore et al., 2017; Kyaw Oo D’Amore et al., 2018). The synthesis route is based on the preparation of a glass-alginate hydrogel, which is then freeze-dried. Initially, a three-dimensional porous network is formed; its structure is preserved by freeze-drying: the water entrapped during gelation is removed by sublimation, preventing the pores to collapse and leaving a porous structure. This material includes the benefits of secondary

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raw materials and the green-chemistry process, and it also addresses the problem of glass waste disposal. Details of the process and thermal acoustic characterization are available in our previous works (Kyaw Oo D'Amore et al., 2017; Kyaw Oo D’Amore et al., 2018). Thanks to its good properties, this innovative material could be appealing for the buildings sector. Life Cycle Analysis (LCA) can be a useful tool to compare various products for building insulation, since it aims at addressing the potential environmental impacts of a product throughout its life cycle and highlights potential improvements that can be used to increase the environmental, energy and economic efficiency of the process (Zabalza Bribián et al., 2011). In this context, this paper deals with the production on environmental impacts of this recycled glass-based foam (RGF) through an LCA. This study was conducted according to the guidelines of ISO14040 and ISO14044 standards.

2. Material and methods

2.1. Foam production and properties

RGF studied in this work was produced following a slightly modified recipe, based on the one reported in our previous work (Kyaw Oo D'Amore et al., 2017). The RGF composition used was the following (% wt.): glass 80%; sodium alginate 11%; glucono-delta lactone (GDL) 8%; calcium carbonate ($CaCO_3$) 1%. Briefly, a three-dimensional porous hydrogel network is formed after the Ca ions crosslink with the G-blocks of the polysaccharide; these Ca ions are slowly released from $CaCO_3$ while the pH of the solution gradually decreased due to GDL hydrolysis in water. After gelation, the samples were frozen at -20 °C for 12 h and finally freeze-dried to remove the water. The main differences respect to previous work were that glass powder was obtained by grinding municipal glass waste instead of laboratory waste by ball milling (powder size $\leq$ 200 μm) and that reagents quotas were modified in order to optimize thermal insulation properties ($\lambda = 0.040$ W m^{-1} K^{-1}) and density ($\rho = 105$ kg/m^3).

2.2. Goal and scope definition

The objective of this study was to assess an LCA cradle-to-grave of the RGF foam and to compare it with different insulating materials, whose data were available from producers’ environmental product declarations and literature sources. Typical properties of the insulating materials evaluated in this work are reported in Table 1. A critical comparison was made taking into account the production plant location since the same installation that consumes electric energy could use a different amount of natural resources and emit different amounts of pollutants depending on the location where it operates. The location could, therefore, impact on the environmental sustainability of the production process.

2.2.1. System boundaries and Functional Unit

This study focused on the difference between this novel RGF and other available insulating materials concerning production and disposal/recycling phases only. The analyzed phases are reported in Table 2. The production of raw materials, generation of electrical energy (A1), fabrication (A3), end-of-life waste disposal (C4) and reuse, recovery and/or recycling potentials (D) were included in the study. The transport of raw materials from production to assembly site (A2), transport of insulator to utilization site (A4) and assembling of insulating material (A5) were not taken into account, since these processes were considered independent from the type of material chosen as an insulator. Correspondingly, utilization phases (B1–B7) were neglected, since the energy-saving contribution of the different insulating materials were considered similar. According to ISO 14040 standard, the Functional Unit (FU) was defined as the reference unit through which a system performance was quantified in an LCA. Several LCA studies (Schmidt et al., 2004a, 2004b; Anastaselos et al., 2009; Su et al., 2016) of insulating materials use a mass-normalized FU (1 kg). Other works (Schiavoni et al., 2016; Tettey et al., 2014) propose a thermal resistance-normalized FU, defined as the mass of insulation material needed to guarantee a thermal resistance $R = 1$ m^2 K W^{-1} with a panel area of 1 m^2. Given a thermal conductivity λ and a density ρ, the mass m of the thermal resistance-normalized FU (1 m^2 with R = 1) can be calculated as $m = R \times \lambda \times \rho$. Therefore, LCA indexes can be easily converted between the two typologies of FUs by multiplying or dividing by the factor m. In this study, the thermal resistance-normalized FU (1 m^2 with R = 1) was used as reference FU for impact factor assessment.

Table 1
Typical properties of insulating materials evaluated in this work.

	density (kg m^{-3})	thermal conductivity (W m^{-1} K^{-1})	Ref.
RGF	100–110	0.035-0.045	(Kyaw Oo D'Amore et al., 2017; Kyaw Oo D’Amore et al., 2018)
MW	80–200	0.033-0.040	(Schiavoni et al., 2016; Asdrubali et al., 2015; Anastaselos et al., 2009; Su et al., 2016)
EPS	15–40	0.028-0.038	(Schiavoni et al., 2016; Asdrubali et al., 2015; Anastaselos et al., 2009; Su et al., 2016)
PU	30–40	0.025-0.030	(Schiavoni et al., 2016; Asdrubali et al., 2015; Anastaselos et al., 2009; Su et al., 2016)

2.2.2. Inventory method and data

The materials inventory for the RGF originated from primary laboratory data. The process for the production of the RGF comprised grinding of glass waste to powder, mixing in water with biopolymers, casting in molds and extracting water by a low-pressure sublimation process (freeze-drying). The production scheme is shown in Fig. 1. Energy for RGF production flows were estimated according to secondary data from the scientific literature. In particular, data from the industrial-scale freeze-drying process were used (Ratti, 2001; Keselj et al., 2017) to estimate an electric energy consumption of 25 MJ for 1 kg of dry material. Materials inventory, energy flow and emission for biopolymers production were obtained from relevant literature (Clarens et al., 2010; Benemann and Oswald, 1996; Renouf et al., 2008). Taking into account energy production shares by sources, energy conversion efficiencies and calorific values (ENEA, 2015; EU Environ. Agency, 2017a; EU Environ. Agency, 2017b; Fuel Emission Factors, 2006; US Dept. of Energy, 2014; IEA, 2017), the corresponding primary energy consumption and emissions deriving from electric power generation were obtained, assuming an energy mix averaged on 4 European countries (Italy, Austria, France and Germany). Materials inventory, energy flow and emission data for PU, EPS and MW were acquired and averaged from relevant literature data (Schmidt et al., 2004a, 2004b; Anastaselos et al., 2009; Su et al., 2016; Papadopoulos and Giama, 2007; Hill et al., 2018) and published Environmental Products Declarations (EPD) databases (BRE Global Ltd, 2016; EUROPUR, 2015; EPD Int. AB, 2019; IBU e.V., 2016a; IBU e.V., 2018a; IBU e.V., 2018b; IBU e.V., 2016b; IBU e.V., 2016c; IBU e.V., 2015; IBU e.V., 2014; IBU e.V., 2017). For these materials, primary energy data were explicitly declared in available EPDs. Conversely, it was not possible to distinguish between fossil fuel used for heating or electricity generation, nor quantify the electricity used in the production processes. The reliability of data was assessed through the Matrix Pedigree proposed by Weidema and Wesnaes (Weidema and Wesnæs, 1996). For RGF materials inventory, we could assume a data quality index of (1,1,1,1,1), with an overall score of 1 (excellent). Reliability of source = 1 (verified data based on laboratory measurement); Completeness = 1 (data cover all our samples); Temporal correlation = 1 (less than three years of difference); Geographical correlation = 1 (data from area under study); Further technological correlation = 1 (data from process under study). For RGF energy flows, we could assume a data quality index of (2,3,3,2,4) with an overall score of 2.8 (good). Reliability of source = 2 (verified

Table 2
Information of Life Cycle: evaluated phases are marked with "X".

Information on Life Cycle									
production			installation		use	end-of-life			
acquisition of raw materials	transport	fabrication	transport to installation site	installation	use and maintenance	dismantling/ demolition	transport to disposal site	waste treatment	disposal
A1	A2	**A3**	A4	A5	B1–B7	C1	C2	C3	**C4-D**
X	ND	**X**	ND	ND	ND	ND	ND	ND	**X**

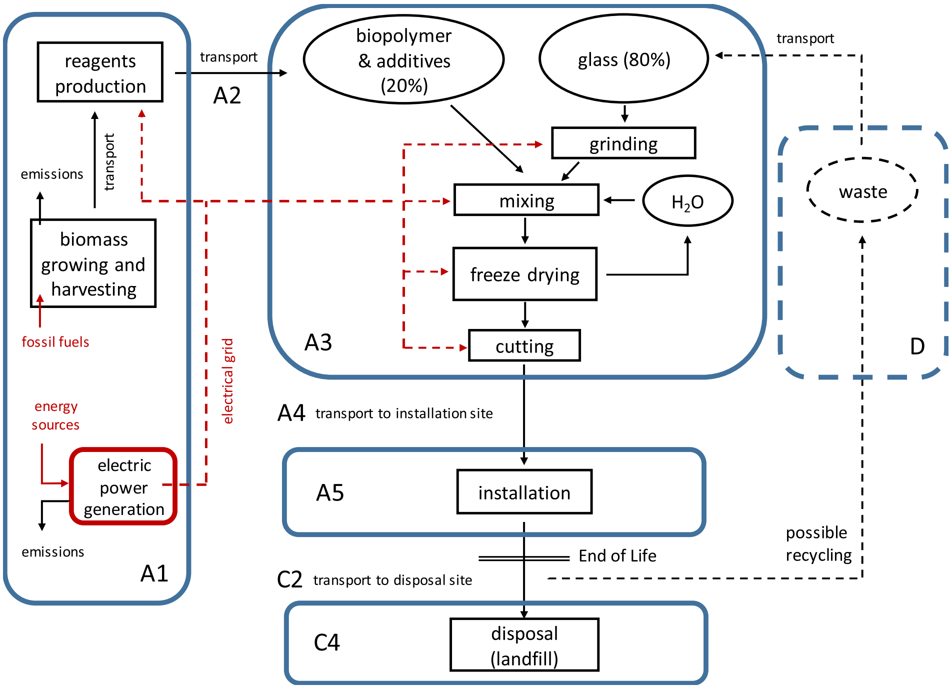

Fig. 1. Schematic production cycle of recycled glass foam (RGF).

data, partially based on assumption); Completeness = 3 (data cover some industrial cases); Temporal correlation = 3; Geographical correlation = 2 (data from larger area); Further technological correlation = 4 (same technology, different material). For other insulators (MW, EPS, PU), we could assume a data quality index for materials inventory and energy flows of (2,1,2,3,3) with an overall score of 2.2 (good). Reliability of source = 2 (official statistics); Completeness = 1 (official EPDs and statistics); Temporal correlation = 2; Geographical correlation = 3 (data from area with similar production condition); Further technological correlation = 3 (same process and materials, different technologies). Overall data quality level for RGF was “excellent” for materials inventory and “good” for energy flows; overall data quality level for MW, EPS and PU was “good”.

2.2.3. *Impact assessment method*

Concerning the environmental impact factors, the global warming potential (GWP, expressed in kg CO_2 eq.), the acidification potential (AP, expressed in kg SO_2 eq.), the eutrophication potential (EP, expressed in kg PO_4 eq.) and the abiotic depletion potential were taken into account both of non-fossil resources (ADP-NF, expressed in kg Sb eq.) and fossil resources (ADP-F expressed in MJ). The selected impact factors were chosen to be representative of broadly recognized areas of environmental concern. These impact factors are commonly found in environmental product declarations and research articles used as references. This evaluation was made according to available guidelines (EU Environ. Agency, 2006; Danish Ministry of the Environ., 2005; Crenna et al., 2018; Sala et al., 2017).

3. Results and discussion

3.1. *Raw materials inventory and energy consumption*

The amount of raw materials needed for the production of 1 FU of different insulating materials is reported in Table 3, while the primary energy used in the processes is reported in Table 4. Materials needed for the production of the RGF derives for 80% from waste (glass), 19% from biopolymers and natural additives (from biomass), and 1% from abundant minerals (calcium carbonate). The reagents are mixed in water; water is then removed by a low-pressure sublimation process (freeze-drying) and it is completely recovered after the process. No toxic, hazardous or fossil-derived chemicals are used or released during production. In the case of mineral wool, 97% of raw material originated from abundant compounds. About 80% of these are primary materials (limestone or other natural rocks), 20% secondary (recycled mineral wool or inert wastes). The remaining 3% constitutes the binder, which is obtained from fossil-derived reagents. Organic foamy materials such as PU and EPS typically derives completely from petrochemical reagents, even if there exist several efforts to obtain them from biomass-based precursors and/or from recycled polymers (Campanella et al., 2009; Petrović, 2008). In the specific case of PU, a relevant fraction of raw materials (isocyanates) is also toxic.

Concerning overall primary energy consumption, 1 FU of RGF seems the most demanding material, followed by MW. RGF, on average, requires around 267 MJ of primary energy for every FU; about 42% of this energy derives from renewable sources, and no feedstock energy is

Table 3
Raw materials needed for the production of 1 FU of insulating materials evaluated in this work (Schmidt et al., 2004a; Bernardo et al., 2007).

RGF (FU = 4.20 kg)		MW (FU = 5.11 kg)		EPS (FU = 0.91 kg)		PU (FU = 0.96 kg)	
glass (from waste)	3.36 kg	**formaldehyde**	0.05 kg	**polystyrene resin**	0.49 kg	**polyol**	0.69 kg
sodium alginate	0.46 kg	**phenol**	0.10 kg	**expansion foam**	0.42 kg	**isocyanate**	0.27 kg
GDL	0.34 kg	**limestone**	3.73 kg				
$CaCO_3$	0.04 kg	**secondary raw materials**	1.23 kg				

Table 4
Primary energy use for the production of 1 FU of insulating materials evaluated in this work (Fuel Emission Factors, 2006; US Dept. of Energy, 2014; IEA, 2017; Papadopoulos and Giama, 2007; Hill et al., 2018; BRE Global Ltd, 2016; EUROPUR, 2015; EPD Int. AB, 2019; IBU e.V., 2016a; IBU e.V., 2018a; IBU e.V., 2018b).

		RGF (FU = 4.20 kg)	MW (FU = 5.11 kg)	EPS (FU = 0.91 kg)	PU (FU = 0.96 kg)
Primary Energy, non-renewable (excluding raw materials)	MJ	154.3 ± 58.7	103.2 ± 36.3	40.8 ± 3.1	52.2 ± 5.2
Primary Energy, non-renewable (raw materials)	MJ	–	8.2 ± 2.6	36.5 ± 0.2	29.1 ± 4.2
Primary Energy, renewable	MJ	112.2 ± 60.5	11.2 ± 2.6	2.2 ± 0.1	4.6 ± 1.9

embodied in raw materials. On the other hand, one FU of organic-based insulators (EPS and PU) requires only 80 MJ of primary energy, but nearly half of this is feedstock (embodied) energy, due to the use of fossil-derived reagents, and only 5% of the total energy derives from renewable sources. If we take into account the mass of the different FUs, it is possible to notice that the energy amount normalized over 1 kg changes (see Table 5). Organic-based insulators are the most demanding materials (around 90 MJ of total primary energy needed for every kg). Mineral wool needs a lower amount (24 MJ/kg), while recycled glass foam, on average, requires around 64 MJ of primary energy for every produced kg. It is also worth pointing that the energy consumption for the production of the innovative recycled-glass foam is mainly electric, and resource allocation for electrical energy production, total energy consumption and its renewable fraction is strongly affected by the local energy sources used (see Table 6). For instance, by using an Italian energy mix, the production of 1 FU of RGF requires 253 MJ of primary energy, whose 42% is renewable. In Austria, 273 MJ are needed, but 77% is from renewable sources. Electric energy production shares of evaluated countries and EU28 averaged value are shown in Table 7. Non-renewable resource depletion (expressed in g) and CO_2 emission (in g) for the production of 1 MJ of electric energy are shown in Table 8.

3.2. *Environmental impact factors analysis*

Environmental impact factors for the production of 1 FU of insulating material are reported in Table 9; their normalized values are shown in Fig. 2. For the innovative foam, as previously shown, the energy consumption in biopolymer synthesis, reagent mixing, freezing and vacuum cycle is mainly electric. Therefore, emissions in the atmosphere originate almost completely (>94%) from electric energy production; the remaining fraction (<6%) comes from growing and harvesting operation of the biomasses (seaweed) required for biopolymer production and from other reagents synthesis. In the examined case, the emissions are calculated from averaged data from Italy, Austria, France and Germany electricity production (using an average conversion factor of 62.7 g CO_2 eq./MJ of used electric energy).

Table 5
Primary energy use for the production of 1 kg of insulating materials evaluated in this work (Fuel Emission Factors, 2006; US Dept. of Energy, 2014; IEA, 2017; Papadopoulos and Giama, 2007; Hill et al., 2018; BRE Global Ltd, 2016; EUROPUR, 2015; EPD Int. AB, 2019; IBU e.V., 2016a; IBU e.V., 2018a; IBU e.V., 2018b).

		RGF	MW	EPS	PU
Primary Energy, non-renewable (excluding raw materials)	MJ	36.8 ± 14.0	20.2 ± 7.1	44.9 ± 3.4	54.2 ± 5.4
Primary Energy, non-renewable (raw materials)	MJ	–	1.6 ± 0.5	40.2 ± 0.2	30.3 ± 4.4
Primary Energy, renewable	MJ	26.7 ± 14.4	2.2 ± 0.5	2.4 ± 0.1	4.8 ± 2.0

Table 6
Primary energy consumption for 1 FU of Recycled Glass Foam produced in different countries.

		Italy	Austria	France	Germany
primary energy (total, non-renewable)	MJ	147.0	61.7	214.2	194.5
primary energy (renewable)	MJ	105.8	211.3	49.6	81.1

Table 7
Energy production shares by source for four representative EU countries and EU28 average (EU Environ. Agency, 2017a).

	Italy	Austria	France	Germany	EU28 Ave.
Coal and lignite	12.3%	2.9%	1.5%	40.3%	21.2%
Oil and oil products	4.2%	1.5%	0.4%	0.9%	1.8%
Natural gas	44.5%	15.4%	6.6%	14.4%	19.7%
Nuclear	0.0%	0.0%	72.5%	13.0%	25.8%
Renewable	37.3%	74.4%	17.5%	29.0%	29.2%
Other	1.8%	5.9%	1.4%	2.3%	2.2%

Table 8
Non-renewable resource depletion and CO_2 equivalent emission, for 1 MJ of produced electric energy, for four representative EU countries and EU28 average (ENEA, 2015; EU Environ. Agency, 2017a; EU Environ. Agency, 2017b; ISPRA, 2017).

	Italy	Austria	France	Germany	EU28 Ave.
Coal and lignite	10.8 g	2.6 g	1.3 g	35.5 g	18.7 g
Oil and oil products	2.4 g	0.8 g	0.3 g	0.5 g	1.0 g
Natural gas	16.2 g	5.6 g	2.4 g	5.3 g	7.2 g
Uranium	–	–	1.0×10^{-3} g	1.8×10^{-4} g	3.6×10^{-4} g
emission (CO_2 eq)	73.2 g	30.6 g	17.5 g	129.7 g	87.3 g

It is worthwhile to remember that also this CO_2 quantity depends strongly on the chosen local energy sources, namely on the energy share produced from fossil fuel-powered plants. As an example, if a French energy mix is used (conversion factor: 17.5 g CO_2 eq./MJ) or an Austrian one (conversion factor: 30.6 g CO_2 eq./MJ), the total emission per FU will

Table 9
Impact factors for 1 FU of different insulating materials.

Impact factor	unit	RGF	MW	EPS	PU
GWP	kg CO_2 eq.	6.7 ± 4.6	13.3 ± 8.2	3.6 ± 0.5	5.0 ± 0.7
AP	kg SO_2 eq.	$(1.4 \pm 0.5) \times 10^{-2}$	$(6.6 \pm 5.1) \times 10^{-3}$	$(1.3 \pm 0.1) \times 10^{-2}$	$(1.5 \pm 0.1) \times 10^{-2}$
EP	kg PO_4 eq.	$(2.9 \pm 0.5) \times 10^{-3}$	$(4.0 \pm 0.8) \times 10^{-3}$	$(9.1 \pm 1.8) \times 10^{-4}$	$(1.1 \pm 0.1) \times 10^{-3}$
ADP-NF	kg Sb eq.	$(2.0 \pm 0.4) \times 10^{-8}$	$(2.0 \pm 0.5) \times 10^{-7}$	$(2.0 \pm 1.0) \times 10^{-6}$	$(6.8 \pm 0.6) \times 10^{-6}$
ADP-F	MJ	90.3 ± 55.9	99.1 ± 52.6	77.7 ± 1.3	69.6 ± 5.5

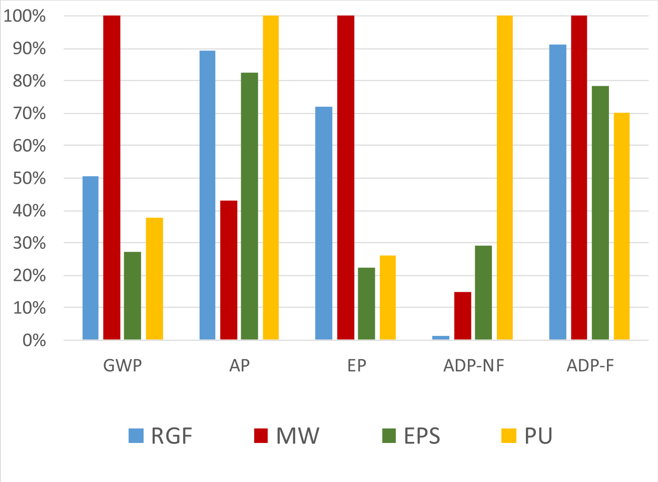

Fig. 2. Normalized impact factors for 1 FU of different insulating materials.

be reduced from 6.7 kg CO_2 (average mix) to 1.7 kg CO_2 eq. (French mix) or to 3.4 kg CO_2 eq. (Austrian mix). This because in France the nuclear-produced energy share outnumbers the fossil fuel one, while in Austria the renewable-produced energy quota is predominant. Conversely, with a production plant based in Italy or Germany, the emissions will rise to 7.6 kg CO_2 eq. and 13.4 kg CO_2 eq., respectively, due to the higher fossil-feed power plants. Similar consideration can be formulated for the other examined insulating materials; unfortunately, the electrical consumption amount is not precisely stated in the producers' EPDs (BRE Global Ltd, 2016; EUROPUR, 2015; EPD Int. AB, 2019; IBU e.V., 2018a; IBU e.V., 2018b; IBU e.V., 2016b; IBU e.V., 2016c; IBU e.V., 2015; IBU e.V., 2014; IBU e.V., 2017). Moreover, in MW manufacturing a relevant share of the energy consumption is ascribable to the fuel burned in the blasting furnace for melting (Schmidt et al., 2004a, 2004b), while for the organic foams (PU and EPS) at least 40–50% of the non-renewable energy contribution is embedded in fossil-derived raw materials (EUROPUR, 2015; IBU e.V., 2016b; IBU e.V., 2015; IBU e.V., 2014; IBU e.V., 2017). Therefore, these contributions cannot be lowered even changing the electric energy sources. Concerning acidification (AP) and eutrophication (EP) potentials, average results for RGF are lower than MW for AP, and higher for AP. RGF value for AP lies in the same order of magnitude lower than those of organic-based insulating foams, while EP value is higher. Also AP and EP are somewhat dependent on the location of energy production, but they seem less affected than GWP. This because about 40% of AP and 70% of EP values are linked to the production of the biomass-derived reagent. After comparing the AP and EP of the RGF produced in different locations (Table 10 and Fig. 3) it appears that moving production plant from Italy to Germany will double the AP value (due to the increased share of coal-powered plants) while moving it to France or Austria will lower the value. EP value shows a similar trend, but seems less affected by the location.

Table 10
Impact factors for 1 FU of Recycled Glass Foam produced in different countries.

Impact factor	unit	IT	AU	FR	DE
GWP	kg CO_2 eq.	7.6	3.4	1.7	13.4
AP	kg SO_2 eq.	8.4×10^{-3}	3.6×10^{-3}	4.1×10^{-3}	1.7×10^{-2}
EP	kg PO_4 eq.	8.4×10^{-4}	6.7×10^{-4}	3.2×10^{-3}	1.7×10^{-3}
ADP-NF	kg Sb eq.	2.3×10^{-8}	2.3×10^{-8}	4.1×10^{-5}	7.1×10^{-6}
ADP-F	MJ	142.0	45.4	19.7	153.7

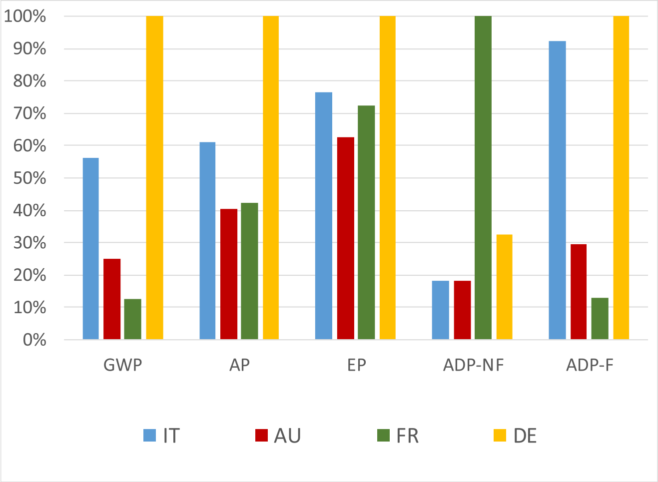

Fig. 3. Normalized impact factors for 1 FU of Recycled Glass Foam produced in different countries.

With regards to the abiotic depletion potential of non-fossil resources (ADP-NF), the value for RGF is negligible respect to that of other materials, since the only abiotic resource used in the production is a minimal part of calcium carbonate (1% in weight). ADP-NF has a maximum value if the production is located in France, due to the uranium used in the nuclear power plants for electricity generation. Fossil fuel depletion (ADP-F) lies in the same range for all four materials, since the organic insulators, even if requiring less energy for every FU, are produced starting from fossil raw materials.

Overall, it is possible to state that MW is the less environmental-friendly material for three indexes out of five (GWP, EP and ADP-fossil); polyurethane for the others (AP and ADP-NF). RGF performs better than MW for all indexes, but worse than organic materials in all except one (ADP-NF).

Considering all but one (ADP-NF) impact factors, Germany appears the least environmental friendly location, whereas France and Austria are the most suitable. The only exception is the ADP-NF, which reaches its maximum in France (due to the high nuclear energy production share).

3.3. End of life

The recycled glass foam and the mineral wool can be completely recycled, generating further benefits by avoiding primary raw materials used in their production. On the other hand, organic foamy materials (PU and EPS) can be incinerated in energy recovery units for electricity generation and district heating, recovering between 25% and 30% of the energy used in their production. EPS can be recycled, recovering raw materials for the manufacturing of new polystyrene products. Since PU is a thermoset polymer, it cannot be melted and recycled into new products.

4. Conclusions

In this paper, a life cycle analysis of an innovative recycled glass foam was evaluated and compared to those of available traditional insulating materials (mineral wool, expanded polystyrene foam e polyurethane foam) in terms of global warming, acidification and resource depletion.

The life cycle inventory was performed on the quantity of product needed to give a thermal resistance $R = 1\ m^2\ K\ W^{-1}$. The production and end-of-life phased were included in the study. Transport, assembly and utilization phases were neglected, since they were considered independent from the material chosen as an insulator. The results of the impact assessments highlighted some possible environmental benefits deriving from the use of this novel recycled material instead of traditional ones. The main strength and weakness points can be summarized as follows:

- No fossil fuels, hazardous chemicals or non-abundant resources are used as raw materials in the RGF.
- Secondary raw materials (glass waste) were used; this avoids landfilling of glass
- The production of one FU of RGF requires more energy than traditional insulator materials (MW, EPS and PU
- The energy required for RGF production is almost only electrical (mixing and freeze-drying processes): it can be obtained from different sources depending on plant location, and its renewable share is variable.
- No feedstock energy is embodied in raw materials used for RGF production
- Global warming potential, emissions and fossil fuel depletion can be lower respect to those of traditional insulator materials.

Overall, it was shown that the production and use of this RGF could have, under certain conditions, a beneficial environmental impact if compared to traditional insulator materials, in particular considering the avoided non-abundant material and fossil resource depletion and extra benefits deriving from glass recycling.

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Declaration of competing interest

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