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Recycled-PET fibre based panels for building thermal insulation: Environmental impact and improvement potential assessment for a greener production

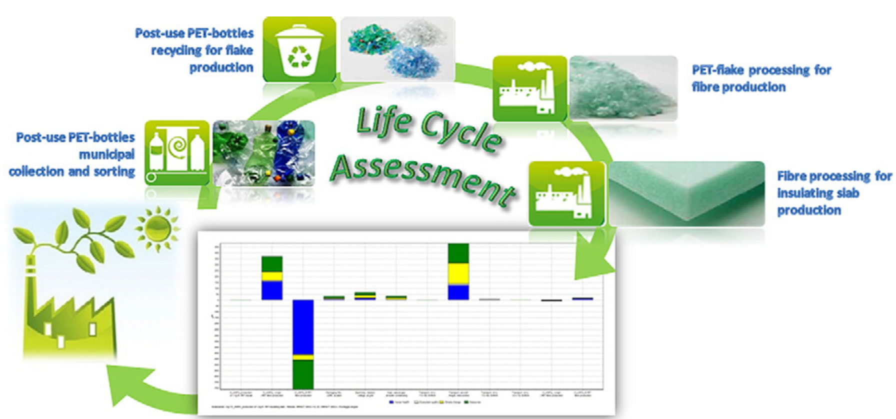
Carlo Ingrao [a,*], Agata Lo Giudice [b], Caterina Tricase [c], Roberto Rana [c], Charles Mbohwa [b], Valentina Siracusa [a]

[a] Department of Industrial Engineering, University of Catania, Viale A. Doria 6, 95125 Catania, Italy
[b] Department of Quality and Operations Management, Faculty of Engineering and the Built Environment, University of Johannesburg, APB Campus, P. O. Box 524, Auckland Park 2006, Johannesburg, South Africa
[c] Department of Economics, University of Foggia, Via Romolo Caggese 1, 71121 Foggia, Italy

HIGHLIGHTS

- The main input and output flows in the production of a RPET insulator were assessed;
- The processes contributing most to the insulator production damage were highlighted;
- Environmental improvement solutions were identified and assessed;
- The insulator was compared to other products with the same function;
- The study proved the importance of using recycled material in building construction.

GRAPHICAL ABSTRACT



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ABSTRACT

A screening of Life Cycle Assessment for the evaluation of the damage arising from the production of 1 kg of recycled Polyethylene Terephthalate (RPET) fibre-based panel for building heat insulation was carried out according to the ISO 14040:2006 and 14044:2006. All data used were collected on site based on observations during site visits, review of documents and interviews with technical personnel and management. These data were processed by using SimaPro 7.3.3, accessing the Ecoinvent v.2.2 database and using the Impact 2002+ method. The study showed damage to be equal to 0.000299 points mostly due to the: 1) PET thermo-bonding fibre supply from China by means of a freight-equipped intercontinental aircraft; 2) production of bottle-grade granulate PET; 3) medium voltage electricity consumption during the manufacturing of RPET fibre panel. It was also highlighted that there were environmental benefits due to recycling through mainly avoiding significant emissions and reduced resource consumption. An improvement assessment was carried out to find solutions aimed at reducing the damage coming from the most impacting phases. Furthermore, the environmental impacts due to the production of the analysed RPET fibre-based panel were compared to other materials with the same insulating function, such as polystyrene foam, rock wool and cork slab. Finally, the environmental benefits of the recycling of PET

* Corresponding author at: c/o Prof. Valentina Siracusa, Department of Industrial Engineering, University of Catania, Viale Andrea Doria, 6 (Edificio n. 10) – 95125 Catania, Italy. Tel.: +39 392 0749606.
E-mail address: ing.carloingrao@gmail.com (C. Ingrao).

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bottles for flake production were highlighted compared to other treatment scenarios such as landfill and municipal incineration.

1. Introduction

The building envelope can be considered the boundary of the thermodynamic system. It is of fundamental importance in the passive control of energy flows and also plays a significant role in maintaining indoor comfort conditions. Over the years, the building envelope has undergone a slow evolution when it concerns both the materials used and the construction technologies adopted (Fassi and Maina, 2009). It is well-known that in order for buildings not to be energy-intensive, they must be equipped with a good heat-resistance envelope. If this is not done, energy consumption and environmental impacts increase and, additionally, the indoor thermo-hygrometric comfort would deteriorate and worsen. It is, therefore, necessary to opt for properly insulated buildings by choosing appropriate technical solutions and materials. This would allow for several advantages, such as: thermal energy dispersion reduction in winter and summer; internal surface temperatures control; condensation phenomena control; temperature fluctuation reduction when the indoor environment is not air-conditioned. As Cabeza indicates (Cabeza et al., 2010), there are different insulation materials available on the market and usable in buildings. They are generally classified based on their origin, which can be from plants, animals, synthetics or minerals and based on their structure (foamy or fibrous) (Papadopoulos, 2005). Furthermore, there is a wide range of combined materials, which are manufactured by processing different materials from different origins so as to be able to improve their heat insulation performance (Fassi and Maina, 2009). According to Ardente et al. (2008), these new insulating-materials and technologies are under continuous development for better contribution to the overall energy efficiency of buildings. Another distinction to make when dealing with such building materials is based on the production process: in this respect, insulators can be made from natural or artificial materials. In the first case, they are taken from nature as they are, without any substantial transformation, even if they are commonly subjected to some processing (washing, cutting, etc.) in order to provide them with specific required characteristics. Second category materials (artificial) are obtained from a specific production process using raw materials appropriately mixed and dosed (Fassi and Maina, 2009). To assess thermo-insulation performance of building materials, their thermo-physical properties, such as density, thermal conductivity and specific heat, must be taken into account (Fassi and Maina, 2009). In Table 1, a classification of the materials commonly used for thermal insulation of buildings is shown indicating, for each of them, the most representative properties, as extrapolated from Fassi and Maina (2009). Considering the merits of the environmental aspects associated with an insulator life cycle, proper evaluations should be done for making sure that the impacts due to the phases of production and disposal are recovered by the benefits associated with the use phase due to energy and carbon dioxide (CO_2) emission savings.

In this context, the present work focuses on the analysis of the main environmental impacts due to the production of a polyester fibre panel for building thermo-insulation. The fibres used are produced through processing flakes obtained from post-consumer Polyethylene Terephthalate (PET) bottles. Therefore, this study can be used as a starting point for the assessment of the environmental sustainability associated to the product's life cycle, thereby including also the phases of use and the end-of-life. Over the years, a number of researchers have dealt with determining the environmental impacts of building thermal insulating products using Life Cycle Assessment (LCA): in this context, Erlandsson et al. (1997) could be considered as a precursor. He applied in fact LCA for assessing the energy and environmental consequences when equipping a dwelling with an additional wall insulation. Since then, lots of studies have concerned the application of LCA in the building thermal insulation field. For instance, Papadopoulos and Giama (2007) developed an energy and environmental performance analysis between stone wool and extruded polystyrene using LCA as a comparative assessment tool. Similarly, Cabeza et al. (2010) compared, in terms of environmental sustainability and thermal insulation performance, three materials, such as polyurethane, polystyrene and mineral wool. In 2009 and 2011, the "Energy and Buildings" journal published the manuscripts written by Anastaselos et al. (2009, 2011), thereby significantly contributing to enriching the knowledge in this field. In the first study, the most common external wall insulation solutions in Greece were assessed considering the energy, economic and environmental issues, while, in the second, these three issues were proposed to be integrated so as to create a decision support tool for optimizing the overall quality of a thermal insulation solution. In this context, Dylewski and Adamczyk (2011, 2012) developed two studies dealing with combining economic and environmental sustainability aspects for assessing building thermal insulation systems benefits and investments feasibility. Another significant research paper to be cited is the one of Audenaert et al. (2012) in which the application of LCA allowed to prove how important it is to choose the best thermal insulation design settings and materials for low energy and environmental impact buildings. Regarding the use of alternative materials for building thermal insulation, the studies of Ardente et al. (2008) and Intini and Kühtz (2011) are believed worth to be mentioned since assessing whether the energy use or the environmental impacts due to a kenaf-fibre board and a panel made of polyester fibre (recycled from post-consumer PET bottles), respectively. Finally, Rakhshan et al. (2013) performed a case-study in the Dubai residential built environment showing that the environmental cost linked to the production and installation of insulation systems are recovered by the operational GHG (Greenhouse Gas) emissions saved by their application. All the studies cited allowed to demonstrate that the building insulation field has been already investigated not only in terms of economic yield and energy efficiency but, also, of environmental sustainability. However, only one study dealt with the environmental assessment of the production of PET from post-use recycling of bottles. In this regard, it was observed that similar studies are needed, since the state of the art appears to be deficient in this area, thereby making the present study original and appealing. This study is also believed significant because it contributes to enriching the current knowledge on the application of LCA in this sector providing quality and reliability of both inventory flows and results so as to enable comparison with similar studies. This will also allow for the development of interesting comparisons with other insulating materials of equal thickness or thermal conductivity, but produced using different methods. In this way, it will be possible to highlight any difference in terms of raw materials, fossil fuels and energy consumption as well as of impacts on the environment. Additionally, LCA practitioners, building designers and construction-material producers will be able to learn more not only about the resources, the materials and the energy used, but also the main environmental impacts due to the production of heat insulating products when using recycled PET (RPET).

The present work was developed with the purpose of pure scientific research as the result of collaboration between a few Universities and a firm, located in the North of Italy, which provided the research group with all the necessary technical support. The study will assist the firm to better understand the environmental impacts linked to its manufacturing processes and will provide more information about the

Table 1
Mostly used insulating materials main properties.
Source: personal elaboration from Fassi and Maina (2009).

Heat insulating materials		*Form*	*Density (kg/m^3)*	*Thermal conductivity (W/m°K)*	*Specific heat (kJ/kg°K)*	*Steam resistance factor*
Plant origin	***Cellulose fibres***	Flakes	25–65	0.037–0.041	1.9–2	1–3
		Panels	30–90	0.039–0.040		
		Bulk granules	300–500	0.069		
	Wood fibres	Panels	45–55	0.038–0.052	2.1	1–10
			150–300			
	Wood fibres with mineral binders	Panels	350–625	0.075–0.095	1.8	5–8
	Cork	Panels	100–300	0.036–0.050	1.7–2	5–11
		Bulk granules	65–120	0.034–0.049		
		Kneaded granules	200–450	0.048–0.1		
	Kenaf fibres	Panels	20–80	0.034–0.042	1.7	1–2
	Hemp fibres		30–190	0.039–0.043	1.7	1–2
	Linen fibres		30–35	0.037–0.040	1.6	1–2
	Maize fibres		10–80	0.040	1.9	3
	Coconut fibres		50–150	0.043–0.047	1.3–1.6	1–2
Animal origin	*Sheep wool*	Panels	14–30	0.033–0.040	1.75	1–4
Mineral origin	*Expanded clay*	Bulk granules	320–450	0.09–0.13	0.9–1	5–8
		Granules kneaded with an hydraulic binder	600–1400	0.16–0.31		
	Expanded perlite	Bulk granules	80–130	0.047–0.060	0.9–1.4	3–8
		Granules kneaded with an hydraulic binder	400–650	0.094–0.15		
		Panels	150–280	0.050–0.060		
	Expanded vermiculite	Bulk granules	85–105	0.057–0.077	0.8–1	–
		Granules kneaded with an hydraulic binder	400–600	0.084–0.095		
	Expanded granular glass	Bulk granules	140–400	0.07–0.08	0.8–0.9	5–8
	Natural pumice	Bulk granules	480–1000	0.1	0.9	2–4
		Granules kneaded with an hydraulic binder	800–1600	0.16–0.21		
	Lime-foamy cement	Panels	115	0.045	1	3–6
		Bulk granules	300	0.10–0.13		
		Granules kneaded with an hydraulic binder	450–900	0.15–0.18		
	Foamy glass	Panels	105–170	0.038–0.050	0.84	Unlimited vapour-tight
		Gravel	200–400	0.07–0.09		
	Rock wool	Panels	40–155	0.035–0.040	0.8	1–5
Synthetic origin	*Polystyrene fibres*	Panels	20–100	0.040	0.24	1–5
	Sintered expanded polystyrene		20–50	0.040	1.4	20–80
	Extruded expanded polystyrene		30	0.035	1.45	80–300
	Rigid expanded polyurethane		30–40	0.030	1.3	30–100
	Expanded polyethylene		17–150	0.040	1.2	2000

insulator production critical points and the solutions needed to increase the firm's environmental sustainability.

2. Post-consumer bottles recycling environmental considerations and PET-flake main uses: a brief analysis

Nowadays, several million tonnes of plastics are produced every year and used for packaging materials and almost for every type of consumer product (Papong et al., 2014; Blanco, 2014). There exist natural plastics, such as shellac, tortoiseshell, horns and many resinous tree saps, but the term "plastic" is commonly used to refer to all those synthetically (synthetic or semi-synthetic) created materials which are constantly used in daily-life: from clothing to machinery (Anon., 2009). Synthetic and semi-synthetic plastics can be divided into thermoplastics and thermosets. In particular, thermoplastics are plastics that can be repeatedly soften and melt when heat is applied and then can solidify into new shapes or new plastics products when cooled. This group of plastics includes, among others, PET, Low Density Polyethylene (LDPE), Polyvinylchloride (PVC), High Density Polyethylene (HDPE), Polypropylene (PP) and Polystyrene (PS) (Anon., 2009). Among these, PET is considered as one of the most important technical plastics of the last three decades (Navarro et al., 2008). According to Welle (2011), it has in fact become over the years the most favourable material in the production of bottles for beverages, such as soft and energy drinks, mineral water and juices. The reason for this development is the excellent physicochemical and mechanical properties, such as high transparency, dimensional stability during handling, low permeability levels for gases (CO_2, for instance) and good barrier properties towards moisture and oxygen (Navarro et al., 2008; Welle, 2011; Blanco et al., 2012). Besides these characteristics, it is worth to mention also the very low weight of the bottles compared to glass bottles of the same filling volume (Welle, 2011). A PET bottle is in fact on average eight times lighter than a traditional glass one. For instance, considering a 750 ml filling volume, a PET bottle weighs 50 g compared to its glass counterpart's 400 g (Anon.). The extended use of PET has resulted in an exponential increase of the amount of post-consumer PET in municipal solid waste (Welle, 2011; Dullius et al., 2006). Therefore, PET-waste has to be managed considering, however, its difficult degradation due to the use of petroleum resources in the production process (Blanco et al., 2011). Thousands of years are in fact needed for plastics to be biodegraded, thus causing plastic-waste accumulation and, in turn, serious environmental problems connected to littering and illegal landfill or incineration (Papong et al., 2014; Dullius et al., 2006; Badia et al., 2012; Nampoothiri et al., 2010). For this reason, post-consumer PET management system must be designed adopting solutions oriented to maximising its environmental sustainability. In this context, recycling has been receiving considerable attention due to its main environmental benefits which are acknowledged throughout the world and make it one of the most successful and cleanest waste-recovery processes (Badia et al., 2012). In the particular case of plastic waste, recycling can be chemical or mechanical. As Navarro et al. (2008) indicates, the first consists of depolymerisation via hydrolysis, methanolysis or glycolysis for producing different monomers, while the second is based on the elimination of contaminants and the subsequent elaboration of pellets via extrusion. Mechanical recycling presents advantages over chemical recycling, as it uses equipment similar to that used in transformation, thereby making investments in complex installations unnecessary (Navarro et al., 2008). From an environmental perspective, it should be underlined, as already done by Barboza et al. (2009), that both of the above-mentioned technologies contribute to reducing the environmental impacts linked to fossil fuels and energy consumption, GHGs emission and resources exploitation, as well. This is because they allow for the production of a secondary raw material which can be used in several industrial sectors replacing partly, or completely, the use of virgin raw materials depending on the type of application. In the process, care should be taken to avoid compromising the quality and functionality of the finished products.

Petcore, the European trade association fostering post-consumer PET collection and recycling (Petcore), reported that in Europe 1.68 million ton of PET bottles were collected in 2012 out of which about 1.18 million tons of PET flake were produced and, in agreement with Dullius et al. (2006), used in several applications, as reported in Fig. 1.

The miscellaneous applications encompass also the use of PET-flake for the production of concretes and other construction materials. In this regard, high quality technical assessments have been developed over the years. For instance, Frigione (2010) developed a study in which an attempt to substitute in concrete the 5% by weight of fine aggregate (natural sand) with an equal weight of PET aggregates manufactured from the waste un-washed PET bottles was assessed. Similarly, Albano et al. (2009) studied the mechanical behaviour of concrete with RPET, changing the water/cement ratio, the PET content and the particle size. PET use in concrete was also tested in terms of thermal degradation when blends were exposed to different temperatures. In addition to these, the manuscript of Akçaözoğlu et al. (2010) is dedicated to investigating the utilization of shredded waste PET bottle granules as a lightweight aggregate in mortar considering two groups of mortar samples, one made with only PET aggregates and the other with PET and sand aggregates together. Finally, Ahmadinia et al. (2011) carried out a research aiming at determining the effect of incorporating waste plastic bottles on the engineering properties of stone mastic asphalt (SMA) mixture. From Fig. 1, it can be observed that miscellaneous applications cover just a very small percentage in the use of PET-flake compared to the others, especially fibre production, which results, indeed, the most widespread practice. For this reason, considerations on the environmental impacts due the production of these fibres were believed necessary and useful, thus remarking the importance of this study.

3. RPET fibre insulating panel typical technical characteristics and manufacturing processes

As already anticipated in Section 2, fibre production is the most common way of using PET-flake. From this point of view, this study is an example of this as it reports the case of RPET fibre panel production for thermal and acoustic insulation in buildings. These panels are nonwoven and made of 100% polyester made up of 80% recycled and 20% synthetic origin virgin material. Since the products are in the form of panels, they can be easily handled and used for external walls and coverings for insulation. Table 2 provides their main technical characteristics.

This insulator production process, using recycled PET-waste, can reduce environmental pollution compared to other disposal treatments such as landfill or municipal incineration. This is linked to not using resins or other chemical binders but only virgin and waste PET fibres appropriately mixed and processed. For this reason, the finished-product can be completely recyclable after use, toxic substances free and safely used. The process in question can be divided into the following macro-phases: fibres production by the extrusion of both synthetic PET and RPET granules; thermo-bonded panel manufacturing process from the above-listed produced fibres. Each of the above-listed phases is discussed next:

3.1. Fibre production from synthetic PET granules

This type of fibre is obtained by extruding virgin PET granules and constitutes 20% of the final product, namely the insulating slab. It is a bi-component fibre and is responsible for the thermo-bonded final product resistance, as its low melting temperature (170 ÷ 180 °C) allows for the aggregation of the recycled polyester fibres. Such fibres are produced in Beijing (China) and transported to the insulator production factory in Rome (Italy) by means of a freight-equipped intercontinental aircraft. From Rome, the materials are transported by truck to the insulator production factory in the North of Italy.

3.2. Fibre production from recycled-PET granules

Fibres are produced by processing different sizes and types of PET bottles collected from municipal waste sites. These plastic-packages (bottles, flasks and others) can be sorted mechanically or manually. Any extraneous fraction is removed, so that the waste collected is

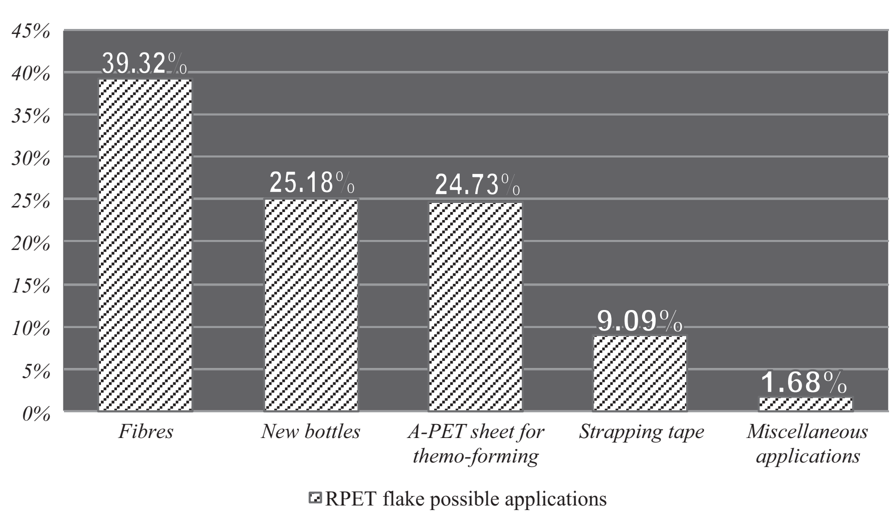

Fig. 1. Most common ways of using RPET-flake (personal elaboration from Petcore, 2012).

Table 2
Examined product main technical characteristics.
Source: personal elaboration using data provided by the firm on the insulator characteristics.

Composition	- Polyester staple fibre - Polyester staple fibre with thermo-bonding function
Thickness (cm)	5–10
Manufacturing process main phases	Carding; Cross-lapping; Thermo-bonding; Cutting; Packaging
Main uses	- Thermal insulation - Sound absorption
Finished-product type and dimensions	500 × 1000 mm dimensioned slabs
Main parameters	Fire reaction class: 1 Drip: absent Operating temperature range: 40 ÷ 110 °C Apparent dynamic rigidity: s′ < 30 MN/m^3 Lower calorific value: 21,600 kJ/kg Specific heat: 0.24 kJ/kg °K Thermal conductivity (λ): 0.036 W/m °K Density (ρ): 30 kg/m^3

suitable for recycling. The waste plastic is carefully selected and each type of polymer is subjected to the next production processes starting with grinding. There is a wide range of mills that can grind all types of plastic packaging, producing a coarse material of homogeneous but irregular size. Once ground, the PET plastic is washed by spraying caustic-soda water solution. Centrifugal treatment of the plastic flake is done for better cleaning and water removal and drying is carried out using a hot air stream until required water content specifications are met. Further milling is done to reduce material size. The obtained material is transported to the extrusion plant where it is stored in appropriate silos. Extrusion is the final step in the RPET fibres manufacturing process. The material is levied from the storage area and conveyed to an extruder. The fibres produced through extrusion are cooled and cut-off. Packed polyester fibres, consisting of PET both virgin granulate and recycled chips are transported to the thermo-bonding plant for nonwoven slab manufacturing.

3.3. Thermo-bonded product manufacturing process

Once the fibres are levied from the storage silos and mixed in accordance with a defined recipe, they are subjected to a carding treatment to produce veils to be further processed by the cross-lapper. Here each veil is tidily disposed and overlapped on itself a prescribed number of times. The output looks like a mattress in terms of shape and thickness: its mechanical resistance, however, is still poor. After cross-lapping, the work in progress is carefully conveyed to the furnace where the thermal bonding process is triggered using a bi-dimensional hot air flow. At its output side, the furnace is equipped with a metal mesh used for pressing the material to make it more compacted and to allowing for a greater reaction of the bi-component fibres. At this step, panels are semi-produced. After cooling, they are cut, longitudinally and transversally. The first cut is done using band-saw blades, while the second one is performed using a metal blade rotating at a high speed. The material is, then, hot-pressed for triggering another thermo-bonding reaction. Once cooled, the slabs are finally packed stacking up units of 25 to 60 kg.

4. Material and methods

Products' life cycle sustainability can be evaluated from an environmental, social and economic perspective (Andrews et al., 2009). However, these three aspects can be separately assessed and, then, matched together and reciprocally weighed in an integrated approach. Their interconnection has been emphasised over the last decade and has since been acknowledged to be the basis for sustainability assessment in life-cycle of products (Andrews et al., 2009). In this context, the present work deals only with the environmental issues and should be part of a larger project in which socio-economic aspects will be evaluated and, hopefully, weighed and compared to the environmental ones. For the present analysis, an E-LCA (Environmental Life Cycle Assessment), world-widely known as LCA, was carried out. This methodology aims at addressing the environmental aspects of a product and its potential environmental impacts throughout its life cycle (Guinée et al., 2011). For this reason, it can be considered the perfect tool for highlighting and assessing both critical points and margins for environmental improvement in products' life cycle. According to the ISO 14040:2006 (International Organization for Standardization (ISO), 2006a) and 14044:2006 (International Organization for Standardization (ISO), 2006b), the present study was divided in the following phases: 1) *Goal and scope definition*, which includes the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions; 2) *Life Cycle Inventory (LCI) analysis*: this phase involves the compilation and quantification of both input and output flows and includes data collection and analysis; 3) *Life Cycle Impact Assessment (LCIA)*: in this phase, based on the inventory analysis results, it is possible to qualify, quantify and weigh the main environmental impacts linked to a product life cycle; 4) *Life Cycle Interpretation and Improvement Assessment (LCIIA)*, in which the results from the impact assessment and the inventory analysis are analysed and interpreted for establishing recommendations oriented towards damage reduction.

According to the ISO standard 14040:2006, the inventory analysis phase involved data collection, classification and interpretation. All the data used was processed using the SimaPro 7.3.3 (SimaPro, 2006) software, accessing the Ecoinvent v2.2 (Ecoinvent, 2010) database and choosing Impact 2002+ (Joillet et al., 2003) as the calculation method for carrying out the impact assessment phase. According to the ILCD handbook, entitled "Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA)" (Anon., 2010), this method proposes a feasible implementation of a combined midpoint/endpoint approach, linking LCI results via midpoint (impact) categories to endpoint (damage) categories. In this regard, Table 3 shows the distinction between impact and damage categories as provided by the Impact 2002+ method. The first ones represent the negative effects to the environment through which the damage (due to an emitted substance or an used resource) occurs, while the second are obtained by grouping the impact categories into major ones and represents the environmental compartments suffering the damage (Joillet et al., 2003). Furthermore, this method calculates the non-renewable energy consumption and recognizes carbon dioxide as the emitted substance having the greatest responsibility for the greenhouse effect and then climate change. These are both believed fundamental aspects to be considered, especially in the case of industrial processes such as the one under study. Finally, the method is set-up so as to be more comprehensible for insiders and also more accessible if compared to other methods.

Regarding the LCIA, this phase was conducted using both a midpoint and an end-point approach, thereby including in the assessment, also, the optional elements, such as Normalization and Weighing. The midpoint approach was used because it allows for enabling comparative assessments between similar products and processes. This is usually done, indeed, mutually comparing, for each impact category, the related

Table 3
Damage and Impact categories in Impact 2002+.

Damage category	Impact category
Human Health	Carcinogens; Non-carcinogens; Respiratory inorganics; Respiratory organics; Ionizing radiations; Ozone layer depletion
Ecosystem Quality	Aquatic eco-toxicity; Terrestrial eco-toxicity; Terrestrial acidification/nitrification; Aquatic acidification; Aquatic eutrophication; Land occupation
Climate Change	Global warming
Resources	Non-renewable energy; Mineral extraction

damage values which result from the characterization stage and, therefore, are expressed using equivalent indicators (for instance, kg CO_2 for Global Warming, kg $PM_{2.5}$ for Respiratory Inorganics, kg C_2H_3Cl for Carcinogens). In addition, the endpoint approach was used because it allows for results to be expressed with equivalent numerical parameters (points) and, therefore, the environmental effects of the analysed system to be represented quantitatively. In this way, according to Siracusa et al. (2014), damage and impact categories, processes and both emitted-substances and used-resources can be compared to each other based on the damage unit-point. The end-point approach allows for highlighting those processes which are most impactful and, for this reason, represent the critical issues of the system under study, thus requiring environmental improvement priority. In this context, as already said, this study will allow the firm to re-examine the merits of the environmental issues associated to the insulating panel manufacturing system, representing a valid tool for decision making.

Furthermore, for a better comprehension of LCA methodological setup, it was decided to clarify the meaning of "total damage" since often used along the manuscript. The total damage is the one associated to the production of 1 kg of RPET fibre panel. It can be calculated by summing up the contributions of the processes and materials included in the system boundaries or of the damage and impact categories or even of all substances emitted and resources used (Ingrao et al., 2014).

4.1. Goal and scope definition

The goal of an LCA must state, unambiguously, what the intended application, the motivation to conduct the study and the type of audience that is targeted are (Lo Giudice et al., 2014). This paper explores the application of LCA in buildings thermo-insulation field so as to identify and weigh the impact indicators best representing the production of a fibre-based insulating material when RPET is used. The main goal of the study is, indeed, to qualify and quantify the environmental impacts due to the production of the fibre-based insulator in question so as to highlight: 1) the most impacting phases in the insulator production; 2) the most impacted damage category among those considered by the method chosen for the LCIA development; 3) the most impacting substances emitted and resources used; 4) the processes causing the emission and consumption of the above-mentioned substances and resources; 5) the most significant impact categories; and 6) the environmental improvement potentials.

Furthermore the study arises with the aim of identifying and quantifying the environmental benefits resulting from the use of RPET plastics in fibre production.

As established by the ISO 14044:2006, the "Goal and scope definition" phase includes both functional unit (FU) and system boundaries definition. In this case, the chosen FU is 1 kg of recycled-PET insulating panel produced whom the input and output flows are referred to. As shown in Fig. 2, the system boundaries were divided into the following blocks (subsystems): a) virgin PET granulate production and processing for bi-component fibre production; b) door-to-door collection and sorting of waste plastics, such as HD/LD-PE, PP, PS and PET, coming from domestic uses; c) PET flake production, from post-use PET bottles first grinding to washing and drying until second grinding; d) PET flake extrusion for fibre production; and e) insulating material production, from the two fibre-types dosage and mixing to carding and cross-lapping until cutting and packaging of the finished product. Subsystem "b" includes transportation to Municipal Waste Collection Centres (MWCCs), storage within roll-off containers until total filling and next transportation to sorting plant. Roll-off containers life cycle was excluded from the system boundaries due to the absence of specific data and also to the low environmental impacts expected per kg of stored waste plastics. Furthermore, in order to create a model as close-to-reality as possible and also to allow for a quality impact assessment, further involved transports were accounted for.

Insulating panel transportation was not accounted for because of the building construction site location variability which, therefore, results in a lack of knowledge of the building belonging-Municipality and, in turn, of the relative municipal waste management system (MWMS). For this reason, the disposal of the film in the amount used for packaging the FU (1 kg of insulator), as well as the transportation to the corresponding treatment plant, was excluded from the system boundaries. Furthermore, it is important to observe that the use phase was not studied, since it is strictly linked to the thickness used for side-walls and rooftops thermal insulation and to the lifetime of the building in which the insulating material is installed. Buildings lifetime-horizon is generally accepted to be defined at between 50 and 60 years. Afterwards, it is assumed that buildings are dismantled through a selective practice and component materials, including envelope insulation system, are treated as waste in appropriately-equipped plants (Dylewski and Adamczyk, 2012). It should be noted that the end of life of the insulator analysed was excluded from the system boundaries, since building

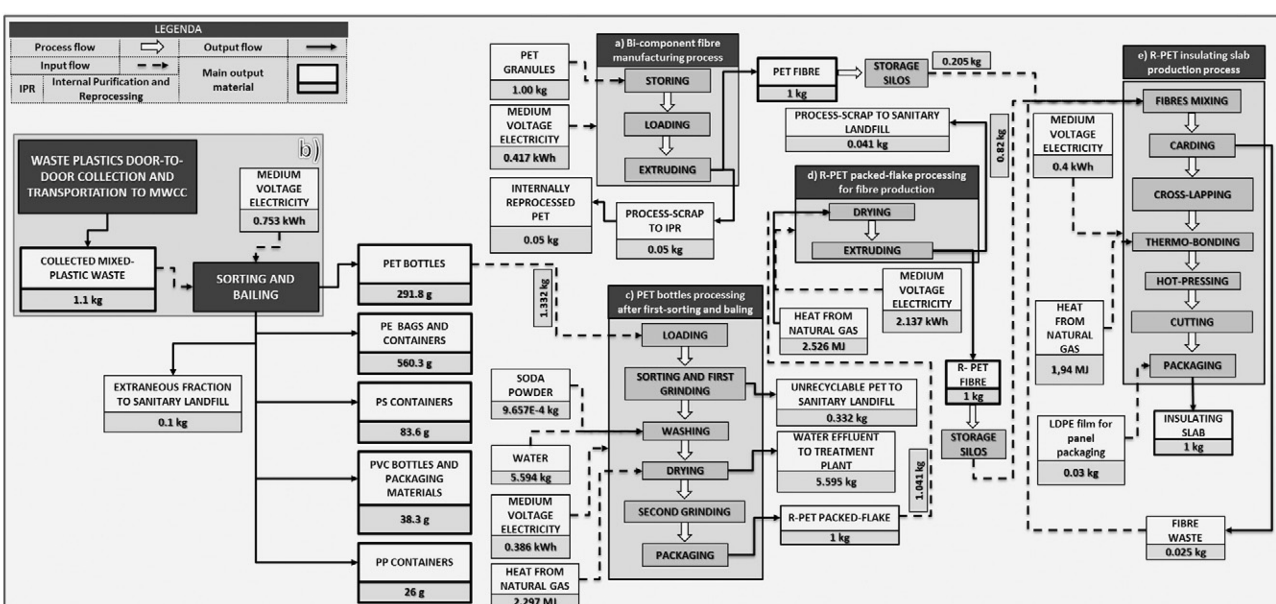

Fig. 2. System boundaries and main input flows from the inventory analysis.

Table 4
Plastic-fractions distribution using a weight percentage.

Plastic-fraction	Weight percentage per kg of clean waste plastics	Typical range
PE	56.03	54 ÷ 58
PET	29.18	28 ÷ 30
PS	8.36	8 ÷ 9
PVC	3.83	3.5 ÷ 4
PP	2.60	2.5 ÷ 3

envelope construction techniques and insulator installation conditions are unknown and many.

4.2. Life Cycle Inventory (LCI) analysis

The LCI analysis was developed collecting all the useful and available data regarding the insulating material in accordance with the firm practice. According to Lo Giudice et al. (2013), this phase aims at quantifying material and energy flows in a product's life cycle. In developing this phase, the maximum level of detail was assured: all the processes and materials expected to be significantly contributing to damage were accounted for. PET post-consumer bottles recycling is an industrial process whose environmental benefits are linked to generating a secondary material (flake) which could replace (partly or completely) the primary one, thereby being used for producing high quality goods. Flake, as produced from recycling post-use PET bottles, allows for avoiding the use of the same amount of virgin PET bottle-grade granule and, as a result, the environmental impacts due to its production. In developing the inventory phase, since a particular specialized system was assessed, it was decided to give great importance to using the data supplied by the firm involved in the study (primary data). The processes used for representing the consumption of resources, materials and energy, as well as the use of transport means, were extrapolated from Ecoinvent v.2.2, because believed a reliable background data source.

Entering into the merits of the main flows taken into account for the subsystems defined in Section 4.1, it can be said that the implementation of subsystem “a” was done considering:

1. the production of 1.05 kg of PET granule needed for producing 1 kg of fibre and its transportation to the fibre production plant considering a travelled distance of 1000 km;
2. the scrap produced during the extrusion process in the amount of 0.05 kg and then internally reprocessed after a purification treatment;
3. the electricity consumption (0.542 kWh per kg of fibre produced) for whether fibre production via granule extrusion or process-scrap beneficiation.

Electricity consumption was modelled accessing the Ecoinvent v.2.2 database using the item “*Electricity, medium voltage, at grid/CN*” which includes electricity production in China, transmission network and direct emissions of sulphur hexafluoride (SF6) to air. Electricity losses, in the form of heat waste, during medium-voltage transformation from high-voltage and transmission, were also accounted for and equate nearly 1% in total. According to the model used, transmission is 100% by means of air-lines. The transmission network includes in turn the phases of production, use, maintenance and end-of-life. Regarding the dataset used, per kWh of electricity produced and transmitted, the following input flows are taken into account by the model: 1) 0.000000189 kg of SF6 (liquid); 2) high voltage electricity at grid in the amount of 1.0103 kWh to be transformed into medium voltage; 3) 0.0000000324 km of transmission lines; 4) heat waste emission both to air and into soil in the amounts of 0.0204 MJ and 0.0167 MJ, respectively; 5) and, the emission to air of 0.000000189 kg of SF6.

For a better comprehension of the process, it is underlined that internal scraps reprocessing after beneficiation is feasible because they are fundamentally pure and uncontaminated. Furthermore, laboratory tests, performed by the firm technicians, whose results were not reported here for reasons of confidentiality, demonstrated that fibre mechanical properties do not become compromised. Regarding subsystem “b”, the phase of plastic fractions separation was implemented using the data provided by the sorting plant involved in the analysed system. This plant is located 50 km away from RPET flake production factory and receives mixed-plastics from six Municipalities as established by a specific agreement. Regarding the data used for representing the sorting phase, it should be observed that:

- 1.1 kg of mixed plastics are needed to be processed so as to generate 1 kg of clean mixed plastics to be addressed to separation into homogeneous polymer fractions;
- 0.753 kWh of electricity are required for the whole phase;
- the extraneous fraction amount resulting from plastics sorting settles at 10% of the input material.

During sorting, plastic fractions are separated from each other based on their polymeric nature creating bales of homogeneous material so as to allow for recycling yield maximisation. On the contrary, the extraneous fraction is disposed of in a sanitary landfill located at 30 km of distance from the sorting plant: the corresponding flow used for the assessment results to be equal to 3 kg*km. Table 4 shows weight percentage values of each polymer fraction per kg of clean mixed plastics, as provided by the sorting plant technicians using the results gained from the latest plastics samples analysed: according to firm technicians, these values fall within those ranges which are typical for the local reality.

As specified in the “Goal and scope definition” section, sorting phase encompasses mixed plastics municipal collection and transportation to the MWCC. This phase was modelled using the information provided by the firms involved in municipal waste collection. In particular, in each of the Municipalities served by the plant, a separate municipal waste collection is carried out through a door-to-door practice. Mixed plastics are collected two days a week and, therefore, a three-day production was considered for the model implementation. In Table 5, it was decided to report for each Municipality the most important data used for the analysis, namely population, number of users, per-capita municipal waste production, daily-produced municipal waste, content of plastic materials and three-day mixed plastic production (MPP_3). According

Table 5
Population, number of users, per-capita municipal waste production, daily-produced municipal waste, content of plastic materials and three-day mixed plastic production.

Municipality	Population*	Users (families)	Per-capita municipal waste production (average value) (kg/person)	Daily-produced municipal waste (kg)	Mixed plastic content (%)	Mixed plastic three-day production (MPP_3) (kg)	Per-capita MPP_3 (kg/person)
A	47,781.00	17,625.00	1.050	50,170.05	14.56	21,914.28	0.459
B	35,332.00	12,791.00	1.220	43,105.04	10.35	13,384.11	0.379
C	27,059.00	9662.00	1.110	30,035.49	15.01	13,524.98	0.500
D	23,835.00	8450.00	1.034	24,645.39	14.13	10,447.18	0.438
E	19,217.00	7639.00	1.000	19,217.00	13.86	7990.43	0.416
F	11,026.00	4684.00	1.013	11,169.34	13.15	4406.30	0.400

* ISTAT (01/01/2013).

Table 6
Most significant information on municipal waste collection per area.

Area	Number of areas in the municipal territory	Users	Habitants	Mixed plastic amount produced (in three days) (kg/area $_i$) (β)	Collection perimeter (average value) (km)	Number of means involved in municipal collection	Number of collection perimeter travel times	Overall km travelled (α)
A_i	15	1175.00	3185.40	1460.95	6.50	2	5	**65.00**
B_i	12	1066.00	2944.33	1115.34	5.80	2	4	**46.40**
C_i	8	1208.00	3382.38	1690.62	6.70	3	4	**80.04**
D_i	8	1057.00	2979.38	1305.90	5.80	2	5	**58.00**
E_i	6	1275.00	3202.83	1331.74	7.00	2	5	**70.00**
F_i	4	1170.00	2756.50	1101.58	6.40	2	4	**51.20**

to firm technicians, plastic waste collection was planned dividing the municipal territory into areas characterized by a specific waste collection perimeter. These areas were identified so as to be homogenous by population density and number of users served, thereby allowing for waste collection optimisation. Furthermore, waste collection perimeters resulted to be of quite equal length among the areas of the same village, thereby being possible to calculate their average. Door-to-door collection perimeter (inclusive of transportation to the MWCC) of each area was defined considering users location and both municipal streetscape and road trim. As shown in Table 6, the amount of mixed-plastic waste produced every three days in each area was calculated from per-capita MPP_3, as reported in Table 5, multiplying the corresponding value for the number of habitants in the area. Furthermore, whether the number of means involved or of collection perimeter travel times was defined based on the means lorry-capacity and also on the maximum number of laps doable in a six-hour working shift. Each means can in fact collect up to 150 kg of mixed-plastic waste along the collection perimeter travelling a maximum of five times.

Based on the values reported in Table 6, it was possible to calculate (per each municipal area) the ratio between "Overall km travelled" (α) and the "Mixed plastic amount produced (in three days)" (β) so as to obtain the km needed for collecting and transporting to the MWCC 1 kg of waste plastics. The use of "collection perimeter (average value) (km)" (Table 6) makes this ratio to be not dependent on the number of areas per Municipality and, therefore, to be directly representative of the Municipality itself. The ratio values obtained were indicated in Table 7. They were also related to the amount (1.1 kg) of mixed plastic waste, contaminated with extraneous fractions and needed for obtaining 1 kg of clean mixed plastics to be separated into polymeric fractions. The obtained ratio is expressed as $(\alpha/\beta)_{1.1}$.

Based on Table 7, it can be said that on average 0.0506 km is needed for 1.1 kg mixed plastic waste collection and transportation to the MWCC. Transportation flow used for the assessment is equal to 0.0557 kg*km resulting from multiplying the distance (0.0506 km) per the transported material (1.1 kg).

Upon arrival at the MWCC, all the plastic-fractions are unloaded and stored in roll-off containers. When the filling volume is saturated, they are transported to the sorting plant where they first undergo to purification by removing the extraneous fractions and then to separation into component fractions as listed in Table 4. In order to calculate the transportation flow (from MWCC to sorting plant) to be considered for the assessment, an average weighted distance was used. This was calculated based on plastics production amounts because it was assumed that the more waste is produced by the village the more it is conferred to the MWCC and, in turn, to the sorting plant. For this purpose, MPP_3 values, already reported in Table 5, were used together with the distances from each MWCC to the sorting plant (see Table 8).

To calculate a weighted average distance (D_{wa}), the following formula was used:

$$\mathbf{D_{wa}} = \sum \mathbf{D_i} * (\mathbf{MPP_3})_\mathbf{i} / \sum (\mathbf{MPP_3})_\mathbf{i}$$

in which "i" is used for labelling the ith Municipality. The obtained value resulted in 8.803 km. Transported mixed plastic amount considered for the calculation is equal to 1.1 kg, because it contains extraneous fractions which, as already anticipated, are landfilled after sorting. Therefore, the accounted value is equal to 9.683 kg*km.

Table 9 shows the input flows taken into account for the sorting phase model creation. It is highlighted that, based on Table 4, this phase was implemented applying a mass-based allocation method so as to represent PE fraction as main product, while the other fractions as co-products to be sent to recycling. This means, for instance, that post-use PET bottles are accounted for as a co-product being responsible for 29.18% of the damage due to sorting.

After sorting and baling, PET post-use bottles are addressed to flake production (subsystem "c"). This phase was modelled considering:

- the amount (1.332 kg) of bottles to be processed for producing 1 kg of PET flake;
- the energy consumption for the process resulting in 0.386 kWh per kg of flake produced;
- water and soda powder for PET-waste washing after first grinding considering 5.594 kg and 9.657E−4 kg per kg of flake produced, respectively;
- 2.297 MJ of heat (for PET-waste drying after first grinding and washing) produced from burning natural gas in a condensing modulating boiler;
- the scrap resulting from second sorting at the flake production plant and being equal to 0.332 kg;
- the treatment of waste water effluent produced from PET grinded waste washing.

In addition to these items, transportation of 1.332 kg PET-bottle bales from sorting to flake production plant was calculated from the above-

Table 7
α/β ratios for each municipality.

Municipality	α/β	$(\alpha/\beta)_{1.1}$
A	0.045	0.048
B	0.042	0.046
C	0.047	0.052
D	0.044	0.049
E	0.052	0.058
F	0.047	0.051

Table 8
Values of distance (from MWCC to sorting plant) and MPP3 (kg) for each Municipality considered.

Municipality	D (Distance from MWCC to sorting plant) (km)	MPP_3 (kg)
A	9.36	21,914.28
B	5.75	13,384.11
C	8.11	13,524.98
D	7.43	10,447.18
E	11.79	7990.43
F	15.28	4406.30

Table 9
Mixed-plastic sorting and baling phase inventory flows.

Main product	560.3	g	PE (food packaging film and bags (LDPE) and detergents containers (HDPE)) ➔ Damage allocation: 56.03%
Co-products	291.8	g	PET post consumer bottles ➔ Damage allocation: 29.18%
	83.6	g	PS containers (trays, cups, plates and cutlery) ➔ Damage allocation: 8.36%
	38.3	g	PVC (bottles, thin sheeting, transparent packaging materials) ➔ Damage allocation: 3.83 %
	26.0	g	PP (Bottles for detergents and cleaning agents) ➔ Damage allocation: 2.60%
Input flow	**Physic amount**	**Measure unit**	**Comment**
Electricity			
Electricity	0.753	kWh	Consumption for plastics sorting and baling
Transports			
Plastics	0.0557	kg*km	1.1 kg waste plastics municipal collection and transportation to MWCC
	9.68		1.1 kg waste plastics transportation from MWCC to sorting plant
Waste			
Extraneous fraction	0.1	kg	

Table 10
A detail of the material transportation accounted for in the environmental assessment.

Material		Transport		Destination plant	Input data (kg*km)
Type	Amount (kg)	Mean	Travelled distance (km)		
Subsystem a					
Bi-component fibre production from virgin PET granules					
PET granulate (bottle grade) for thermo-bonding fibre production	1.05	Road transport (EURO 5) Lorry: 3.5–7.5 t	1000	PET thermo-bonding fibre production	**1050**
Subsystem b					
Post-use PET bottles sorting					
Municipal collection average perimeter of waste plastics (extraneous fractions included)	1.1	Road transport (EURO 4) Lorry: 21 t	0.0506	MWCC	**0.0557**
Collected post-use PET bottles from MWCC to sorting plant (average weighted distance value)	1.1	Road transport (EURO 4) Lorry: 21 t	8.803	Sorting plant	**9.683**
Extraneous fraction	0.1	Road transport (EURO 4) Lorry: 3.5–7.5 t	30	Sanitary landfill	**3**
Subsystem c					
Flake production from post-use PET bottles bales					
PET post-use bottles (from sorting plant)	1.332	Road transport (EURO 4) Lorry: 7.5–16 t	50	R-PET flake production	**66.60**
Unrecyclable PET-waste (from second-sorting)	0.332	Road transport (EURO 4) Lorry: 3.5–7.5 t	43.3	Sanitary landfill	**14.376**
Soda powder (for flake cleaning)	9.657E−4	Road transport (EURO 4) Lorry: 3.5–7.5 t	500	R-PET flake production	**0.483**
Subsystem d					
Flake extrusion for fibre production					
RPET flake	1.041	Road transport (EURO 4) Lorry: 7.5–16 t	6	R-PET fibre production	**6.246**
RPET fibre scrap (from extrusion)	0.041	Road transport (EURO 4) Lorry: 3.5–7.5 t	42.87	Sanitary landfill	**1.758**
Subsystem e					
Insulating slab production from both recycled and virgin PET fibres					
LDPE packaging film	0.03	Road transport (EURO 4) Lorry: 3.5–7.5 t	180	Insulating panel production	**5.4**
R-PET fibre	0.82	Road transport (EURO 4) Lorry: 7.5–16 t	4		**3.28**
Thermo-bonding fibre	0.205	Intercontinental aircraft, freight equipped	8145	Airport of Rome	**1669.725**
		Road transport (EURO 5) Lorry: 7.5–16 t	525	Insulating material production	**107.625**

Table 11
Most significant processes in the insulating slab production.

Most impacting processes	*Damage (pt)*	*Percentage of contribution (%)*
Virgin PET transportation	0.000495	165
Virgin PET fibre production	0.000384	128
Electricity consumption	6.39E−5	21.4
R-PET fibre production	−0.000725	−242
TOTAL of CONTRIBUTIONS	**0.0002179**	**72.40**

mentioned distance of 50 km: the resulting value is 66.6 kg*km. Transportation of caustic soda was also taken into account and resulted in 0.483 kg*km. This value was obtained considering that the soda production plant is 500 km far from the flake production one. Unrecyclable PET fraction resulting from second-sorting in flake production plant was modelled, according to the information provided, considering a sanitary landfill disposal scenario. In this regard, it should be noticed that the related transportation flow was taken into account and resulted in 14.376 kg*km. This value was calculated from the transported amount and the distance (43.3 km) involved between the flake production plant and the sanitary landfill. Finally, for a greater comprehension of the modelling criteria adopted, it is observed that PET flake production from sorted post-use bottles is a recycling process at all effects. Flake can be considered, indeed, a secondary raw material that, as shown in Fig. 1, can be used as such in a number of industry sectors replacing partly or completely the virgin material. For this reason, in order to take into account the related environmental benefits, flake production was modelled considering that 1 kg of flake produced allows for avoiding the production and consumption of 1 kg of virgin PET granule and, therefore, the resulting environmental impacts, such as substances emission (in air, water and soil) and resources consumption.

Subsystem “d” was represented considering that 1.041 kg of flakes are used for producing 1 kg of fibres through a further drying and an extrusion treatment. This phase implies a scrap of about 4% (0.041 kg per kg of fibre produced) and the consumption of electricity and heat in the amount of 2.137 kWh and 2.526 MJ, respectively. Flake are transported to fibre production travelling just for 6 km, thereby resulting in a transportation flow equal to 6.246 kg*km. Scrap is disposed of in the same local sanitary landfill which is 42.87 km far from flake production plant.

Finally, subsystem “e”, which concerns the production of 1 kg of insulating slab, was modelled using the amount of virgin and recycled PET fibre provided by the firm equal to 0.205 kg and 0.82 kg. The scrap produced (0.025 kg), being uncontaminated, is reused as such for the production of 1 kg of PET. For this process, consumption of electricity is equal to 0.4 kWh, while the heat required for thermo-bonding settles at 1.94 MJ. The production of 0.03 kg of LDPE packaging film production was taken into account as well as its transportation to the insulator production firm using the distance value as provided by the firm (180 km). Furthermore, the transportation of the RPET fibre to the insulating product manufacturing plant was included in the assessment and calculated considering the distance existing between the two plants (4 km). As underlined before, virgin-PET fibre transportation from China is done first by means of a freight-equipped international aircraft travelling for more than 8100 km and then by means of a EURO 5 truck with a 7.5–16 t lorry along a distance of 525 km. Fig. 2 shows the boundaries of the analysed system where, additionally, the main input flows were indicated.

Furthermore, as shown in Table 10, all the involved transportation was taken into account. For better understanding the flowchart reported in Fig. 2, it should be noticed that each subsystem was represented choosing 1 kg of its output material as FU and so referring to this one all the involved input and output flows. Then, each subsystem output material was input in the next subsystem in the amount required to produce 1 kg of the output material of this subsystem. This approach is typical of LCA and allows for subsystem interconnection. For instance, 1.332 kg of post-use PET bottles are used for producing 1 kg of flake in subsystem “c”, 1.041 kg of flake, as produced in subsystem “c”, are needed for producing 1 kg of RPET fibres in subsystem “d” which are used in the amount of 0.82 kg for producing 1 kg of insulating slab in subsystem “e”.

4.2.1. Input data and damage allocation

All input flows were allocated on the different phases of RPET fibre heat insulating material production using appropriately defined procedures and tools. Interviews with the firm's technicians during insulator production site investigation were made and check-lists were used for recording data and information. With regard to the total damage, as already said, mass-based allocation was done for polymer fractions obtained through waste plastics sorting. Regarding the other processes included in the system boundaries, due to the absence of co-products, in accordance with the ISO standards, no allocation was done. 100% total damage corresponds in fact to 1 kg of insulator produced.

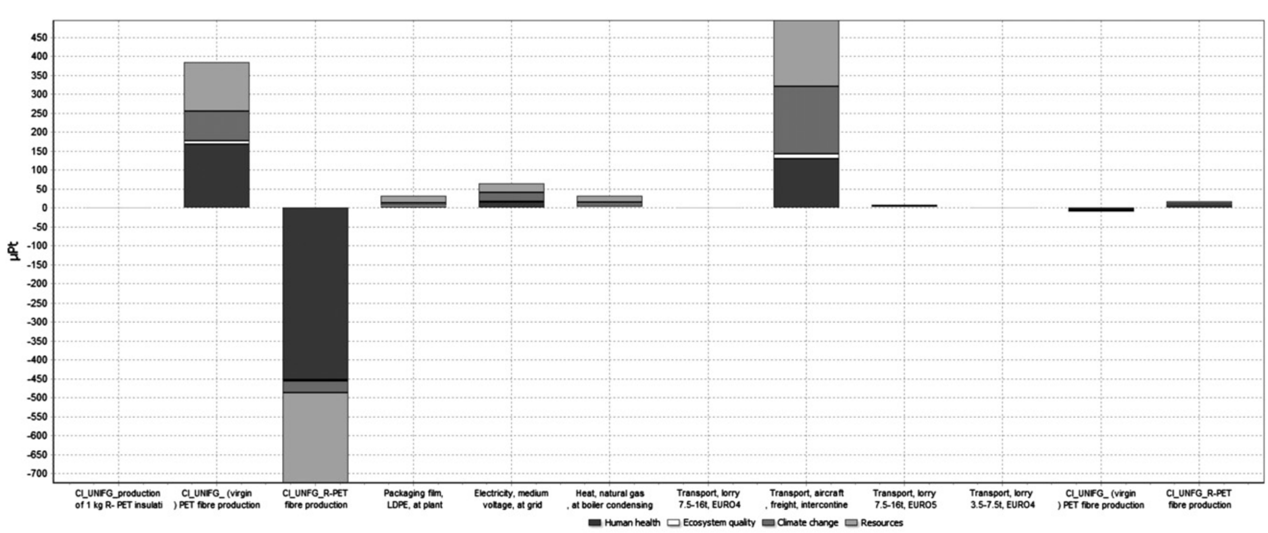

Fig. 3. Single score evaluation per impact categories — Impact 2002+.

5. Results and discussion

5.1. Life Cycle Impact Assessment (LCIA)

The total damage resulted to *0.000299 points (pt)* and is mainly distributed as shown in Table 11.

In Table 11, the most relevant processes were reported in association with both damage value and percentage of contribution to damage. It has to be highlighted that the listed processes cover 72.40% of the total damage (0.000299 pt) due to the insulating material production process. The other processes included within the system boundaries account, in total, for the remaining 27.60%. They were not mentioned since their single contribution to the total damage is low compared to the other processes. A graphical representation of the LCIA results associating the damage categories to the various phases characterizing the panel production process is shown in Fig. 3.

It should be observed that the damage column associated to the “RPET fibre production” is referred to 0.82 kg produced-fibre which requires the production of 0.854 kg flake from 1.137 kg of post-use PET bottles. The associated damage is negative (−0.000725 pt) since flake production and processing pollutant effect is largely recovered through the benefits coming from avoiding the environmental impacts which would be caused if an equivalent amount of virgin-PET granules was produced.

It should be noticed that in all the figures, the initials “CI_UNIFG_” and “CI_” were used for indicating those processes which were created for modelling the insulating material production.

In terms of damage categories, Table 12 shows for all of them the weighing point and the damage assessment value.

The system output flows, in terms of resources used and substances emitted, most affecting the above-mentioned damage categories, were listed in Table 13 in the amount referred to the functional unit, i.e. 1 kg of insulator produced.

Entering into the merits of impact categories, the most significant ones were listed in Table 14.

5.2. Life Cycle Interpretation and Improvement

The study developed attained the objective defined in the “Goal and scope definition" section. As shown in Table 11, the most impacting activities are: 1) PET thermo-bonding fibre supply from China by mean of a freight-equipped intercontinental aircraft; 2) production of thermo-bonding fibre and, in turn, of bottle-grade granulate PET; 3) the medium voltage electricity consumption in the RPET fibre panel manufacturing. In particular, it was observed that the aircraft life cycle (production, use and maintenance, end of life)contribute to 36% of “Climate Change”. It also affects categories: “Resources” 35.2%, “Human Heath” 26% and “Ecosystem Quality” 2.69%.

Furthermore, it was observed that: the most affected damage category is “Climate Change” because of the emission of CO_2 (Table 12) in the amount of 2.657 kg; and that the most significant impact categories for the environmental assessment are “Global Warming (GW)”, “Non-Renewable Energy (NRE)”, “Respiratory Inorganics (RI)” and “Carcinogens (C)” (Table 14).

Regarding the emitted substances, the most impacting one is CO_2 with a damage value equal to 2.69E−4 pt. Nitrogen oxides emitted to air (9.85 g) affects “Human Health” more than “Ecosystem Quality”. This is linked not only to the classification scheme provided by Impact 2002+ but also to the characterization and weighing factors on which this method is based. The avoided product (virgin PET granule) from flake production allows for saving 223 g aromatic hydrocarbons net emissions, thereby most positively affecting “Carcinogens” and “Human Health”. As from Tables 12 and 14, the corresponding damage-point is negative because the environmental benefits, in terms of emissions saved, are greater than the impacts coming from the emissions caused by the activities characterizing the insulating slab production.

Furthermore, in terms of primary-resources used, those with the highest environmental impact are crude oil, gas natural and hard coal of unspecified origin. A flow chart of the damages arising from the most contributing processes composing the RPET fibre insulating material manufacturing is shown in Fig. 4.

From this figure, it can be observed that some processes, such as (for instance) waste plastics municipal collection, could have been neglected since, as evident, they contribute for quite 0.01% to total damage. Nevertheless, they were taken into account for the assessment since believed important for the study completeness and reliability. The positive damage flow due to PET containers recycling and, in particular, to the avoided product appears evident. In the light of the obtained results, suitable solutions aimed at reducing the total damage should be addressed to the most impacting activities characterizing the production of the examined insulating slab. In particular, in order to lower the damage arising from the use of the bi-component fibre, environmental improvement hypotheses should be focussed first on the virgin PET granulate production phase. Then, a reduction of this fibre-type amount would be welcome, proportionally increasing the use of the RPET fibre and so allowing for greater environmental benefits. It should be observed that this improvement solution was not tested, because there was no idea of the maximum reduction to apply without compromising both manufacture quality and heat-insulation performance of the examined product. Regarding the virgin PET fibre supply operation, another possible transportation means could be considered and environmentally evaluated. Specifically, a comparison was developed

Table 13
Most significant output flows per kg of insulator produced.

Substance/resource	Emission compartment	Amount	Unit	Damage points (pt)
Climate change				
Carbon dioxide, fossil	Air	2.657	kg	0.000269
Resources				
Oil, crude, in ground	–	234	g	7.05E−5
Gas, natural, in ground	–	146	dm^3	3.86E−5
Coal, hard, unspecified, in ground	–	175	g	2.20E−5
Ecosystem quality				
Nitrogen oxides	Air	9.85	g	4.11E−6
Aluminium		27.9	mg	2.09E−6
Aluminium	Soil	21.1	mg	9.49E−6
Zinc		1.11	mg	3.79E−6
Human health				
Nitrogen oxides	Air	9.85	g	0.000124
Sulphur dioxide		5.87	g	4.52E−5
Particulates, <2.5 μm		141	mg	1.39E−5
Hydrocarbons, aromatic		−223	mg	−0.000312

Table 12
Weighing points and the damages assessment values for each damage category.

Damage category	Weighing points	Damages assessment	Units
Climate Change	0.000272	2.69	$kg_{eq}CO_2$
Resources	0.000130	19.7	MJ primary
Ecosystem Quality	2.10E−5	0.287	PDF*m^2*yr
Human Health	−0.000123	−8.72E−7	DALY

Table 14
Weighing points and the damages assessment values for each damage category.

Impact category	Weighing points	Characterization value	Equivalent indicator
Global Warming (GW)	0.000272	2.69	$kg_{eq}CO_2$
Respiratory Inorganics (RI)	0.000183	0.00186	kg_{eq}P.M.$_{2.5}$
Non-Renewable Energy (NRE)	0.000130	19.7	MJ primary
Carcinogens (C)	−0.00031	−0.785	$kg_{eq}C_2H_3Cl$

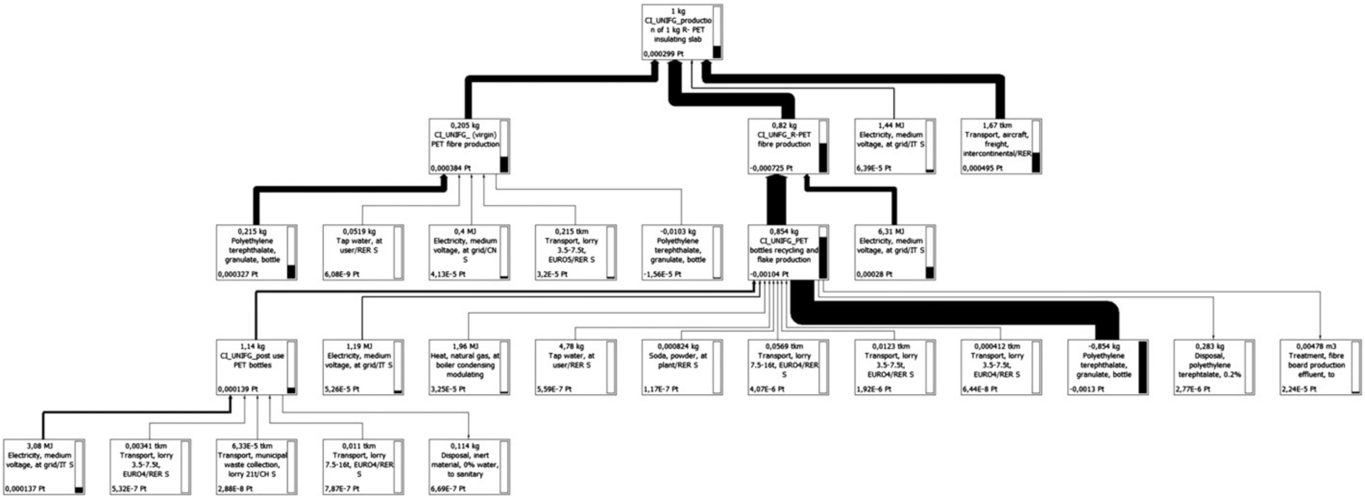

Fig. 4. Insulator production: damages flows — Impact 2002+.

for verifying any damage reduction when using a transoceanic freight ship as an alternative to the air-continental freight aircraft. In this case, it was assumed that goods (PET fibre) are transported by trailer-truck from Beijing to Shanghai travelling for about 1300 km. Then, from Shanghai to Genoa port by cargo-boat covering about 15,000 km and finally, from Genoa to the panel manufacturing firm location, again by trailer-truck for about 360 km. The results are shown in Fig. 5.

It can be observed that, although there is added road-transportation and increased distance to be covered by cargo-boat, the above-mentioned transportation solution is the most sustainable to be used for the fibre supply. The transportation hypothesis proposed allows for a high damage reduction such that the total damage decreases from 0.000299 points to −0.000167 points, thus resulting in a negative value. Finally, for reducing the impacts resulting from the use of electricity in the insulator production, it would be necessary to opt first for appropriate technical solutions oriented to the energy-consumption saving. Then, the use of renewable energy would be desirable in every phase of the slab production chain, thereby allowing for a reduction of fossil fuels consumption and CO_2 emissions. In particular, according to the firm technicians, a 150 kW wind-power plant (WPP) will be installed so as to supply the electricity required for insulator production from fibres mixing. This solution was tested from an environmental point of view so as to highlight its effectiveness in reducing damage. From the comparative study, it was possible to observe that the total damage is reduced by nearly 20% (from 0.000299 to 0.000241 pt), as evident from Fig. 6. Furthermore, the CO_2 emitted decreases from 2.657 kg to 2.45 kg, while natural gas, crude oil and hard coal respectively reduces from 146 dm^3 to 99.9 dm^3, from 234 g to 220 g and from 175 g to 146 g.

Comparing results from the two improvement assessments, it could be observed that changing the means of transportation is far more effective in reducing damage compared to the use of a renewable energy source. However, the two solutions could be applied together after having assessed them in terms of a socio-economic feasibility.

5.3. A comparative assessment

5.3.1. Different insulator-types

The examined insulator was compared to an extruded-expanded (sintered) polystyrene (EPS) and to a stone wool and a cork slab having the same insulating function. The three insulators have different origins: synthetic for the first one, mineral for the second and natural for the third. Such insulating materials were chosen for the assessment because they are three of the currently most world-widely used insulating

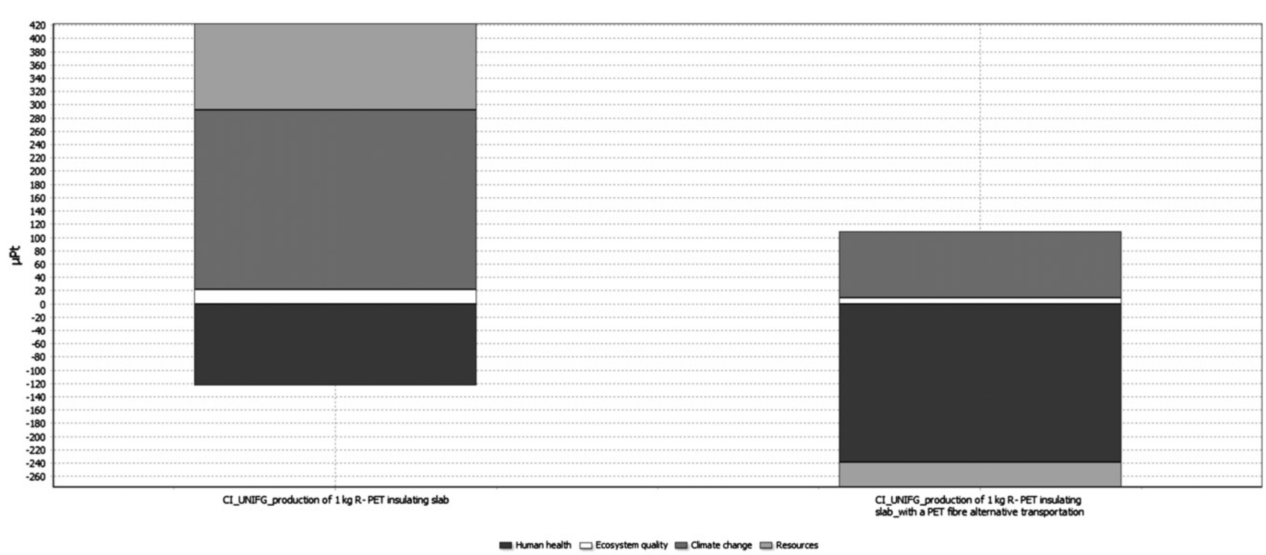

Fig. 5. Transport means comparison: intercontinental freight aircraft vs. transoceanic freight ship (cargo boat).

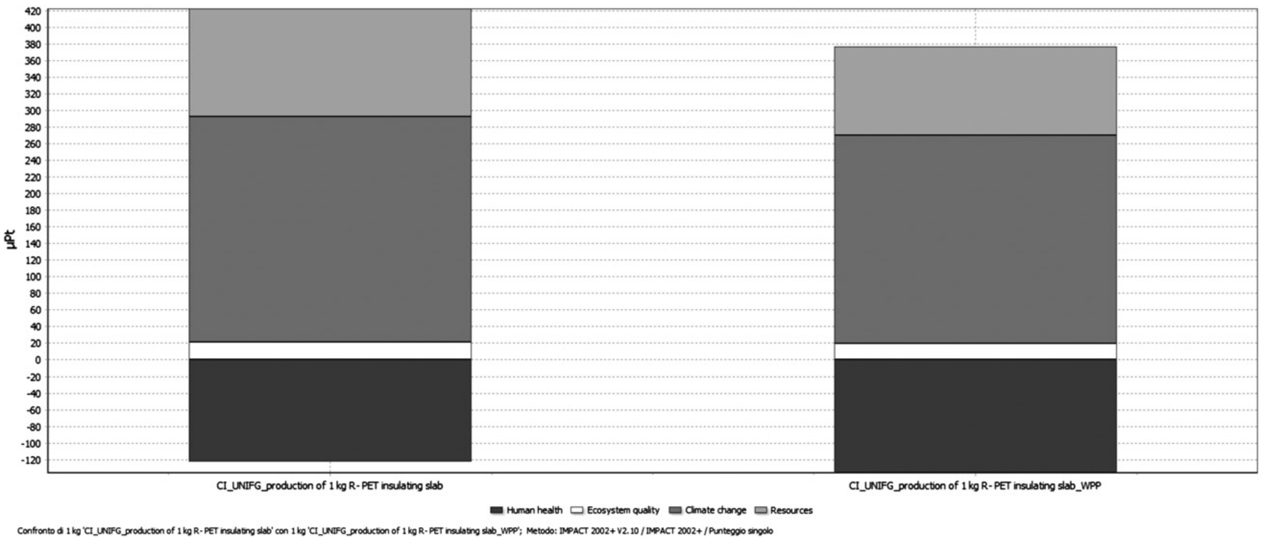

Fig. 6. A wind-power plant (WPP) for the insulator production: a comparative assessment using Impact 2002+.

products and also because they represent different origin groups. They are valid alternatives to the polyester fibre panel and are mainly used for walls and roofs, thereby allowing for a good level of thermo-insulation. This study focussed only on the production process referring to a functional unit of 1 kg of insulator. Insulator use phase was not considered for the comparison because, as already stated in Section 4.1, it is dependent on the thickness used for thermally insulating side-walls and rooftops and to the lifetime of the building in which the insulating material is installed. Same was done for the end-of-life. This phase was in fact not taken into account because building envelope construction techniques and insulator installation conditions are unknown and highly variable. Therefore, this comes to be a preliminary comparative assessment, carried out on equal FU and system boundaries, which will be extended to the next abovementioned phases (use and end-of-life) once more detailed information on insulator thickness, thermal conductivity and installation conditions are available. The study will allow as such for environmental considerations on the production of different insulator-types which, despite being preliminary, were believed necessary to be made in light of the increasing importance of building insulation materials production industry. Finally, it is believed that the choice of 1 kg of insulator as FU is appropriate because it allows for input and output flows to be better referred and handled and also for comparisons to be easily conducted.

It is important to note that, contrary to the work done on the RPET fibre panel, no specific data was collected on site for representing the EPS insulator and for the stone wool and the cork slab production. For this reason, the models already existing in Ecoinvent v2.2, named “Polystyrene foam slab, at plant” (EPS), “Rock wool, at plant” and “Cork slab, at plant” were used, making sure that system boundaries were comparable to those considered for the RPET fibre panel. The dataset includes raw materials production and supply, main processing activities, energy consumption and waste production and treatment. Furthermore, it should be noted that, according to the model considered by Ecoinvent v.2.2, cork slabs are obtained from hot-pressing, at a temperature between 160 and 180 °C, from granules previously mixed with formaldehyde-based resins, such as urea and melamine. For each kg cork slab produced, 56 g of both melamine and urea are used. Comparing to the self-pasted cork-slabs, it can be said that the main differences are due to the fact that in this case no artificial resins are used but the compression temperature is much higher settling at between 350 and 400 °C. For the comparison, based on the type of processes included in the analysed system, the most significant impact categories were chosen among those considered by the Impact 2002+ method. They were reported in Table 15 indicating the respective characterization values for each of the insulating materials considered for the assessment.

From Fig. 7, extending the comparative assessment to the normalization and weighing steps using the Impact 2002+ conversion factors, for the impact categories listed in Table 15, it results that the RPET-fibre based insulator is: 1) the less impacting in terms of Non-carcinogens and Land occupation; 2) less impacting than cork and EPS, but little more impacting than rock wool in terms of Non-renewable energy; 3) less impacting than EPS and rock wool, but more impacting than cork, in terms of Respiratory inorganics; 4) less impacting than EPS, but more impacting than the other two products (cork slab and rock wool) in terms of Global warming; and 5) less impacting than cork slab but more impacting than EPS and rock wool in terms of Terrestrial ecotoxicity. Furthermore, it appears evident how positively the RPET-fibre based insulator contributes to the damage occurring to Carcinogens thanks to the avoided product considered in the process of post-use bottles recycling. The resulting environmental benefits are so high to compensate the impacts due to the examined insulator with respect to the other impact categories identified.

Table 15
Characterization values of the most significant impact categories within Impact 2002+.

Impact Category	Unit	CI_UNIFG_production of 1 kg R-PET insulating slab	Cork slab	Polystyrene foam slab	Rock wool
Carcinogens	kg C_2H_3Cl eq	−0.785	0.0122	0.1083	0.00789
Non-carcinogens		0.00825	0.0177	0.0155	0.00782
Respiratory inorganics	kg PM2.5 eq	0.00186	0.0012	0.0019	0.0022
Terrestrial eco-toxicity	kg TEG soil	27.30	35.9900	10.9791	14.1114
Land occupation	$m_2$org.arable	0.00246	0.5772	0.0012	0.0108
Global warming	kg CO_2 eq	2.69	1.1146	3.7145	1.0359
Non-renewable energy	MJ primary	19.7	25.2931	107.0302	19.0441

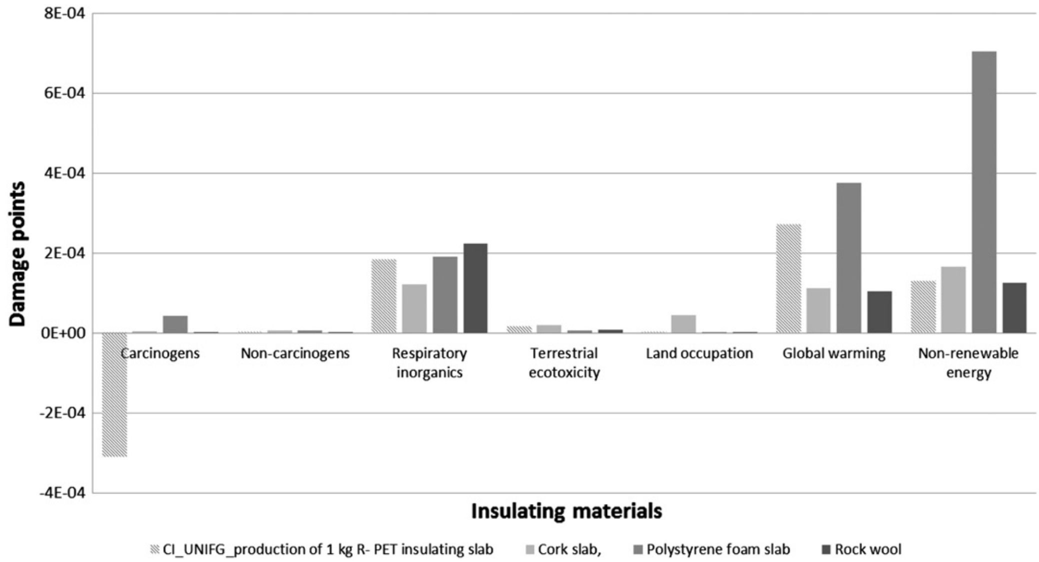

Fig. 7. RPET fibre panel vs. other insulators: most significant impact categories.
Source: Personal elaboration from Impact 2002 + LCIA.

Based on this concept, the developed comparison leads to conclude that, as confirmed in Fig. 8, among the examined insulators: the polystyrene foam slab is the most impacting one (0.00133 pt); the RPET fibre panel (0.000299 pt) is the most environmentally sustainable being even less impacting than the cork slab (0.000484 pt); cork slab and rock wool (0.000469 pt) are quite the same in terms of environmental damage.

It goes without saying that the results would be even more in favour of the RPET fibre panel if the comparison took into account also the improvement hypotheses discussed at paragraph 5.2. Finally, it was observed that, though a different method was used for the assessment, the obtained results are quite in agreement with those from Intini and Kühtz for EPS and stone wool focussing just on the same impact categories. Any existing difference is attributable to the type of processes and materials involved and to the method chosen for the environmental assessment.

5.3.2. Waste treatment scenarios

This second part of the comparative assessment is dedicated to verifying that the use of beverage post-use containers for producing fibre-based insulating materials is less impacting if compared to other practicable treatment processes such landfill and municipal incineration. The comparison was developed considering that 1 kg post-use bottles are used for producing 0.751 kg flake instead of going to landfill or being incinerated. The processes after the bottles were recycled were not taken into account for the present assessment, since the flake produced is believed to be usable for producing other goods, as already shown in Fig. 1. Furthermore, both landfill and incineration plants nearest to the firm

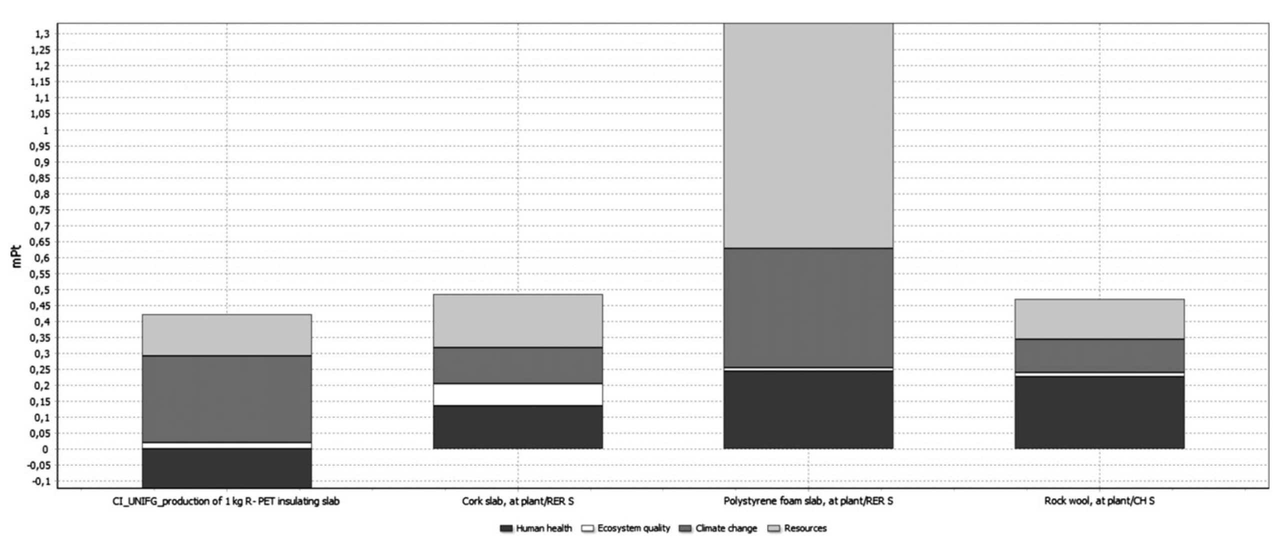

Fig. 8. RPET fibre panel vs. other insulators: single-score evaluation per damage categories.

were considered for the assessment and then PET-waste (post-use bottles) transportation accounted for. From the comparison, the recycling of PET bottles to produce flake is confirmed to be the most sustainable waste treatment with a total avoided damage equal to −0.00122 pt per kg of treated bottles, mostly avoiding the emission of 1.56 kg of CO_2, 2.74 g Nitrogen oxides, 4.03 g Sulphur dioxide, 399 mg Particulates with grain size less than 2.5 μm, 358 mg aromatic hydrocarbons as well as the consumption of 527 dm^3 gas natural, 142 g hard coal and 722 g of crude oil. This avoided output flows allow for environmental benefits, in terms of avoided damage, to all damage categories in the following order: 1) Human health (−0.000612 pt); 2) Resources (−0.000424 pt); 3) Climate change (−0.000169 pt); 4) Ecosystem quality (−0.0000131 pt).

6. Conclusions

Huge amounts of PET post-consumer containers are collected every year. In this regard, several recycling techniques are possible to be adopted depending on the material which is intended to be produced. In this context, this study regarded the application of LCA for analysing the main input and output flows associated to 1 kg of RPET-fibre based insulating material so as to be able to define an eco-profile of its production. The study highlighted the environmental benefits resulting from recycling and the need of resorting, when possible, to this waste-treatment technique so as to progressively reduce primary resources and materials use as well as energy consumption. Thanks to this study, it was possible to highlight the processes mostly contributing to the total damage and to the improvement solutions believed most effective in reducing it. In particular, LCA showed the environmental impact reduction resulting from using renewable energy and from replacing the intercontinental freight aircraft with a cargo-boat considering all the additional road-transportation to be involved. From this point of view, this study is believed to be of great interest for the virgin PET fibre production firm, because it can be used as a starting point for reconsidering the transportation system used for fibre supply, thus preferring a more environmentally sustainable solution. This approach is the basis of a Green Economy since it allows the diffusion, into the market, of environmentally sustainable and energy efficient products. In this context, this LCA study could represent the starting point for developing the Environmental Product Declaration (EPD) (III type voluntary environmental label) of this kind of insulating products in accordance with the standard ISO 14025:2006 (International Organization for Standardization (ISO), 2006c). Doing so, in addition to what is already mentioned above, would make it possible to: facilitate any comparison, in terms of materials use and constructive technique, with other concrete types, which this labelling has already been applied to; encourage eco-friendly materials and products demand and supply; and boost the environmental improvement. The study was also enriched with two comparative assessments. The first was carried out between the examined insulator and three of the most used insulating materials such as EPS, rock wool and cork. In this regard, the study highlighted that being natural does not mean being 100% environmentally sustainable and that recycled materials could be preferred to natural materials of equal quality and insulation performance.

The second assessment was developed for comparing flake production from bottle recycling with a landfill and a municipal incineration scenario, confirming the great environmental advantages in waste recycling. In this context, the developed study, although dealing with a specific recycling-case, arises also with the aim of encouraging recycling of goods, when their reuse is no longer possible, thereby avoiding wasting precious primary resources and materials.

Finally, the results of the study are believed useful for the comparative assessment of the life cycle environmental impacts of a building starting from the envelope design and considering different stratigraphy solutions. This practice is generally based on specific requirements such as solidity, eco-friendly material use, quality, low-impact assembly technique and thermo-acoustic insulation performance. Doing so, for each part of the envelope (side-walls, roof and ground-floor), can result in the identification of a solution with the highest levels of thermal resistance and environmental sustainability. In addition to this, by focussing on the insulating layer, it would be possible to verify the environmental benefits resulting from its use, in terms of saved fossil fuels consumption and CO_2-emissions both achieved from reduced heating and cooling and to cover the pollutant effect due to the phases of production and end of life. A similar result would confirm the large energy and environmental advantages related to the use of insulating materials and, agree with Ardente et al. on the need of including LCA in the most advanced building energy legislation.

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Contribution of authors

This article was thought, discussed and written by the six authors and it is the result of their common commitment. In particular, their main contributions are: bibliographical research on the state of the art of building thermo-insulating materials environmental assessment, analysis of the insulator-types currently available in the market and of the production process of the analysed product (*C. Tricase and R. Rana*); development of the whole LCA including inventory flows collection/calculation, classification and evaluation (*C. Ingrao and A. Lo Giudice*); planning and final review of the research study (*C. Mbohwa and V. Siracusa*).

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