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Eco-balance of 3D-shaped renewable biopolymer foam for a novel generation of transportation packaging: a “Cradle to grave” approach using life cycle assessment (LCA) methodology

(CHIM/06)

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1 INTRODUCTION

Almost all consumer goods purchased in everyday life come with packaging. Cushioning packaging is defined as a packaging system which ensures that the product contained is not damaged in distribution and handling operations [1]. World demand for protective packaging was $15.3 billion in 2009. Focusing on European market, it accounted for about 26% of the total demand that year. Foam plastic protective packaging made of Expanded Polystyrene (EPS), Polyurethane (EPU), Polyethylene (EPE) and Polypropylene (EPP) are the most popular cushioning materials thanks to their light weight and the excellent cushioning capabilities. Recent studies have shown that the demand of this kind of packaging is expected to increase to $ 22.2 billion in 2014 [2]. Factors such as the growth in manufacturing activity and the continued proliferation of internet shopping could explain these estimations. However, despite of their functionality, the widespread use of these polymer foams of synthetic origin implies considerable environmental concerns like the use of non renewable resources (e.g. oil, natural gas) for its production and concerns regarding waste disposal associated with their short life. Recycling, which is the solely applicable solution for preventing those synthetic foams entering the waste stream, appears in fact to be not always applied due to cost-ineffectiveness. Further, primary packaging, which are normally in contact with the good, are taken home by consumers and, they are not only more dispersed into households, they are also largely mixed, contaminated and often damaged and thus pose problems in recycling or reuse of the materials [3].

With this in mind, biodegradable and compostable bio-based plastics represent an emerging highly promising solution for two main reasons:

1) the use of renewable and potentially more sustainable sources of raw materials (crops instead of crude oil), especially in the long run;

2) to facilitate integrated waste management approaches so as to reduce landfill disposal.

However, when innovative products are presented instead of the traditional fossil-based ones, several questions surface about the effective environmental sustainability of the renewable raw materials. This is not surprising, considering that not necessarily renewability and or biodegradability is a proof of a lower environmental impact. Several factors can contribute to increase a higher environmental impact: agricultural practices, extraction processes, complicated conversion processes, etc. To answer to this question and show that a shift from fossil-based products to bio-based products is meaningful and sustainable, a life cycle based approach namely Life Cycle Assessment (LCA) analysis should be applied, taking into account all the valuable phases, including the agricultural phase up to product disposal.

The EU-funded REBIOFOAM project (Seventh Framework Programme for Research - FP7) targeted the development of a biodegradable and REnewable BIO-polymer FOAM to be applied as protective packaging material through the development of a new manufacturing process where the expansion of the starch-based polymer granules was driven by microwave technology by exploiting the inner water content of the granules themselves so as to generate vapour which triggered the foaming process.

The packaging system developed within the project (i.e. from now and on prototype pck) consisted in a port-hole spacer used for protecting washing machine port-holes, however, it is important to point out that such a prototype pck represented just a possible application of the innovative foamed material.

The prototype pck manufacturing process was characterized by three main steps:

- Formulation and processing: the base materials, i.e. mainly starch and water, were processed with smaller quantities of other required bio-based additives and renewable or synthetic polymers.
- Extrusion and granuleizing: the material was extruded into controlled morphology granules of well defined water content; this, combined with subsequent conditioning, allows achieving tailor made chemical and physical properties of granules as required for the expansion.
- Microwave-assisted expansion and moulding: granules were transferred into a microwave transparent mould and are further processed in a microwave environment with controlled temperature and pressure conditions. Rapid dielectric heating of the granules to a temperature beyond the flash point of the blowing agent, which was the inner contained water, caused the granules to foam in the mould thus resulting in a 3D-shaped foamed product.

The present doctoral thesis provides a preliminary fact-based analysis regarding the environmental performance of the prototype pck developed within REBIOFOAM project. To this end the Life Cycle Analysis (LCA) methodology was applied covering the whole packaging's life cycles as foreseen by the project itself (i.e. Work Package 8 or WP8). The main objectives of WP8 were:

- to analyze potential changes in the management of expanded pck waste stream caused by a hypothetical introduction of the (compostable) prototype pck;
- to investigate the environmental performance of the prototype pck from a life cycle perspective;
- to compare the environmental performance of innovative packaging against that made of EPS[1] (i.e. benchmark);
- to provide recommendations so as to improve the environmental profile of the prototype pck.

A sensitivity analysis for the most important key parameters was performed so as to increase the reliability of the research outcomes. Also an estimation of the potential magnitude of the use of renewable feedstock like tapioca, potato and maize for producing an amount of prototype pck able to replace 30% of packaging products consumed in EU was carried out.

[1] A market study commissioned by Istituto Italiano Imballaggio (Italian Institute of Packaging) in 2004 showed that moulded EPS is the largest material used in protective packaging sector (i.e. 35%). Though data were referring to 2004, the present situation has not significantly changed. According to PlasticsEurope , always in 2004, EPS consumption in EU by protective packaging sector was about 210 kton where the major part of EPS used was for transport and protective packaging (www.plasticseurope.org)

2 LCA METHODOLOGY

Life Cycle Assessment is a methodology useful to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment. The aim is to assess the impact of those energy and materials used and releases to the environment and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal. A LCA consists in four different steps, defined by ISO 14040 [4] and ISO 14044 [5] (Figure 1).

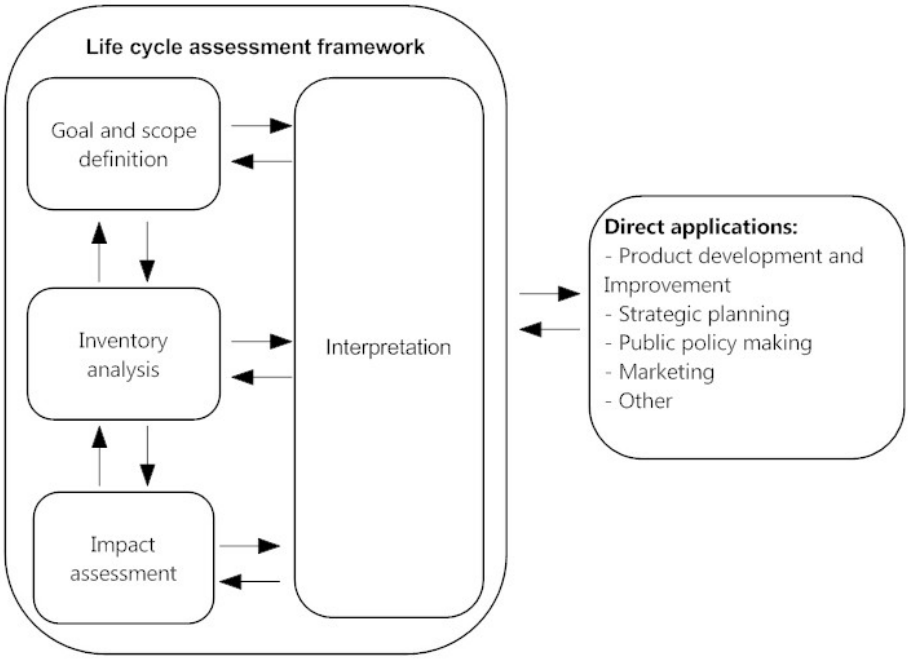


Figure 1 Life cycle assessment framework (adapted from ISO 14040)

1. The goal and scope definition is the preliminary step which defines the aims of the study, the F.U., the boundaries of the system being studied, the data requirements, the assumptions, the limits and the exclusion criteria.
2. The inventory analysis is the step dedicated to studying the process or activity, its main aim is to reconstruct the model which represents the flow of materials and energy in the production system of the product being studied, including all valuable processes of transformation, transport, use, and end of life.
3. The impact assessment is the step where, based on calculation methods, the inventory data of the product is analysed in order to obtain the environmental impact. This can be identified in specific impact categories.
4. The interpretation is the conclusive step of a LCA and it has the objective of providing a preliminary evaluation of the environmental impact of the processes and materials used. These simplified LCA considerations will also help highlighting the main areas where the eco-design could be implemented.

It is important to point out that the LCA is, however, affected by some valuable issues that may heavily influence the reliability of analytical outcomes thus conclusions. Basically conducting an LCA according to somehow established rules (i.e. ISO 14040 and 14044) does not necessarily provide consistent, "descriptive" models that are useful as a decision support tool [6]. Such aspects are well known by scientific community and LCA practioners [7].

The limitations of the methodology mainly concern the aspects outlined in Table 1.

Table 1 LCA methodology hotspots overview

Hotspots	**Remarks**
• **Simplified models**	LCAs are based on descriptive models that might not be enough consistent (i.e. scientific robustness).
• **Compression of time and space**	Potential impacts are calculated as they were generated all in the same place and at the same time.
• **High number of hypothesis and assumptions**	Many decisions have to be made during the execution of a LCA study. Final results depend on the definition of the system boundary, data sets, approximations, data gaps as well as the allocation and recycling procedures used etc.
• **Inventory data collection**	Data quality like completeness, representativeness of inventory is a fundamental requirement quite often not easy to reach.
• **Inconsistency**	The most commonly used databases for LCA usually show more or less substantial differences in the details of inputs and outputs considered (i.e. inconsistency), even if they analyze the same products and processes and are derived from the same primary data sources.
• **Allocation**	The problem of coproduct allocation is one of the most debated issue in LCA
• **Impact assessment**	E.g. for Human and Ecotoxicity impacts no robust methods exist
• **Approach in modelling: attributional or consequential?**	In the consequential approach the induced effects related to the introduction of products are investigated and quantified.
• **Uncertainty**	How real are the results? When A is better than B?

In reference to the second last point (Table 1) it is important to provide more details about the meaning of Attributional and Consequential approaches since they were both adopted in this analysis.

Attributional (ALCA) accounting describes the environmentally relevant physical flows to and from unit processes (i.e. sub-systems of the life cycle) that compose the supply chain without considering how other relevant environmental flows will change in response to possible decisions. By contrast a "Consequential" (CLCA) approach aims to describe the environmental consequences of an analysed decision (e.g. an alternative raw material source or the introduction of a new product in the market etc.). Such a approach is broader in scope in the sense that it should include all processes that they are expected to be affected by the decision, regardless of whether or not they are part

of the existing supply-chain (i.e. also effects that occur via market mechanisms) [8]. This includes the identification of affected processes that, due the complexity of our socio-economic systems, it is not a simple task at all. Therefore it may happen that such models provide low levels of accuracy and analysis outcomes have to be interpreted with caution. Scientific community and LCA practioners suggest to adopt the ALCA or CLCA based on the decision-context of the study and on the knowledge needs of the target audience [8], however, there are several products whose effects are intimately linked to other systems to be on the point that it is impossible to adopt an ALCA accounting if we want to get a complete and consistent environmental profile of the product itself [9]. Further the CLCA approach, beyond to ensure that mass balance and energy are maintained intact, it definitively resolves the allocation problem [10] thanks to system expansion that includes the avoided function/s. Nevertheless so as to properly define the avoided functions and related unit process or processes to be considered (i.e. credited) it is not always a simple task even if I-O databases can represent a valid support to modelling system expansion. For these reasons, a consequential approach would be always preferable compared to attributional one, however, in order to maintain as more homogeneous as possible the two systems (prototype pck and EPS one), a "hybrid" approach was here followed.

In particular, for upstream processes (e.s. intermediates and raw material production) an attributional approach was adopted, whereas for End of Life (EoL) scenarios a consequential one (i.e. system expansion). Tapioca or maize starches were examples of a joined multioutput processes where, beyond the product of our interest (starch), also other coproducts were produced (feed products). In this case a physical relationship (mass allocation) was adopted for partitioning the impacts. This choice was mainly motivated by the fact that one of the polystyrene intermediate (i.e. ethylene) is obtained in a joined multioutput process namely cracking where a mass allocation was applied [11]. Therefore so as to maintain the analyzed systems as more as possible consistent, an attributional approach was followed.

On the contrary for EoL treatments a system expansion including the avoided functions (i.e. electricity and heat produced by the incinerator or peat replaced by compost) was modelled thus the avoided impacts were credited to the corresponding pck systems. A "consequential scenario" was also investigated within the sensitivity analysis regarding GHG emissions coming from a hypothetical Land Use Change (LUC) (§ 4.2.3).

Aware of these aspects (Table 1), the analysis was performed trying to approximate as more as possible the reality, using consistent and representative data[2]. In addition, a particular focus was dedicated to the robustness of results. For the sake of clarity all hypothesis and assumptions made along with used inventory data were reported in this report so the reader (e.g. LCA practioner) can easily understand what has been done and identify areas of further improvements of the analysis. Just few data were not completely disclosed due to confidential reasons.

The LCA elaboration was performed by using one of the most diffused and tested LCA software (SimaPro Version 7.3.2) along with the most update and reliable databases regarding materials production, energy systems and transports (e.g. Ecoinvent 2.2). The following international standards and rules were considered:

- ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework

[2] Foreground inventory data (i.e. data related to the processes under operational control by the project partners) were directly collected by the REBIOFOAM partners involved in the development of the innovative process and reflected the sperimental outcomes. For EPS, average industrial data were used (EU context).

- ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines
- Product Category Rules (PCR 2010:16) “Plastic in primary forms” UN CPC CODE 347 Version 3.0 (July 29th 2010)
- General Programme Instructions for Environmental Product Declaration, EPD Version 1.0 (2008-02-29) www.environdec.com
- Supporting annexes for Environmental Product Declaration, EPD Version 1.0 (2008-02-29)

3 THE LCA STUDY

3.1 GOAL AND SCOPE DEFINITION

Functional Unit

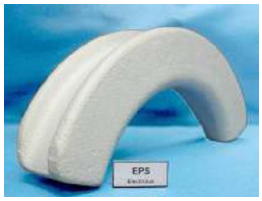
The F.U. is defined as "quantified performance of a product system for use as a reference unit". In this study the F.U. was defined as the "**the production, use and disposal of 100 port-hole spacers**". The functionality of the prototype pck was equivalent to that of EPS pck as showed by characterization analysis and tests performed by a partner of the project within WP7.

The packaging products analysed were:

- Starch-based bioplastic prototype pck
- EPS pck (benchmark).

The main characteristics of the innovative and current one pck systems are shown in Table 2.

Table 2 Main characteristics of packaging systems analyzed (source: Novamont)

Characteristic	**Prototype packaging**	**Current packaging**
		
Material	Starch-based bioplastic	EPS
Density [kg/m^3]	40	20 (range:18-25)
Volume [L]	≈0.6	≈0.6
Weight [g]	24	12

System boundaries

Since the study was designed to be a "Cradle to grave" LCA, it covered all relevant process steps from raw material sourcing to the final waste treatment of used packaging. A simplified process flow diagram of the analyzed systems is shown in Figure 2.

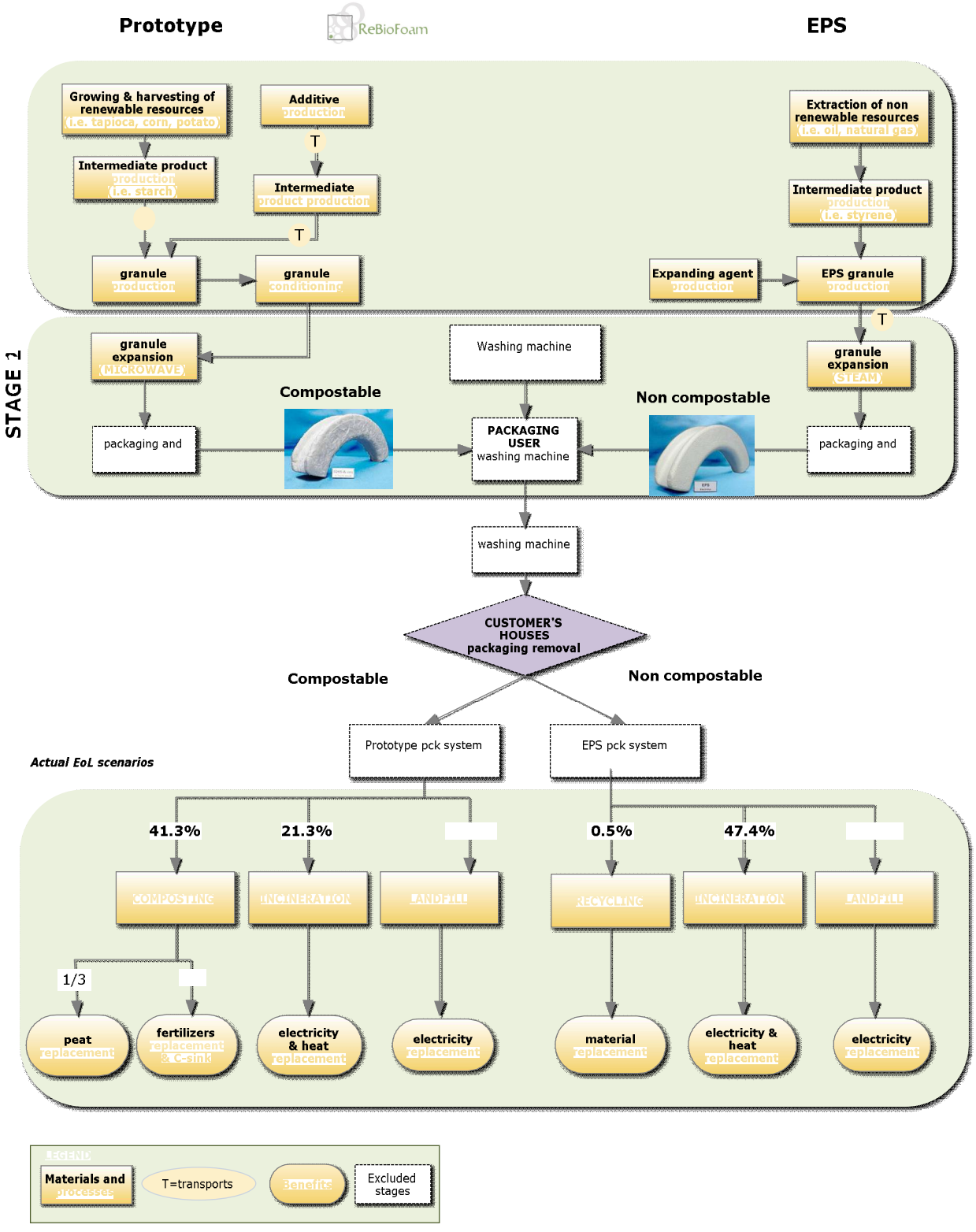


Figure 2 Simplified process flow diagram of analyzed systems (i.e. system boundaries)

The modelled systems started with the extraction of raw materials from their natural sources (renewable like tapioca or non renewable like oil), followed by the polymer granules (i.e. prototype starch-based and EPS) and pck systems production, then the used phase (equal for both systems) was followed by the disposal stage which represented the last part of pck systems' life cycle. Based on the nature of materials different End of Life (EoL) scenarios were considered. The percentage values for each waste treatment reflected the real situation since they were worked out starting from statistics data on waste management (a detailed description is provided in the inventory). Overall three main stages were identified which were in turn composed by sub-stages as shown in Table 3.

Table 3 Life cycle stages of analysed products

Life cycle stage	Sub-stages
STAGE 1 *Granule production & conditioning*	• Extraction of non renewable resources (e.g. oil) and growing & harvesting of renewable resources (e.g. tapioca) • Intermediate product production (e.g. styrene for EPS or tapioca starch for prototype) • Intermediate product transports • Polymer granulates production
STAGE 2 *Packaging production*	• Pck system production (i.e. prototype process and steam expansion for EPS)
STAGE 3 *Packaging disposal*	• Pck disposal (average real scenarios) • Environmental credits from waste treatments (e.g. peat replacement due compost use or electricity replacement due to electricity from incineration) due to system expansion

The washing machine production along with the pck system distribution, use, sorting and disposal stages were left out since they did not affect the comparison between the two pck systems.

Allocation rules

Allocation refers to partitioning of input or output flows of a process or a product system between the product system under study and one or more other products system [12]. In this study, when possible, allocation was avoided for example expanding the product system to include the additional functions related to co-products (e.g. electricity production coming from pck incineration, see EoL treatments). However in all cases where it was not possible to avoid allocation, a criteria based on physical properties (e.g. mass) [13] was applied. For materials production, transports etc. coming from Ecoinvent 2.2 databases the allocation rules applied were followed.

Waste management rules

According to *"Supporting Annexes for Environmental Product Declaration, EPD® (Version 1.0 2008-02-29)"* document, the waste (solid and liquid) produced in all life cycle stages were considered as follows:

- Hazardous waste to be disposed of: the environmental loads related to their disposal were included in the system boundaries
- Non hazardous waste to be disposed of: the environmental loads related to their disposal were included in the system boundaries

- Waste to recycling: no environmental loads were accounted for since they have to charge in the "subsequent system" (i.e. collection and recycling of the waste).

Electricity use

Whenever possible the electricity country mix related to the place where the processes take place was used. In all remaining cases the average European electricity mix was used.

Cut-off rules

Materials that contribute less 1% on mass basis were excluded from the analysis (i.e. natural additive for prototype material)

Excluded LCA phases

Building and equipment construction and maintenance for prototype and EPS granule production and expansion processes were not accounted for in the analysis since, based on other studies, they were supposed to be negligible. Also the packaging and distribution of the pck system were not accounted since no significative differences between analysed systems were expected.

Impact categories

The environmental performance of the examined pck systems was assessed considering the following impact categories or indicators:

- Global Warming Potential (GWP)

The Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to climate changes and have serious consequences for many ecosystems. Global warming can be caused by a variety of factors, both natural and human-induced. Greenhouse gases (GHG) concentration in the atmosphere increased is significantly in the last 200 years, mostly because of fossil fuels burning and deforestation. As a consequence there's an enhanced greenhouse effect which causes Earth's temperature increase. The greenhouse effect is a global effect.

- Primary energy demand (cumulative energy demand, CED or gross energy requirements, GER), measured as lower heating value (LHV) in MJ, differentiated into:

- Non renewable primary energy resources (NRER)

Much of energy supply comes from fossil fuels, such as coal, oil and natural gas, which are considered non-renewable, because their deposits took millions of years to form and once removed from the ground; they cannot be replaced within human time scales. Uranium, which is used for nuclear energy, has limited supply as well. Non renewable resources are used to produce energy or materials (e.g. petrochemical sector).

- Renewable primary energy resources (RER)

Energy sources (i.e. wind, hydropower, solar etc.) or other natural resources (e.g. timber, maize) that can be replaced after being used by environmental processes in a time frame meaningful to humans. Renewable resources are used to produce energy or materials for manufacturing, food and feed industry.

- Acidification Potential (AP)

Several human activities and natural sources (such as volcanoes and decaying vegetation) cause acid substances to be emitted in the atmosphere, in this way its content in nitric and sulphuric acids become higher than normal amounts. It affects a variety of plants and animals. The main chemical forerunners of acidification are SOx, generated by combustion of oil and coal (which have high sulphur content), NOx, originates at high temperatures (especially in combustion engines) and NH3 which is produced mainly by agricultural activities. Gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. If the acid chemicals are blown into areas where the weather is wet, they can fall to the ground in the form of acid rain, snow or fog (wet deposition). Otherwise, in dry areas, they may become incorporated into dust or smoke and fall through dry deposition, sticking to the ground, buildings and trees. Rain can wash the particles from these surfaces, leading to increased runoff. As a consequence serious damage to woodlands, lakes and rivers ecosystems occur. Acidification of the soil cause the dissolution of several chemicals, naturally present in the soil, which are toxic to plants and animals. Acidification is a typical continental problem.

- Eutrophicating Potential (EP)

Eutrophication refers to an increase in the rate of supply of organic matter to an ecosystem, which most commonly is related to nutrient enrichment enhancing the primary production in the system [14]. It can occur on land or in water. Nitrogen (in the form of nitrate, nitrite or ammonium) and phosphorus (in the form of ortho-phosphate) are the main nutrients causing eutrophication. They enter the environment and stimulate plant growth but a considerable increase in nutrients supply, means for example in rivers and lakes, an increase of algae growth and decay. The consequently shortage of oxygen results in the disappearance of varieties of fish. The result in water as well as on land is that biodiversity could diminish considerably. Eutrophication is a regional problem.

- Ozone Depletion Potential (ODP)

There is a natural shield located 10 to 50 km above the Earth's surface, this layer, rich in ozone, is the stratosphere and it works as protection against UV radiation and X-rays radiated from the Sun. Their amounts would be extremely dangerous but ozone uses some of the more dangerous forms of solar radiation to dissociate into oxygen atoms. The same radiation is also a constant source of ozone formation. The ozone layer is affected by halogenated substances which can reduce its thickness increasing the risk of skin cancers. Chlorine (Cl), fluorine (F), and bromine (Br) stable compounds (e.g. CFC), emitted in the troposphere, migrate to stratosphere through slow diffusion processes. Here, thanks to the Sun radiation, they release halogens radicals which react with other chemicals, and become stabile compounds. They can be decomposed only under specific circumstances, for example on the surface of ice crystals which are abundant in the polar region especially near the South Pole. Particularly during spring, thanks to solar radiation, these stable compounds release again halogen radicals which rapidly decompose the ozone. Causing a very intense depletion of the ozone layer in this region. Ozone layer depletion is typically a global problem.

- Photochemical Ozone Creation Potential (POCP)

The main mechanism of tropospheric ozone production and disappearance is a natural cycle through reactions in which NOx (nitric oxide NO and nitrogen dioxide NO_2) and sunlight are involved. A higher concentration in the troposphere of NOx and VOC (hydrocarbons, such as gasoline, solvents, and biogenic substances) breaks the natural equilibrium, resulting in an increasing formation of ground-level ozone, which is particularly dangerous. VOC and NOx control ozone concentrations in a complicated way. Tropospheric, or ground-level ozone production occurs in

particular periods of the year due to a complex reaction in which a combination of hydrocarbons (CxHy, mostly emitted by motor vehicles, vegetation, and industrial processes), nitrogen oxides (NOx, derived from motor vehicles, power plants, industrial facilities, biomass burning, and lightning), sunlight and high temperatures leads to the formation of ozone. This phenomenon is also known as 'summer smog'. Ozone is a very corrosive substance at this level. It is a strong oxidant which is capable of damaging virtually any material and cause serious damage to human health, animals and plants (its corrosiveness can affect the lung tissue of humans and others animals). Photochemical ozone creation is a regional problem.

- ❖ Abiotic Depletion Potential (ADP)

The Abiotic Depletion Potential (ADP) measures the extraction of natural resources such as iron ore, scarce minerals, and fossil fuels such as crude oil. This indicator is characterised based on ultimate reserves and extraction rates using Antimony (Sb) as a reference.

To notice that the primary energy demand (synonymously, cumulative or gross energy demand) is, strictly speaking, not an impact indicator, but a technical indictor of the total energy input to the system. From an environmental perspective, the depletion of non renewable resources is measured as Abiotic depletion (ADP).

The selection of impact calculation methods is not arbitrary because results can differ substantially. The methods here used were selected considering the following aspects:

- International consensus has been reached;
- High degree of certainty;
- Publicly availability of related documentation
- Representativeness of plastic materials

A description of impact categories, the corresponding sources and characterization factors is provided in Table 4.

Table 4 Impact categories

Impact categories (ABBREVIATION)	Midpoint reference substance (unit)	Source/Method	Characterization factors
Global Warming Potential (**GWP 100**)	kg CO_2 eq.	Intergovernmental Panel on Climate Change (IPCC) http://www.ipcc.ch/	Climate change factors of IPCC with a time frame of 100 years. Climate Change 2007: The Physical Science Basis. IPCC fourth assessment report http://www.ipcc.ch/ipccreports/ar4-wg1.htm
Non renewable Energy Resource consumption (**NRER**)	MJ eq.	IMPACT 2002+ method or Cumulative Energy Demand (CED) method (SimaPro 7.1 software)	Calculated as Low Heat Value (LHV) of fossil energy resources
Renewable Energy Resource consumption (**RER**)	MJ eq.	Cumulative Energy Demand (CED) method (SimaPro 7.1 software)	Calculated as Low Heat Value (LHV) of Renewable energy resources.
Eutrophication (**EP**)	kg PO_4 eq.	EPD Supporting Annexes for Environmental Product Declaration, EPD® (Version 1.0 2008-02-29)	CML, 1999; Heijungs et al. 1992
Acidification (**AP**)	kg SO_2 eq.	EPD Supporting Annexes for Environmental Product Declaration, EPD® (Version 1.0 2008-02-29)	CML, 1999; Huijbregts, 1999; average Europe total, A&B
Stratospheric Ozone Depletion (**OD**)	kg CFC-11 eq.	EPD Supporting Annexes for Environmental Product Declaration, EPD® (Version 1.0 2008-02-29)	Solomon & Albritton, 1992, in Nordic Guidelines on Life-Cycle Assessment, Nord 1995:20, Nordic council of Ministers, Copenhagen
Photochemical Ozone Formation (**POF**)	kg C_2H_4 eq.	EPD Supporting Annexes for Environmental Product Declaration, EPD® (Version 1.0 2008-02-29)	References: Heijungs et al., 1992, in Nordic Guidelines on Life-Cycle Assessment, N of Ministers, Copenhagen. Andersson-Sköld et ord 1995:20, Nordic council al., 1992, in Environmental Assessment of Products, Institute for Product Development, Copenhagen, Denmark
Depletion of abiotic resources (**AD**)	kg Sb eq.	CML 2001 (update to 2007)	CML, 1999

Further, also two inventory level categories were investigated. These were:

- Water consumption [m^3]
- Land occupation [m^2/y]

Water consumption is an important indicator since almost all industrial processes use water either as cooling water or process water.

Land can be defined as the terrestrial bio-productive system that comprises soil vegetation, other biota, and the ecological and hydrological processes that operate within the system [15], however, in our research we focused on

land use for agriculture only. Land taken by the expansion of artificial areas and related infrastructure, industrial plants, waste management plants etc. was assumed comparable for current plastic materials and prototype one and thus not taken into account. The different types of land use (i.e. agriculture) were aggregated 1:1. It means that no weighting of different types of land use was carried out according to the CML 2001 method.

Human and Eco-toxicity impact categories were not considered due to inconsistency issues on inventory data coming from different background databases (i.e. PlasticsEurope and Ecoinvent 2.2) as observed after some consistency checks.

3.2 INVENTORY

Inventory is the second step of a LCA analysis and it consists of quantification and qualification of the main stream of materials and energy in input and output to the system.

To this study's ends primary and/or specific data were used. In particular inventory data for the prototype granule production and granule expansion come directly from the semi-industrial trials of project partners (i.e. primary data). In reference to the tapioca starch production, average industrial data (i.e. secondary specific data) were used as well as for tapioca cultivation. For the additives secondary specific data were used. Data for EPS granule came from the Eco-profile of PlasticsEurope (2005) and they reflected the European average industrial EPS production, whereas for EPS granule expansion primary and secondary industrial data were used. Regarding the disposal of pck systems, a real disposal scenario was set both for prototype and EPS pck systems by matching washing machine market distribution information, and national statistics on Municipal Solid Waste (MSW) management. Emissions to air, water etc. coming from waste treatments were elaborated by using the tool developed by Ecoinvent 2.2 [16] [17].

The life cycle stages, and sub-stages, for both packaging systems are here described along with sources, hypothesis and assumption done.

3.2.1 Granule production & conditioning (Stage 1)

- *Prototype granule production*

Within prototype technology the base materials, i.e. mainly starch and water, were processed with smaller quantities of other required components (i.e. natural additives and natural or synthetic polymer). The granule (figure 3) production consisted of an extrusion of these base materials followed by pelletizing. The material was extruded into controlled morphology granules of well defined water content; this, combined with subsequent conditioning, allowed achieving tailor made chemical and physical properties of granules as required for the expansion. The mass balance, reflecting the best experimental results (i.e. best optimized blend), is shown in Figure 4 whereas the complete inventory data for prototype granule production and conditioning are given in Table 5 and Table 6. They reflected the real consumptions measured and/or estimated in the semi-industrial plant.

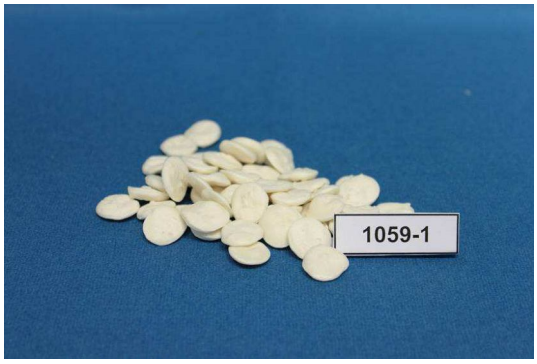


Figure 3 Prototype granule (source: Novamont)

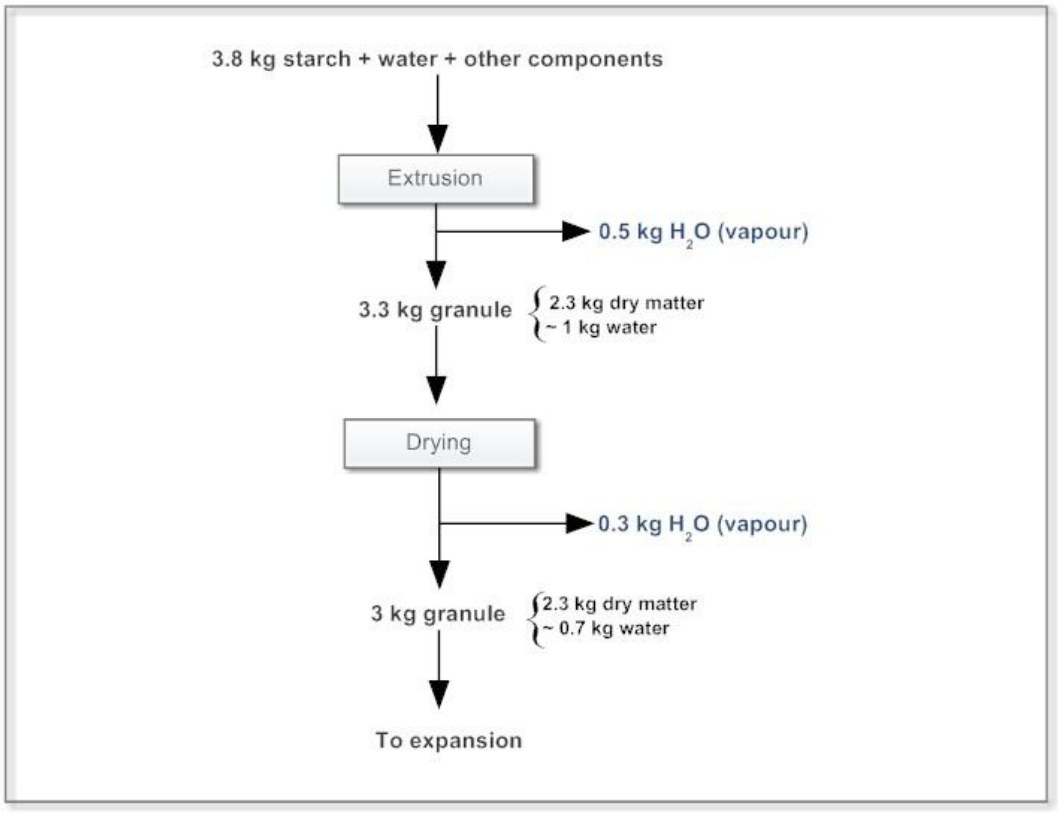


Figure 4 Mass balance for prototype granule production and conditioning (figures related to the F.U.)

Table 5 Inventory for prototype granule extrusion (figures related to F.U.)

	Unit	Amount
Product in output		
Granule	*kg*	*3.3*
Input		
Material		
Starch+ water + other components	kg	3.8
Energy		
Electricity, medium voltage, at grid/IT U	kWh	0.7
Natural gas, burned in industrial furnace low-NOx >100kW/RER	MJ	1.1
Output		
Emission to air		
Water	kg	0.5

Table 6 Inventory for prototype granule drying or conditioning (figure related to F.U.)

	Unit	Amount
Product in output		
Conditioned granule	*kg*	*3*
Input		
Material		
Granule	kg	3.3
Energy		
Electricity, medium voltage, at grid/IT U	kWh	0.1
Natural gas, burned in industrial furnace low-NOx >100kW/RER	MJ	1.6
Output		
Emission to air		
Water	kg	0.3

The detailed electricity consumption for each component of the extruder semi-industrial line is available in the technical documentation.

Different types of starch (potato, maize and tapioca) were suitable to be used for prototype granule production. In this report tapioca starch produced in Thailand was described as:

b. Thailand is the second biggest producer of tapioca starch after Nigeria [18];

c. High quality inventory data (i.e. representativeness and completeness) for tapioca starch production were found out in literature [19].

However, also starch from maize and potato produced in Germany and Italy were analysed within the sensitivity analysis. The term other components referred to natural additives (less than 1% on mass basis) and a biodegradable polymer that can be derived from renewable or non renewable resources. The latter component, for confidential reasons, was dealt with in this study using a generic nomenclature and inventory data.

The following chapters described the processes and the related inventory data for the starch and polymer production along with hypothesis and assumption applied.

- *Tapioca starch*

Tapioca starch production can be divided into two main phases: tapioca cultivation and starch extraction and refining.

- *Tapioca cultivation*

In 2008 Thailand produced about 28 million t of tapioca [18] with a share of 12% at World level and the second largest producer after Nigeria. The average crop yield in 2008 was about 24 t/ha.

Tapioca accumulates food in its roots. After growing leaves and other green parts, it starts to produce carbohydrate. The ability to produce and accumulate starch depends on the variety, the age at which it is harvested, the amount of rainfall and other factors. The typical tapioca composition is given in Table 7.

Table 7 Typical composition of tapioca [20]

Composition of tapioca root.	Amount per 100 gram
Water	60.21-75.32
Peel	4.08-14.08
Flesh (Starch)	25.87-41.88
Cyanide (ppm)	2.85-39.27

As can be observed the composition of tapioca root is, apart from water, mainly starch.

The list of farm machinery and equipment used in tapioca production is given in Table 8. It also includes those with potential to be adopted among farmers.

Table 8 List of farm machinery ad equipment for tapioca production in Thailand

Production Stage	With engine power	With animal power	With human labour
First land preparation	Two-wheel or four-wheel tractor with mould board plough / rotary tiller / disk plough / ridge tiller / tooth plough	Wooden plough / tooth harrow / mould board / plough	Hoe
Second land preparation	Four-wheel tractor with tooth plough /disk harrow / rotary disk / ridge tiller		
Planting	Planting machine*	----------	By hand
Eradication of plant pests and diseases	Tractor-driven sprayer /Two-wheel tractor with plough / Back-packed sprayer		Back-packed sprayer / Hoe / Blade
Fertilization	----------	----------	Broadcast by hand Hoe
Irrigation	Water pump	----------	----------
Harvesting	Digger Tapioca root collector* Tapioca root transporter*	----------	Blade Hoe

*To be further developed and adopted [20]

As can be observed from Table 8 tapioca cultivation in Thailand is currently not fully mechanized as other crops like maize, wheat etc. in USA or Europe. For example, weeding and harvesting are generally carried out by hand. Sandy soils and sandy loam are preferred for tapioca cultivation whereas clayey soils not.

Figure 5 Cross section of tapioca roots (source: Wikipedia)

No primary data were available for tapioca cultivation so literature data were used. In particular a study related to the production of bio-ethanol from cassava (tapioca) was used for modelling the tapioca cultivation.

According to the ethanol performances [21], amounts of inputs for cassava cultivation step in Thailand per one kg of fresh roots (25% starch content) are shown in Table 9:

Table 9 Inventory data for 1 kg fresh root (60% moisture, starch: 25%)

	Unit	Amount	Note
Product in output			
Fresh root	*kg*	*1*	*60% moisture*
Input			
Resources from nature			
Occupation arable	m^2	0.42	Yield: 23.8 t/ha
Energy, gross calorific value, in biomass	MJ	6.55	Gross calorific value of starch
Fertilizers and pesticides			
Urea, as N, at regional storehouse/RER	kg	0.00221	
Single superphosphate, as P2O5, at regional storehouse/RER	kg	0.00208	
Potassium chloride, as K2O, at regional storehouse/RER	kg	0.00262	
Pesticide unspecified, at regional storehouse/RER	kg	$7.67x10^{-5}$	
Glyphosate, at regional storehouse/RER	kg	$9.67\ x10^{-5}$	
Energy			
Diesel, at regional storehouse	kg	0.000313	Transport of fertilizers
Diesel, at regional storehouse	kg	$8.57\ x10^{-5}$	Transport from distribution center to retailers
Diesel, at regional storehouse	kg	$8.26\ x10^{-5}$	Transport from retailers to farm
Output			
Emission to air			
Nox	kg	$1.82\ x10^{-5}$	
N_2O	kg	$8.68\ x10^{-5}$	
Carbon dioxide	kg	0.00346	
Ammonia	kg	0.0004	
Emission to water			
Nitrate	kg	0.00024	
Phosphorus	kg	$2.49\ x10^{-5}$	
Phosphate	kg	0.000144	
Phosphate	kg	$3.06\ x10^{-5}$	

As no inventory data were available for emissions to air and in soil (due to fertilizers application), they were worked out using the formulas adopted by Ecoinvent 2.2 database. Fertilizers production reflected the European context.

- *Starch extraction and refinering*

In 2005, Thailand had 92 tapioca processing plants with a total production capacity of native and modified starch at about 16910 and 4350 t/day, respectively [22]. Normally, these tapioca plants operated 24 h a day for 8–9 months, from September to May.

The production of native starch from cassava root involves seven major stages. These are: root washing, chopping and grinding, fibrous residue separation, dewatering and protein separation, dehydration, drying, and packaging. The production facilities require generally large volumes of water and energy, and the generation of high organic-loaded wastewater and solid waste, nevertheless, improvements of the process efficiency are being undertaken [19]. According to the study of Tanticharoen and Bhumiratanatries [23] the generation of wastewater at the tapioca starch plants averages 20 m^3 for every t of starch being produced, whereas the characteristics of wastewater from the Vietnam tapioca starch plants with the values of 11,000–13,500 mg COD/L, 4200–7600 mg SS/L, and pH of 4.5–5.0 [19] were reported. The approximate generations of wastewater and solid waste (fibrous residue and peel) are 12 m^3 and 3 kg per t of starch, respectively.

Figure 6 reported the wet matter mass and water mass balance for tapioca starch production, whereas the complete inventory data are given in Table 10.

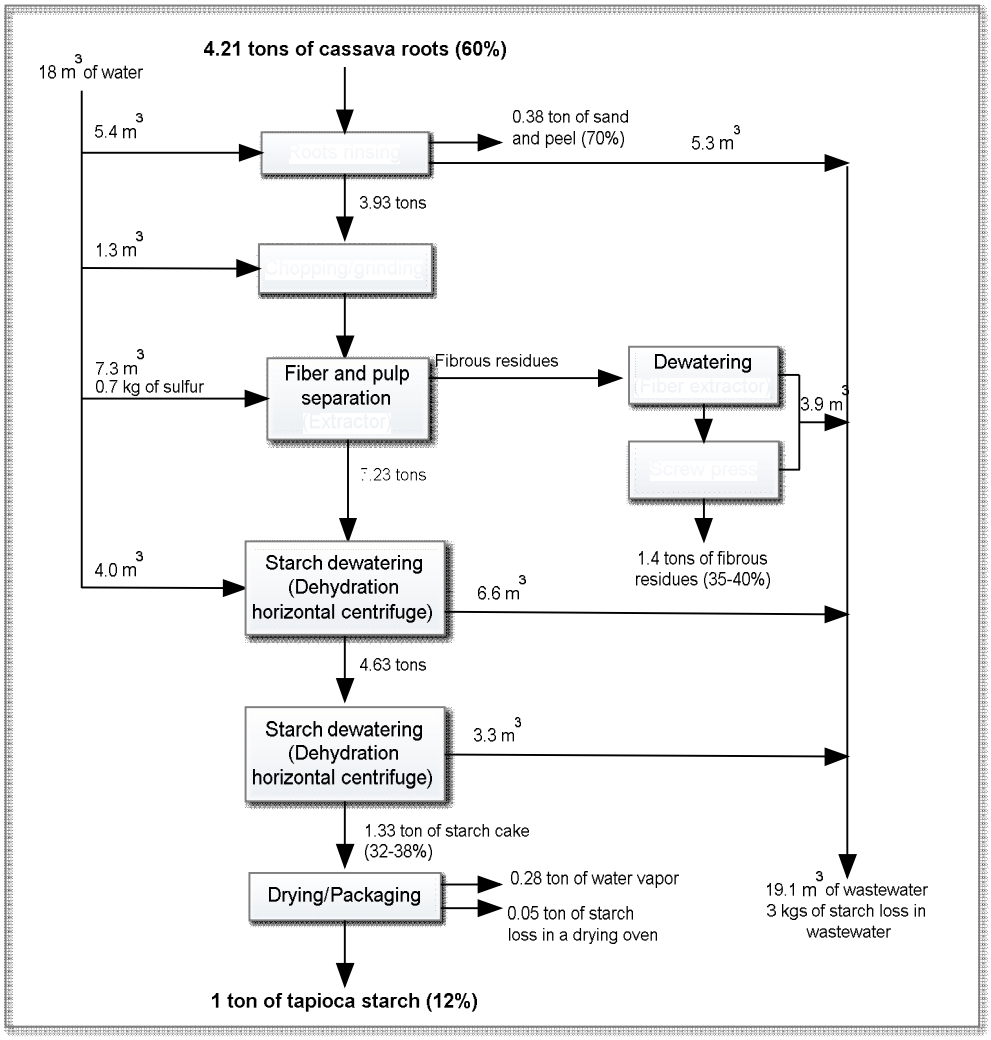


Figure 6 Wet matter mass and water mass balance for tapioca starch production (adapted from Chavalparit et al.)

The total amount of water used, wastewater generated, sand and peel, and fibrous residues were averaged from the eight studied plants [19].

Table 10 Inventory data for 1 t starch from tapioca (moisture: 12%)

	Unit	Amount	Note
Product and co-product in output			
Starch from tapioca (12% moisture)	*t*	*1*	*mass allocation: 42%*
Fibrous residues	*t*	*1.4*	*mass allocation: 58%*
Input			
Resources from nature			
Water , processes, unspecified natural origin	m^3	18	
Material			
Tapioca (fresh root)	t	4.21	Water content = 60%
Sulphur, from crude oil, consumption mix, at refinery, elemental sulphur EU-15 S	kg	0.7	
Energy			
Electricity, medium voltage, production THAILAND, at grid/UCTE	MJ	608	
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER	MJ	1303	
Transport, lorry >16t, fleet average/RER	tkm	0.421	distance from farm to starch production plant (i.e. 100 km)
Output			
Emission to air			
Water	t	0.28	
Emission to water			
BOD5, Biological Oxygen Demand	mg	$6.11x10^5$	
COD, Chemical Oxygen Demand	mg	$2.54\ x10^6$	
Solved substances	mg	$4.2\ x10^7$	
Suspended substances, unspecified	mg	$1.43\ x10^6$	
Waste			
Process waste	t	0.38	Sand and peel (70%)
Treatment, potato starch production effluent, to wastewater treatment, class 2/CH	L	19,000	
Disposal, gypsum, 19.4% water, to inert material landfill/CH	t	0.38	

As the tapioca starch was sourced in Thailand the Thai electricity mix was modelled (Table 11), using statistic data of the International Energy Agency (IEA) [24] since no data were available in the Ecoinvent 2.2 database.

Table 11 Electricity mix in Thailand (2007) – EIA statistics

	Electricity	**Percentage share**
	Unit: GWh	
Production from:		
- coal	30.681	21.4%
- oil	3.848	2.7%
- gas	96.542	67.3%
- biomass	4.190	2.9%
- waste	0	-
- nuclear	0	-
- hydro	8.114	5.7%
- geothermal	3	Negligible
- other sources	0	-
Total Production	143.378	100%
Imports	4.491	3%
Exports	-926	0.6%

Imports (i.e. 3%) were not accounted in the mix since no data about the used technologies were available. The technology of the different electricity power plants reflected the European context since all the datasets used for modelling Thai electricity mix came from Ecoinvent 2.2. Also transformation from high voltage to medium voltage and distribution losses were those representative for EU. To notice (Table 11) how the Thai mix is heavily based on fossil resources (>90%).

- *Other component – polymer*

In addition to starch and natural additives, the prototype granule preferably contains another polymer of synthetic or natural origin but always biodegradable. In the case of natural polymers these are preferably selected from cellulose, lignin and other many sources. As far as synthetic polymers are concerned, these may also be obtained from fermentation and are advantageously selected from several polymer families like polyesters and co-polyesters, vinyl polymers, synthetic rubber etc.

In Table 12 the inventory data related to a synthetic polymer manufacturing belonging to a one of the polymer family suitable for such purposes are shown. For confidentiality reasons the intermediates, the polymer and co-products were reported in the inventory as generic names. Energy inputs considered for the polymer production were average industrial data of the organic chemical sector [25]. The polymer was sourced in Italy.

Table 12 Inventory data for polymer production

	Unit	Amount	Note
Product and co-product in output			
Polymer	*kg*	*0.511*	*Allocation mass: 37.3%*
Chemical (co-product)	*kg*	*0.859*	*Allocation mass: 62.7%*
Input			
Material			
Raw material A, at plant/RER	kg	0.999	
Raw material B, at plant/GLO U	kg	0.372	
Energy			
Electricity, medium voltage, at grid/IT	MJ	0.6	
Heat, heavy fuel oil, at industrial furnace 1MW/RER U	MJ	0.15	
Steam, for chemical processes, at plant/RER U	kg	2.33	

- *Raw material transports*

The prototype raw materials transports from the place where they are produced to Italy (Terni) were included in the analysis. The details are shown in Table 13. Among them, tapioca starch has the highest relevant transport phase since it was sourced in Thailand.

Table 13 Inventory data for prototype raw materials transports

Raw material	Type	Distance (km)	Transport characteristics
Tapioca starch	Sea	12873	Transoceanic freight ship
	Road	200	Lorry 32 t
Other components – polymer	Road	392	Lorry 32 t

- *EPS granule*

Polystyrene belongs to Styrenics which is a family of major plastic products that use Styrene as their key building block. The production of Styrene monomer can be thought of as replacing one of the hydrogen atoms in ethylene by a benzene ring (C_6H_6) as shown in Figure 7.

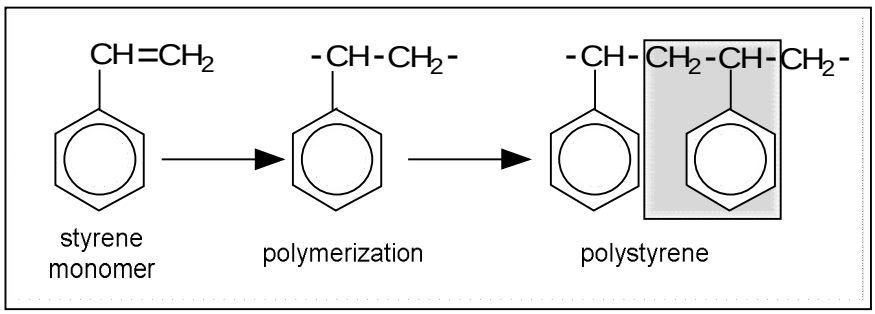


Figure 7 Reaction scheme for producing polystyrene (adapted from PlasticEurope Eco-profile [26])

Polystyrene's production route is shown in Figure 8. Three main forms can be obtained: crystal or general purpose polystyrene (GPPS), high impact polystyrene (HIPS) and expandable polystyrene (EPS).

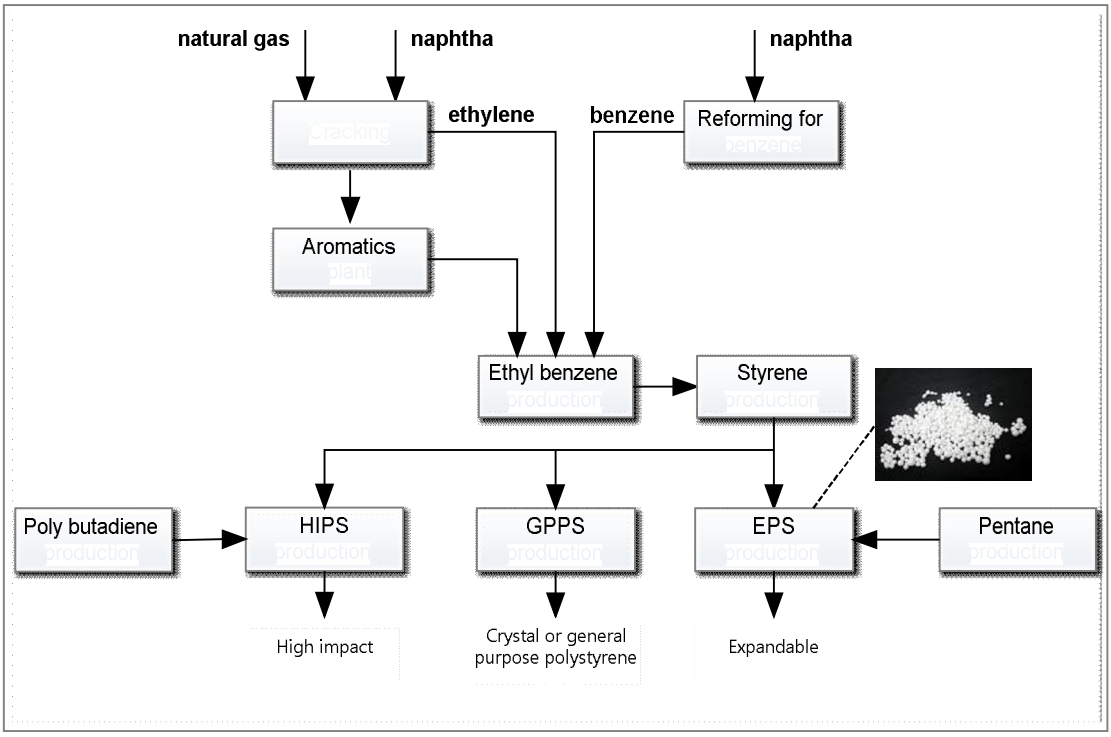


Figure 8 Polystyrene's production route (adapted from PlasticsEurope Eco-profile [26])

With regard to EPS, this material is widely used in building and construction sector (70%) due to their main properties: thermal insulation ability and low weight. The second most important application (25%) is related to the packaging sector such as cushioning of valuable goods and food packaging. Polystyrene is the fourth biggest polymer produced in the world after polyethylene, polyvinyl chloride and polypropylene. The total demand in 2001 was around 10.6 million t. Europe contributes 26 percent to the global demand for polystyrene and was approximately 2.7 million t in 2001, where packaging applications accounted for 37% (i.e. 1 million t) [27]. According to the Eco-profiles of PlasticsEurope, for each kg of EPS produced about 0.64 kg of oil and 0.33 kg of natural gas of feedstock are required [26].

In Table 14 the inventory for the production of 1 kg EPS is given.

Table14 Inventory for 1 kg of EPS (source: Ecoinvent 2.2 database based on Eco-profiles of PlasticsEurope)

	Unit	Amount
Product in output		
EPS (granule)	kg	1
Input		
Resources		
Oil, crude, in ground	kg	1.0429
Gas, natural, in ground	m^3	$9.08x10^{-1}$
Coal, hard, unspecified, in ground	kg	$1.46x10^{-1}$
Coal, brown, in ground	kg	$3.09x10^{-5}$
Peat, in ground	kg	0.000853
Wood, unspecified, standing/m3	m^3	$8.27x10^{-8}$
Energy, potential (in hydropower reservoir), converted	MJ	$2.27x10^{-1}$
Uranium, in ground	kg	$6.54x10^{-6}$
Energy, gross calorific value, in biomass	MJ	$1.93x10^{-1}$
Barite, 15% in crude ore, in ground	kg	$1.29x10^{-6}$
Aluminium, 24% in bauxite, 11% in crude ore, in ground	kg	$1.75x10^{-4}$
Clay, bentonite, in ground	kg	$8.29x10^{-5}$
Anhydrite, in ground	kg	$8.42x10^{-6}$
Calcite, in ground	kg	$3.88x10^{-4}$
Clay, unspecified, in ground	kg	$1.15x10^{-7}$
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	kg	$2.33x10^{-8}$
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	$1.89x10^{-4}$
Dolomite, in ground	kg	$4.26x10^{-6}$
Iron, 46% in ore, 25% in crude ore, in ground	kg	$3.47x10^{-4}$
Feldspar, in ground	kg	$2.73x10^{-16}$
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	kg	$4.48x10^{-7}$
Fluorspar, 92%, in ground	kg	$1.50x10^{-5}$
Granite, in ground	kg	$4.94x10^{-13}$
Gravel, in ground	kg	$1.28x10^{-6}$
Cinnabar, in ground	kg	$8.98x10^{-9}$
Magnesite, 60% in crude ore, in ground	kg	$2.45x10^{-10}$
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	kg	$2.73x10^{-5}$
Olivine, in ground	kg	$3.26x10^{-6}$
Lead, 5.0% in sulphide, Pb 3.0%, Zn, Ag, Cd, In, in ground	kg	$5.62x10^{-7}$
Phosphorus, 18% in apatite, 12% in crude ore, in ground	kg	$1.56x10^{-11}$
Sylvite, 25 % in sylvinite, in ground	kg	$6.42x10^{-6}$
Sulfur, in ground	kg	$1.98x10^{-4}$
Sand, unspecified, in ground	kg	$5.64x10^{-4}$
Shale, in ground	kg	$2.38x10^{-5}$
Sodium chloride, in ground	kg	$2.27x10^{-3}$
Sodium nitrate, in ground	kg	$7.35x10^{-10}$
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	kg	$2.57x10^{-5}$
Water, unspecified natural origin/m3	m^3	$4.73x10^{-3}$
Water, river	m^3	$6.68x10^{-4}$
Water, salt, ocean	m^3	$5.20x10^{-4}$

Water, well, in ground	m^3	$2.78x10^{-10}$
Water, cooling, unspecified natural origin/m3	m^3	$1.65x10^{-1}$
Output		
Emissions to air		
Heat, waste	MJ	42.383
Particulates, > 10 um	kg	$2.84x10^{-4}$
Particulates, > 2.5 um, and < 10um	kg	$3.81x10^{-4}$
Particulates, < 2.5 um	kg	$2.22x10^{-4}$
Carbon monoxide, fossil	kg	$3.77x10^{-3}$
Carbon monoxide, biogenic	kg	$7.54x10^{-6}$
Carbon dioxide, fossil	kg	2.5405
Carbon dioxide, biogenic	kg	$5.09x10^{-3}$
Sulfur dioxide	kg	$7.00x10^{-3}$
Hydrogen sulphide	kg	$1.19x10^{-8}$
Nitrogen oxides	kg	$4.84x10^{-3}$
Ammonia	kg	$7.35x10^{-9}$
Chlorine	kg	$9.82x10^{-7}$
Hydrogen chloride	kg	$5.95x10^{-5}$
Fluorine	kg	$3.59x10^{-8}$
Hydrogen fluoride	kg	$2.20x10^{-6}$
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	$5.17x10^{-3}$
Aldehydes, unspecified	kg	$1.08x10^{-13}$
Lead	kg	$2.75x10^{-7}$
Mercuri	kg	$1.84x10^{-9}$
Sulfate	kg	$7.51x10^{-15}$
Dinitrogen monoxide	kg	$2.15x10^{-8}$
Hydrogen	kg	$6.00x10^{-5}$
Ethane, 1,2-dichloro-	kg	$1.57x10^{-9}$
Ethene, chloro-	kg	$7.59x10^{-10}$
Hydrocarbons, chlorinated	kg	$6.82x10^{-7}$
Cyanide	kg	$2.00x10^{-18}$
Methane, fossil	kg	$3.12x10^{-2}$
Methane, biogenic	kg	$6.25x10^{-5}$
Hydrocarbons, aromatic	kg	$2.82x10^{-5}$
Hydrocarbons, aliphatic, alkanes, cyclic	kg	$5.59x10^{-6}$
Carbon disulfide	kg	$4.25x10^{-9}$
Methane, dichloro-, HCC-30	kg	$3.01x10^{-9}$
Copper	kg	$6.87x10^{-8}$
Arsenic	kg	$1.02x10^{-8}$
Cadmium	kg	$1.16x10^{-9}$
Silver	kg	$1.02x10^{-9}$
Zinc	kg	$3.24x10^{-8}$
Chromium	kg	$2.83x10^{-6}$
Selenium	kg	$3.5x10^{-11}$
Nickel	kg	$5.15x10^{-6}$
Antimony	kg	$3.33x10^{-11}$

Ethene	kg	$6.66x10^{-6}$
Benzene	kg	$1.83x10^{-5}$
Toluene	kg	$2.54x10^{-6}$
Xylene	kg	$1.06x10^{-6}$
Benzene, ethyl-	kg	$5.30x10^{-6}$
Styrene	kg	$4.51x10^{-5}$
Propene	kg	$4.93x10^{-6}$
Methane, chlorodifluoro-, HCFC-22	kg	$1.12x10^{-6}$
Emissions to water		
COD, Chemical Oxygen Demand	kg	$1.92x10^{-3}$
BOD5, Biological Oxygen Demand	kg	$2.69x10^{-4}$
Lead	kg	$2.05x10^{-9}$
Iron, ion	kg	$4.34x10^{-8}$
Sodium, ion	kg	$2.81x10^{-4}$
Acidity, unspecified	kg	$7.82x10^{-6}$
Nitrate	kg	$8.27x10^{-6}$
Mercury	kg	$1.95x10^{-10}$
Ammonium, ion	kg	$2.93x10^{-5}$
Chloride	kg	$5.65x10^{-4}$
Cyanide	kg	$3.29x10^{-11}$
Fluoride	kg	$3.77x10^{-7}$
Sulfide	kg	$1.83x10^{-7}$
Hydrocarbons, unspecified	kg	$1.64x10^{-4}$
Suspended solids, unspecified	kg	$1.75x10^{-3}$
Oils, unspecified	kg	$3.70x10^{-5}$
Chlorinated solvents, unspecified	kg	$3.36x10^{-8}$
Chlorine	kg	$2.14x10^{-8}$
Phenol	kg	$4.10x10^{-7}$
Solved solids	kg	$1.18x10^{-3}$
Phosphorus	kg	$6.29x10^{-5}$
Nitrogen	kg	$3.20x10^{-6}$
Sulfate	kg	$4.00x10^{-4}$
Ethane, 1,2-dichloro-	kg	$2.46x10^{-11}$
Ethene, chloro-	kg	$1.72x10^{-11}$
Potassium, ion	kg	$2.03x10^{-7}$
Calcium, ion	kg	$1.63x10^{-5}$
Magnesium	kg	$5.22x10^{-9}$
Chromium, ion	kg	$8.71x10^{-12}$
Chlorate	kg	$6.09x10^{-7}$
Bromate	kg	$3.28x10^{-9}$
TOC, Total Organic Carbon	kg	$3.82x10^{-5}$
AOX, Adsorbable Organic Halogen as Cl	kg	$6.05x10^{-8}$
Aluminium	kg	$1.10x10^{-6}$
Zinc, ion	kg	$3.78x10^{-8}$
Copper, ion	kg	$1.85x10^{-7}$
Nickel, ion	kg	$1.29x10^{-7}$

Carbonate	kg	$1.15x10^{-4}$
Arsenic, ion	kg	$8.29x10^{-10}$
Cadmium, ion	kg	$2.92x10^{-11}$
Manganese	kg	$2.63x10^{-10}$
Tin, ion	kg	$4.4x10^{-14}$
Strontium	kg	$5.05x10^{-11}$
Benzene	kg	$1.63x10^{-6}$
Molybdenum	kg	$7.24x10^{-9}$
Sulfite	kg	$6.4x10^{-9}$
Waste to treatment		
Disposal, facilities, chemical production/RER U	kg	$1.11x10^{-4}$
Disposal, tailings from hard coal milling, in impoundment/GLO U	kg	$7.88x10^{-3}$
Disposal, spoil from coal mining, in surface landfill/GLO U	kg	$4.55x10^{-2}$
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH U	kg	$2.70x10^{-2}$
Disposal, average incineration residue, 0% water, to residual material landfill/CH U	kg	$1.55x10^{-2}$
Disposal, wood untreated, 20% water, to municipal incineration/CH U	kg	$1.19x10^{-4}$
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	kg	$1.90x10^{-3}$
Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U	kg	$1.20x10^{-2}$

3.2.2 Packaging production (Stage 2)

Stage 2 addressed the granule expansion so as to get a foamed pck material. For EPS, average industrial data were considered, whereas for the prototype primary data were used as they were directly collected from the partner involved in the semi-industrial pilot plant development.

- *Prototype granule expansion*

The core of the REBIOFOAM project was the development of an innovative manufacturing process for the production of foamed 3D-shaped packaging material originating from expandable starch-based polymer granule. In this new process, expansion of the granules was driven by microwave technology that heating up exploits the inner water content of the material to generate vapour at high pressure, which triggers the foaming process. Nevertheless so as to meet the functional requirements for the innovative protective packaging three fundamental development steps were overcome. These were:

1. The achievement of a proper formulation (i.e. blend of raw materials) and processing conditions so as to get a suitable prototype granule (e.g. water content, peel thickness etc.) for the subsequent microwave expansion (Figure 9).

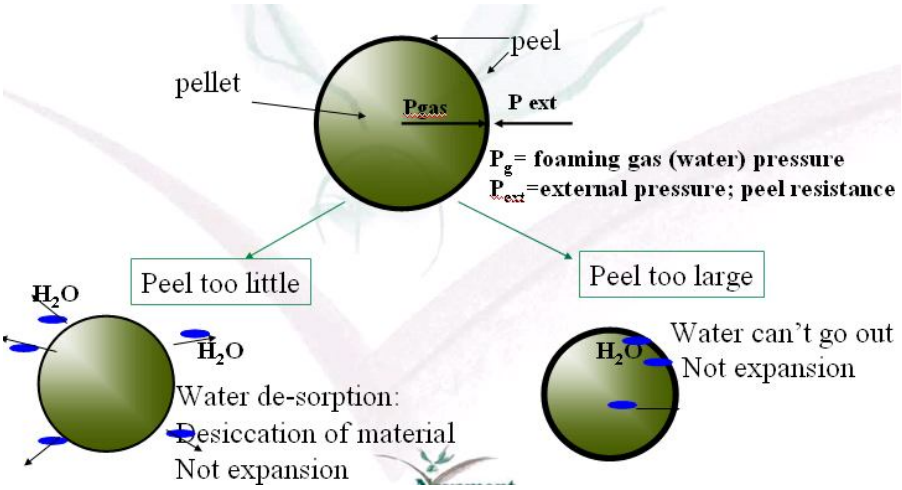


Figure 9 Granule peel influences microwave expansion (source : Novamont)

2. The achievement of a adequate foaming of the bio-based polymer, in terms of expanded cell's size and conformation/shape, cell's morphology, and, finally, mechanical characteristics and cushion behaviour of the expanded samples. This implied a carefully evaluation effects of microwave fields (e.g. thermal homogeneity), an efficient design of the microwave oven and finally, an efficient tuning of the operational parameters required for the expansion.

Figure 10 Example of foamed granules with mean diameter of round granules: D = 28.5 mm (source: Novamont)

3. An adequate mould design accomplished for successful processing of moulded, 3D-shaped, foam products. To this extent, a thorough comparison of dielectric properties of mould materials as well as a careful selection of the most appropriate material for mould construction, guaranteeing proper adhesion to the substrate while achieving at the same time inherent surface temperature control, was achieved. At the same time, the occurrence of viscous shear stresses at the foam / mould interface was minimized, thus facilitating complex 3Dshaping during the moulding process, through the proper design of the mould surface.

Based on the experimental outcomes focusing on points 1, 2 and 3 and other technical-economic considerations in May 2011, a flow sheet of material and energy balances about prototype process in pilot scale were designed by

involved partners in the development of the pilot line. The pilot line was a rotary machine able to produce around 120 pcs/h (port-hole spacers) in a semi-automatic way made of four different steps represented in Figure 11. The achieved density of the prototype pck was of 40 kg/m^3 .

The process consisted of four stages: storage and dosing unit for granules, microwave system for foaming granules, extraction stage for removing the product and conditioning unit for cooling or heating mould before restarting process.

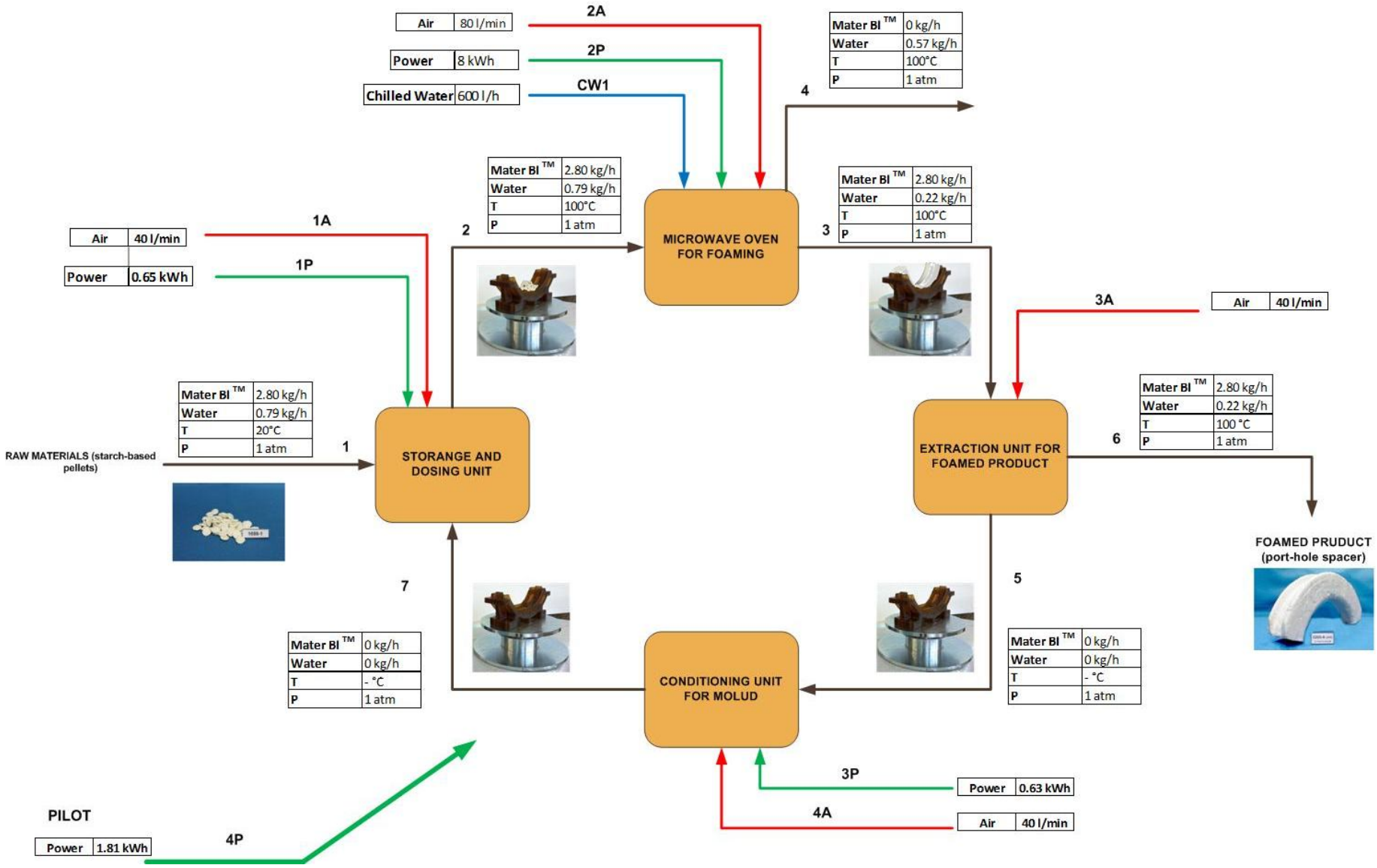


Figure 11 Flow sheet of prototype process in pilot scale (mass balance and power of equipments, source: REBIOFOAM consortium)

In general, the pilot line has a central shaft able to turn around a main table. On this table four plates were jointly installed and on each plate as installed only one mould. A central table was able to turn around in order to transfer each plate supporting the mould from a station to another one. Figure 12 showed the assembling semi-industrial pilot.

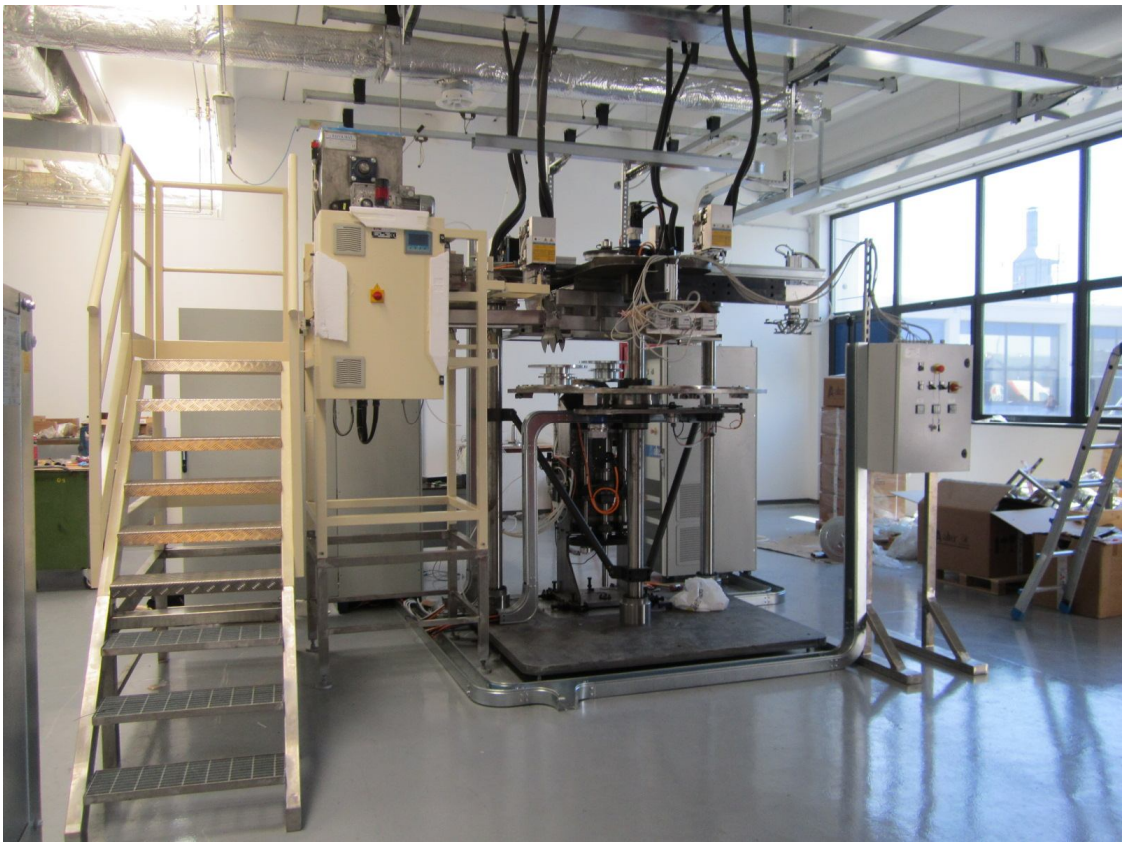


Figure 12 Assembling the pilot line (source: REBIOFOAM consortium)

The expansion process for prototype pck requires only electricity for its operation: neither thermal energy nor blowing agents are needed. Inventory data here reported reflected a pilot line designed to produce 120 pieces/h with a time cycle of 30 seconds.

The pilot machine has been fully industrial-oriented and was able to manage the foaming process in continuous state. The machine has been supposed to be equipped with four stations supporting one-half mould each (see also Figure 11). To point out that the level of scale-up from the pilot line depends on the production capacity definition to be able to identify the technology fulfils technical requirements. As in many industrial cases, the pilot line is technologically different with respect to a higher production capacity plant, where efficiency and reliability are enhanced. Up to a limited scaling-up, the machine concept keeps the same; whereas for larger scales the machine type could change. In our case this aspect was not investigated.

The mass balance for expansion is shown in Figure 13, whereas the whole inventory data are provided in Table 15.

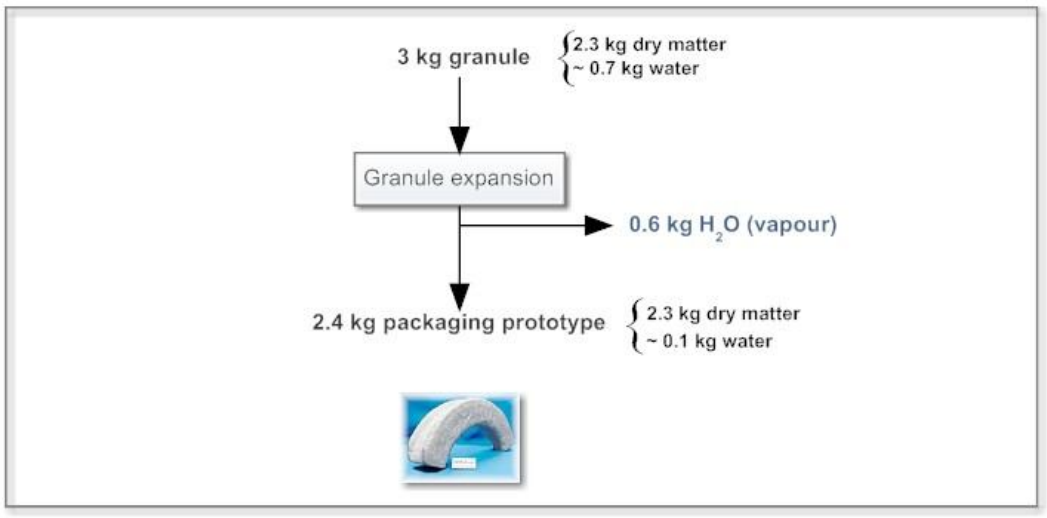


Figure 13 Mass balance for expansion (prototype pck)

Table 15 Inventory for expansion (figures related to 100 pcs prototype pck)

	Unit	Amount
Product in output		
100 port-hole spacers	*kg*	*2.4*
Input		
Material		
Starch-based granules	kg	3.0
Energy		
Electricity, medium voltage, at grid/IT U (undoped mould)	kWh	4.7
Output		
Emission to air		
Water	kg	0.6

The partitioning of electricity consumption for expansion is provided in Figure 14.

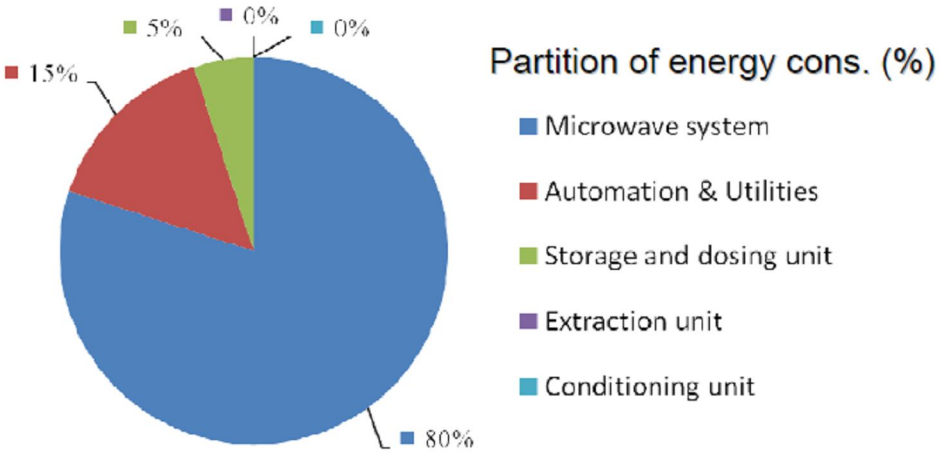


Figure 14 Electricity consumption break down for expansion (source: REBIOFOAM consortium)

To notice that the microwave system dominated the overall electricity consumption for expansion process. Calculations about the electricity consumption were done considering the installed power for each component (see Figure 11), operational time and other parameters according to the typology of the component itself.

- *Port-hole spacer surface*

An important aspect related to the expansion process for prototype pck was the achievement of a proper refined surface of the end product (i.e. port-hole spacer). Many research activities were performed so as to handle this aspect. For example the influence of mould temperature on foamability was investigated finding out that per-heating the mould allows to achieve better samples. The most promising solutions identified were:

- to heat the mould with a IR system (inventory data presented in Table 15 are referred to this option)
- to dope the mould with iron-based layer that when exposed to microwave electromagnetic field increases the temperature of the mould surface.

Both solutions permitted to optimize the granules flow within the mould (before the expansion) thus achieving a more refined end product (i.e. port-hole space), however, the IR system seemed to be preferable to the doped mould, as the absence of a doped layer allowed to optimize the irradiation time (also according to analysis carried out in WP3 and WP4) thus reducing electricity consumption. The expansion with a doped mould was, anyhow, addressed in the sensitivity analysis. The estimated electricity consumption for the microwave system using a doped mould was approximately twofold higher compared to IR system.

- *EPS granule expansion*

Before being formed into the final article (i.e. port-hole spacer), the EPS beads need to be processed. When these expandable pearls are heated with steam, they expand to about 40 times their original size (i.e. pre-foaming). After a stabilisation period - maturing - the expanded beads are then transferred to a mould. Further steam-heating makes them fuse together to form a rigid foam containing 98% air. Finally, the foam can then easily be cut into the desired shape [28]. The figure 15 below summarizes the expansion steps.

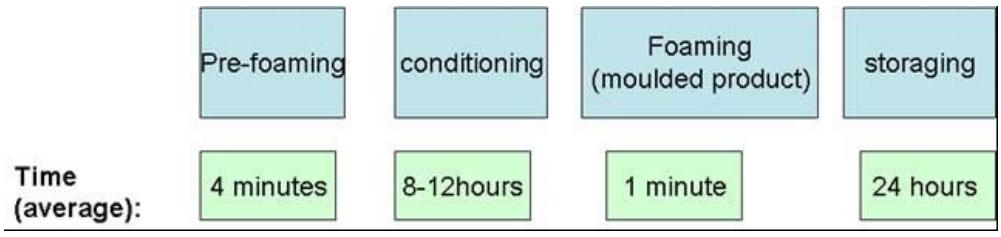


Figure 15 EPS granule expansion steps and related timing

Inventory data for EPS expansion were derived from different sources summarized in Table 16.

Table 16 Inventory data for the foaming expanding EPS process (data per kg of EPS foamed product)

Per kg output	Unit	Ecoinvent database			Literature	Primary data			This study
		Habrsatter et al (1998)		Ritcher et al (1995)	LCA study on EPS pck systems [29]	Company 1	Company 2	Company 3	
		Company 1	Company 2						
Input									
Material input									
EPS granulate	kg	1.008	1.075	1	1.065				1.065
Compressed air	M^3	1.053	2.61						1.053
Water process	kg	5.9		0.661	3.8				5.9
Water cooling	kg	closed sys.							-
Energy input									
Electricity	kWh	0.57	0.805	0.788	0.14	0.4	0.95	0.9	0.8
Natural gas[a)]	MJ	-	-	-	0.1	28.1	-	32.2	32[b)]
Light fuel oil	MJ	-	-	0.141	4.91	-	-	-	
Heavy fuel oil	MJ	59.1	19	2.72	-	-	34.2	-	
Diesel,	MJ	-	-	0.056	-	-	-	-	
Lubricating oil	kg				0.0087				-
Output									
Emission to air									
Heat waste	MJ			2.84					-
Pentane	G	37.4	43	15					37.4
Particulates	G				0.0204				*0.0204*
VOC	G				0.1401				*0.1401*
Nitrogen oxides	G				0.0204				*0.0204*
Sulfur oxides	G				3.269				*3.269*
Emission to water									
COD	mg				226				*226*
BOD5	mg				79.4				*79.4*
Suspended substances	mg				39.69				*39.69*
Organic substances	mg				0.397				*0.397*
Waste									
Waste to recycling	kg				0.064				*0.064*
Disposal to incineration	kg				0.001				*0.001*

Empty cells: data not available; a) Calorific value for natural gas: 40.3 MJ/Nm^3; b) avg value (primary data), supplied 50% from natural gas and 50% from heavy fuel oil (assumption)

Representing data for EPS used in packaging sector

Representing data for EPS used in building sector

Three out off six sources referred to primary data provided by three different companies that produced EPS pck products. For confidential reasons they were named “company 1, 2 and 3”. Among them, the figures on thermal energy were quite homogeneous whereas the electricity consumption for company 1 was two times lower compared to companies 2 and 3. To notice that the figures from Ecoinvent 2.2 database were quite close to primary ones with

the exception of thermal energy reported in the Ritcher et al. source. In that case it could be argued that such a difference could be associated with a different technology for producing EPS for building sector compared to EPS for packaging purposes. Finally the literature source, related to an LCA study on EPS pck systems [29], reported inventory data for electricity and heat consumptions significant lower compared to those reported on all other sources.

At the end it was decided to consider for EPS expansion the most representative inventory data, also taking into account the primary sources available. These were reported in the last column on the right side of Table 16. To point out that the figures in blue were not accounted for in the impact assessment since the level of detail was higher compared to the data collected for the prototype process, so to keep the systems as more homogeneous as possible they were left out. Only pentane emissions were accounted for since, they represent a well recognized and specific emission of EPS expansion process.

IMPORTANT NOTE

The use phase for the port-hole spacer consisted of its utilization within washing machine packaging and shipment phases. For such phases no valuable differences were identified between prototype and EPS pck systems, therefore they were not taken into account.

3.2.3 Packaging disposal (Stage 3)

As soon as the pck system has fulfilled its (short) duty, it has to be disposed of according to its characteristics like material recyclability or compostability and waste management systems running across the countries in which the washing machines were sold. Thanks to the (tested) compostability of the prototype pck it was assumed to be suitable for biological recycling through an industrial composting process. Consequently it was assumed to be collected along with household bio-waste fraction. Compostability is a crucial feature of the prototype pck because it opens to new routes of waste treatments contributing in diversion from landfill. In APPENDIX A biodegradation and compostability tests performed on the prototype along with achieved results were reported.

In this study, the “basic” disposal scenario reflected, as more as possible, the real fate of both pck systems. To this end statistic data on waste management [30] along with data on washing machines distribution were matched. The latter data, provided directly from the project partner, were of extreme importance for the reliability of the model since according to Eurostat 2008 data on waste management there was a very high variation on waste treatments across European countries: for example landfill passed from ≈1% in the Netherlands up to ≈100% in Bulgaria. However, a sensitivity analysis considering different EoL disposals was performed (see § 4.2.3).

To set a real End of Life (EoL) scenario for EPS pck and prototype one, the following methodological approach was adopted. It consisted of four steps.

1st Step (for both EPS pck and prototype pck) - Identification of the countries included in each region and its relative weight

As mentioned above a partner of the project provided primary data about the washing machine market distribution (Table 17).

Table 17 Washing machine distribution (primary data coming from a project partner)

Regions in which washing machines are sold	Market share
West Europe	9.3%
Central Europe	36.9%
East Europe (+ Russia)	30.5%
Scandinavia + Baltic Countries	21.1%
Extra Europe	2.2%

Figure 16 a, b, c, and d showed the countries that constituted each region.

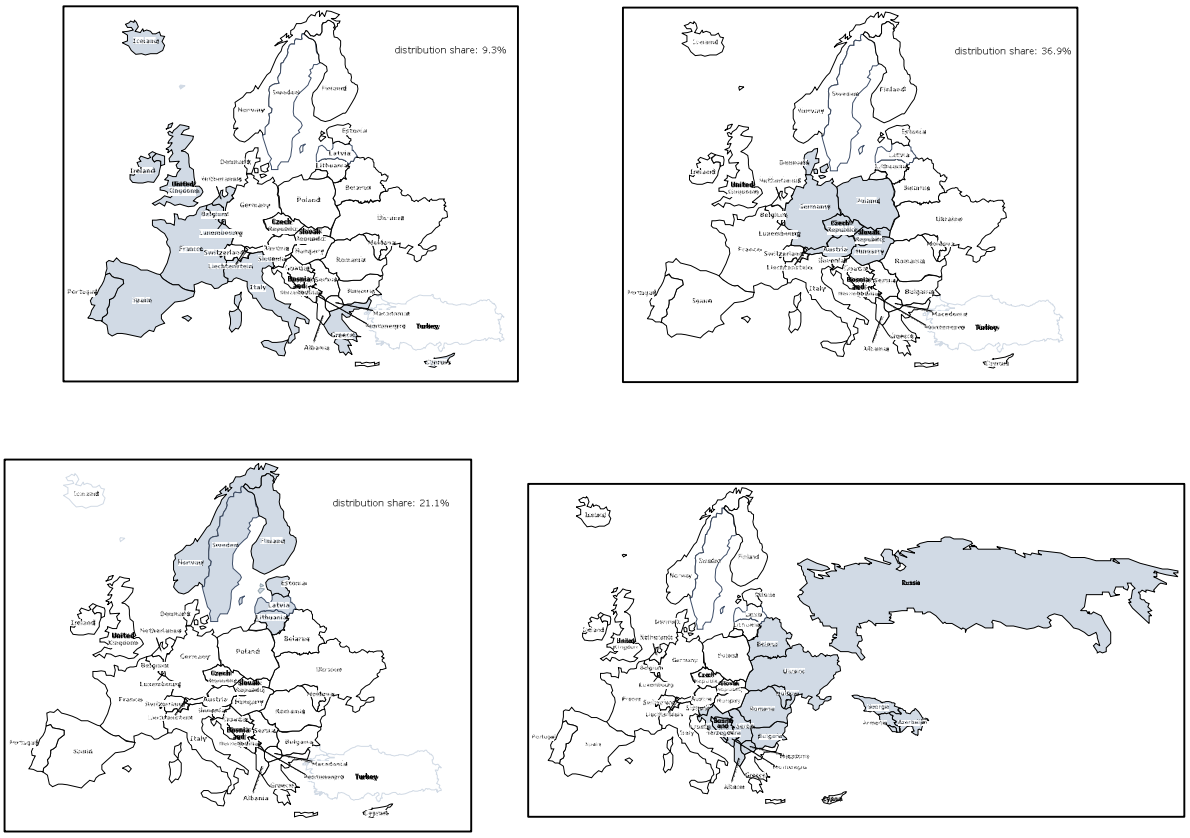


Figure 16 Countries considered for each region

As observed in Table 17, the regions of Extra Europe were also included considering that 2.2% of the commercialization of the washing machines was focused in this area. Nevertheless, only the most important economies were considered in order to simplify the calculation (EU, China, Japan, India, Brazil, Mexico and Australia).

Table 18 showed the countries that were considered for each region and their corresponding population and relative weight. An important assumption made was that all washing machines were equally sold in the countries. It meant,

for example, that for central Europe region (market share of 36.9%) about 52% of washing machines were sold in Germany. In absolute terms the washing machine sold in Germany would have been: 36.9% x 52% = 19.2% of the total.

Table 18 Population and weight for countries considered

Region	Countries considered	Population	Weight in the region (%)	Region	considered Countries	Population	Weight in the region (%)
Region 1. Scandinavia + Baltic countries	Norway	4,743,193	17.9	**Region 4. East Europe**	Albania	3,544,841	1.3
	Sweden	9,076,744	34.2		Armenia	3,330,099	1.2
	Finland	5,302,545	20		Azerbaijan	7,798,497	2.8
	Estonia	1,415,681	5.3		Belarus	10,335,382	3.8
	Latvia	2,366,515	8.9		Bosnia and Herzegovina	3,964,388	1.4
	Lithuania	3,601,138	13.6		Bulgaria	7,621,337	2.8
	TOTAL	26,505,816	**100**		Croatia	4,490,751	1.6
Region 2. West Europe	Ireland	4,234,925	1.5		Kosovo	2,000,000	0.7
	UK	60.587.000	21.7		Georgia	4,960,951	1.8
	France	60,765,983	21.7		Republic of Macedonia	2,054,800	0.7
	Spain	45,061,270	16.1		Moldova	4,434,547	1.6
	Portugal	10,084,245	3.6		Montenegro	630,548	0.2
	Italy	59,715,625	21.3		Romania	22,303,552	8.1
	Netherlands	16,491,461	5.9		Russia	142,978,573	51.9
	Belgium	10,274,595	3.7		Serbia	7,780,000	2.8
	Luxemburg	448,569	0.2		Slovenia	1,932,917	0.7
	Iceland	312,384	0.1		Ukraine	45,276,000	16.4
	Malta	397,499	0.1		**TOTAL**	275,437,183	**100**
	Greece	10,645,343	3.8	**Region 5. Extra Europe**	EEUU	308,745,538	9.6
	Chipre	767,314	0.3		China	1,313,973,713	40.8
	TOTAL	279,786,213	**100**		India	1,166,079,217	36.2
Region 3. Central Europe	Germany	83,251,851	51.7		Japan	126,874,000	3.9
	Poland	38,625,478	24		Australia	22,000,000	0
	Czech Republic	10,256,760	6.4		Brazil	190,732,694	5.9
	Slovakia	5,422,366	3.4		Mexico	112,322,757	3.5
	Hungary	10,075,034	6.3		**TOTAL**	3,218,749,919	**100**
	Denmark	5,368,854	3.3				
	Austria	8,169,929	5.1				
	TOTAL	161,170,272	**100**				

2nd Step (prototype pck) - Identification of the end of life scenarios of the Municipal Solid Waste in the different countries.

The end of life scenario of the Municipal Solid Waste was worked out for the different EU27 countries (Table 19) using statistic data available in the public domain. Nevertheless, this information was not found out for the European countries not included in the EU and for the non European countries (EU, China, Japan, India, Brazil, Mexico and Australia). Therefore, it was considered that these countries present the average end of life scenario of the EU27 (landfill 40%, incineration 20%, recycling 23% and compost 17%).

According to this decision Table 20 was worked out.

Table 19 End of life scenario of Municipal Solid Waste in the EU countries. [30]

	Municipal waste generated kg per person	**Municipal waste treated, %**			
		Landfilled	**Incinerated**	**Recycled**	**Composted**
EU 27	**524**	**40**	**20**	**23**	**17**
Belgium	493	5	36	35	25
Bulgaria	467	100	0	0	0
Czech Republic	306	83	13	2	2
Denmark	802	4	54	24	18
Germany	581	1	35	48	17
Estonia	515	75	0	18	8
Ireland	733	62	3	32	3
Greece	453	77	0	21	2
Spain	575	57	9	14	20
France	543	36	32	18	15
Italy	561	44	11	11	34
Cyprus	770	87	0	13	0
Latvia	331	93	0	6	1
Lithuania	407	96	0	3	1
Luxembourg	701	19	36	25	20
Hungary	453	74	9	15	2
Malta	696	97	0	3	0
Netherlands	622	1	39	32	27
Austria	601	3	27	29	40
Poland	320	87	1	9	4
Portugal	477	65	19	9	8
Romania	382	99	0	1	0
Slovenia	459	66	1	31	2
Slovakia	328	83	10	3	5
Finland	522	50	17	25	8
Sweden	515	3	49	35	13
United Kingdom	565	55	10	23	12

Data for the EU27, Belgium, Denmark, Germany, Estonia, Spain, France, Italy, Cyprus, Luxembourg, Netherlands, Austria, Poland, Romania, Portugal and the United Kingdom were estimated.

Table 20 End of life scenario of Municipal Solid Waste in the European and non European countries considered.

Region	Countries	Landfill (%)	Incineration (%)	Recycling (%)	Compost (%)
Region 1. Scandinavia + Baltic countries	Norway	40	20	23	17
	Sweden	3	49	35	13
	Finland	50	17	25	8
	Estonia	74.3	0	17.8	7.9
	Latvia	93	0	6	1
	Lithuania	96	0	3	1
Region 2. West Europe	Ireland	62	3	32	3
	UK	55	10	23	12
	France	35.6	31.7	17.8	14.9
	Spain	57	9	14	20
	Portugal	64.4	18.8	8.9	7.9
	Italy	44	11	11	34
	Netherlands	1.0	39.4	32.3	27.3
	Belgium	5.0	35.6	34.7	24.8
	Luxemburg	19	36	25	20
	Iceland	40	20	23	17
	Malta	97	0	3	0
	Greece	77	0	21	2
	Chipre	87	0	13	0
Region 3. Central Europe	Germany	1.0	34.7	47.5	16.8
	Poland	86.1	1.0	8.9	4.0
	Czech Republic	83	13	2	2
	Slovakia	82.2	9.9	3.0	5.0
	Hungary	74	9	15	2
	Denmark	4	54	24	18
	Austria	3.0	27.3	29.3	40.4
Region 4. East Europe	Albania	40	20	23	17
	Armenia	40	20	23	17
	Azerbaijan	40	20	23	17
	Belarus	40	20	23	17
	Bosnia and Herzegovina	40	20	23	17
	Bulgaria	100	0	0	0
	Croatia	40	20	23	17
	Kosovo	40	20	23	17
	Georgia	40	20	23	17
	Republic of Macedonia	40	20	23	17
	Moldova	40	20	23	17
	Montenegro	40	20	23	17
	Romania	99	0	1	0
	Russia	40	20	23	17
	Serbia	40	20	23	17
	Slovenia	66	1	31	2
	Ukraine	40	20	23	17
Region 5. Extra Europe	EEUU	40	20	23	17
	China	40	20	23	17
	India	40	20	23	17
	Japan	40	20	23	17
	Australia	40	20	23	17
	Brazil	40	20	23	17
	Mexico	40	20	23	17

2nd Step (EPS) - Identification of the end of life scenario of plastic packaging

The end of life scenario of the plastic packaging waste was defined for the different EU27 countries based on the databases of Eurostat [31]. Nevertheless, as for prototype pck, this information was not found out for the European countries and for the non European countries. Therefore, it was considered that these countries presented the average end of life scenario of the EU27 (landfill 43%, incineration 57%, recycling 43%).

According to this decision, Table 21, reporting the end of life scenario of plastic packaging in the different countries, was worked out.

Table *21 End of life scenario of plastic packaging waste in the European and non European countries considered.*

Region	Countries considered	Landfill (%)	Incineration (%)	Recycling (%)
Region 1 Scandinavia + Baltic countries	Norway	15.5	54.7	29.8
	Sweden	21.7	36.6	41.7
	Finland	57.0	24.6	18.4
	Estonia	61.7	0.1	38.2
	Latvia	77.2	0.0	22.8
	Lithuania	71.5	0.0	28.5
	TOTAL	50.8	19.3	29.9
Region 2 West Europe	Ireland	77.8	0.0	22.2
	UK	68.5	9.0	22.5
	France	46.6	32.3	21.1
	Spain	61.9	14.8	23.3
	Portugal	77.4	7.3	15.3
	Italy	41.5	30.3	28.3
	Netherlands	8.5	65.5	25.9
	Belgium	14.1	47.5	38.4
	Luxemburg	9.9	51.4	38.7
	Iceland	43.0	57.0	27.7
	Malta	43.0	57.0	27.7
	Greece	86.3	0.0	13.7
	Cyprus	85.7	0.0	14.3
	TOTAL	51.1	28.6	24.6
Region 3 Central Europe	Germany	4.7	52.6	42.7
	Poland	53.5	18.5	28.0
	Czech Republic	42.6	11.9	45.5
	Slovakia	55.0	3.3	41.7
	Hungary	56.2	26.8	17.0
	Denmark	2.3	75.9	21.8
	Austria	4.7	62.5	32.7
	TOTAL	31.3	35.9	32.8
Region 4 East Europe	Albania	43.0	57.0	27.7
	Armenia	43.0	57.0	27.7
	Azerbaijan	43.0	57.0	27.7
	Belarus	43.0	57.0	27.7
	Bosnia and Herzegovina	43.0	57.0	27.7
	Bulgaria	80.5	0.0	19.5
	Croatia	43.0	57.0	27.7
	Kosovo	43.0	57.0	27.7
	Georgia	43.0	57.0	27.7
	Republic of Macedonia	43.0	57.0	27.7
	Moldova	43.0	57.0	27.7
	Montenegro	43.0	57.0	27.7
	Romania	78.8	6.0	15.3
	Russia	43.0	57.0	27.7
	Serbia	43.0	57.0	27.7
	Slovenia	43.0	57.0	27.7
	Ukraine	43.0	57.0	27.7
	TOTAL	47.3	50.6	26.5
Region 5 Extra Europe	EEUU	43.0	57.0	27.7
	China	43.0	57.0	27.7
	India	43.0	57.0	27.7
	Japan	43.0	57.0	27.7
	Australia	43.0	57.0	27.7
	Brazil	43.0	57.0	27.7
	Mexico	43.0	57.0	27.7
	TOTAL	43.0	57.0	27.7

3rd Step (prototype pck) - Identification of the percentage of the organic fraction, on average, in the municipal solid waste.

The percentage that represents the organic fraction in the MSW has been defined for several European countries (Table 22). Nevertheless, this information has not been found for some other European countries and for the non European countries considered (EEUU, China, Japan, India, Brazil, Mexico and Australia). Therefore, the average percentage of organic mater in MSW of the EU (i.e. 32%) was adopted for these countries.

According to that, a final table of the percentage of organic fraction in the MSW of the different countries and regions considered was worked out (Table 23).

Table 22 Organic part in the MSW in different European countries. Source: Eunomia. Research and consulting [32]

Country	Organic part in MSW (Barth)	Organic part in MSW (Amlinger)
Austria	29% (1991)	29% hhld (1995) 17% MSW (1198)
Belgium	48% Flanders (1996) 45% Wallonia (1991)	Flanders: 48% (1996) Wallonia: 45% (1991)
Denmark	37% (1994)	37% (1994)
Finland	35% (1998)	35% (1993)
France	29% (1993)	29%
Germany	32% (1992)	32%
Greece	49% (1987-1993)	49%
Ireland	29% (1995)	29%
Italy	32-35% (1999)	33%
Luxembourg	44% (1994)	44%
Netherlands	46% (1995)	38%
Portugal	35% (1996)	44%
Spain	44% (1996)	44%
Sweden	40% (1996)	25%
UK	22% (1997)	21%
EU average	**32%**	

Table 23 Organic part in the MSW in different countries and regions considered.

Region	Countries considered	Biowaste in MSW (%)	Region	Countries Considered	Biowaste in MSW (%)
Region 1 Scandinavia + Baltic countries	Norway	32.0	**Region 4 East Europe**	Albania	32.0
	Sweden	32.5		Armenia	32.0
	Finland	35.0		Azerbaijan	32.0
	Estonia	32.0		Belarus	32.0
	Latvia	32.0		Bosnia and Herzegovina	32.0
	Lithuania	32.0		Bulgaria	32.0
Region 2 West Europe	Ireland	29.0		Croatia	32.0
	UK	21.5		Kosovo	32.0
	France	29.0		Georgia	32.0
	Spain	44.0		Republic of Macedonia	32.0
	Portugal	39.5		Moldova	32.0
	Italy	34.0		Montenegro	32.0
	Netherlands	42.0		Romania	32.0
	Belgium	46.5		Russia	32.0
	Luxemburg	44.0		Serbia	32.0
	Iceland	32.0		Slovenia	32.0
	Malta	32.0		Ukraine	32.0
	Greece	49.0	**Region 5. Extra Europe**	EEUU	32.0
	Chipre	32.0		China	32.0
Region 3 Central Europe	Germany	32.0		India	32.0
	Poland	32.0		Japan	32.0
	Czech Republic	32.0		Australia	32.0
	Slovakia	32.0		Brazil	32.0
	Hungary	32.0		Mexico	32.0
	Denmark	37,0			
	Austria	29			

3rd Step (EPS pck) - Identification of the recycling rates of household EPS pck

The specific recycling rates of domestic EPS waste stream was found only for Spain (~0%) [33], Italy (~1%) [34], Germany (~2.3 %) [35] and France (~2.5 %) [36] whereas for all the remaining countries it was not possible.

However, according to Eumeps' study [37], 80% of domestic EPS pck was landfilled and 20% incinerated on average in the EU (2001) with a recycling rate substantially equal to 0%. This value was assumed for all the remaining countries, nevertheless, so as to properly handle this lack of data for EPS pck, two hypothetic scenarios were assumed in which EPS recycling rate was assumed equal to 30% and 50% respectively.

The final recycling rates of household EPS pck are included in table 24.

Table 24 Recycling rates of household EPS pck

Region	Countries considered	EPS pck recycling (%)	Region	Countries considered	EPS pck recycling (%)
Region 1. Scandinavia + Baltic countries	Norway	0.0	Region 4. East Europe	Albania	0.0
	Sweden	0.0		Armenia	0.0
	Finland	0.0		Azerbaijan	0.0
	Estonia	0.0		Belarus	0.0
	Latvia	0.0		Bosnia and Herzegovina	0.0
	Lithuania	0.0		Bulgaria	0.0
	TOTAL	0.0		Croatia	0.0
Region 2. West Europe	Ireland	0.0		Kosovo	0.0
	UK	0.0		Georgia	0.0
	France	2.5		Republic of Macedonia	0.0
	Spain	0.0		Moldova	0.0
	Portugal	0.0		Montenegro	0.0
	Italy	1.0		Romania	0.0
	Netherlands	0.0		Russia	0.0
	Belgium	0.0		Serbia	0.0
	Luxemburg	0.0		Slovenia	0.0
	Iceland	0.0		Ukraine	0.0
	Malta	0.0		TOTAL	0.0
	Greece	0.0	Region 5. Extra Europe	EEUU	0.0
	Cyprus	0.0		China	0.0
	TOTAL	0.8		India	0.0
Region 3. Central Europe	Germany	2.3		Japan	0.0
	Poland	0.0		Australia	0.0
	Czech Republic	0.0		Brazil	0.0
	Slovakia	0.0		Mexico	0.0
	Hungary	0.0		TOTAL	0.0
	Denmark	0.0			
	Austria	0.0			
	TOTAL	1.2			

4th Step (prototype pck) - Extrapolation of the end of life scenario for the prototype pck

The end of life scenario of bio-waste, and consequently of the prototype pck, in the different countries was extrapolated from the data collected in steps 1°, 2° and 3°, following the methodology explained below for the specific case of Slovakia.

In Slovakia we know that 82.2%, 9.9%, 3.0% and 5.0% of the MSW is landfilled, incinerated, recycled and composted respectively. Moreover, we know that 32.0% of MSW is bio-waste (section 2.3.). Considering that the composting material is always bio-waste, that means that 15.6% of the biowaste present in the MSW is composted (5*100/32=15.6%). Therefore, the remaining 84.4% of the biowaste is managed through other strategies (landfilling, recycling and incineration). We also know that the organic matter can not be recycled, so 84.4% has to be divided between landfilling and incineration. Therefore, this percentage was divided between both end of life strategies considering their relative weigh: landfilling 89.2% (82.2/(82.2+9.9)) and incineration 10.8% (9.9/(82.2+9.9)). Hence:

- Recycling = 0%
- Composting = 15.62%
- Landfill = 84.38%x(82.2/(82.2+9.9)) =75.3%
- Incineration = 84.38x(9.9/(82.2+9.9)) =9.1%

4th Step (EPS pck) - Extrapolation of the end of life scenario of the household EPS pck

The end of life scenario of household EPS pck in the different countries was extrapolated from the data collected in the 1st, 2nd and 3rd steps following the methodology explained below for the specific case of Italy.

In Italy we know that 41.5%, 30.3% and 28.3% of the plastic packaging is landfilled, incinerated and recycled (Table 21). Moreover, we know that 1% of EPS pck is recycled. Therefore, 99% of EPS pck is landfilled and incinerated. From this data, the percentage of landfilling and incineration of household EPS pck was calculated considering the relative weight of each end of waste strategy in the case of the packaging waste since household EPS pck is included in this fraction. Hence:

- Recycling: 1 %
- Incineration: 41.5x99/(41.5+30.3)=57.22%
- Landfilling: 30.3x99/(41.5+30.3)=41.78%

- *Results for prototype pck*

The extrapolation described in the methodology was carried out for the different countries considered in each region (Table 25). Moreover, the weight of the countries was considered in order to calculate the final end of life scenario of bio-waste, and consequently of the prototype pck in the different regions. The results are shown in Table 26.

Table 25 End of waste scenario of the prototype pck in each country

Region	Countries considered	Biowaste in MSW (%)	Prototype pck landfilled (%)	Prototype pck incinerated (%)	Prototype pck composted (%)
Region 1. Scandinavia + Baltic countries	Norway	32.0	31.3	15.6	53.1
	Sweden	32.5	3.5	56.5	40.0
	Finland	35.0	57.6	19.6	22.9
	Estonia	32.0	75.2	0.0	24.8
	Latvia	32.0	96.9	0.0	3.1
	Lithuania	32.0	96.9	0.0	3.1
Region 2. West Europe	Ireland	29.0	85.5	4.1	10.3
	UK	21.5	37.4	6.8	55.8
	France	29.0	25.8	23.0	51.2
	Spain	44.0	47.1	7.4	45.5
	Portugal	39.5	61.9	18.1	20.1
	Italy	34.0	0.0	0.0	100.0
	Netherlands	42.0	0.9	34.2	64.9
	Belgium	46.5	5.7	41.1	53.2
	Luxembourg	44.0	18.8	35.7	45.5
	Iceland	32.0	31.3	15.6	53.1
	Malta	32.0	100.0	0.0	0.0
	Greece	49.0	95.9	0.0	4.1
	Chipre	32.0	100.0	0.0	0.0
Region 3. Central Europe	Germany	32.0	1.3	46.1	52.6
	Poland	32.0	86.6	1.0	12.4
	Czech Republic	32.0	81.1	12.7	6.3
	Slovakia	32.0	75.4	9.1	15.5
	Hungary	32.0	83.6	10.2	6.3
	Denmark	37.0	3.5	47.8	48.6
	Austria[3]	40.4	0.0	0.0	100.0
Region 4. East Europe	Albania	32.0	31.3	15.6	53.1
	Armenia	32.0	31.3	15.6	53.1
	Azerbaijan	32.0	31.3	15.6	53.1
	Belarus	32.0	31.3	15.6	53.1
	Bosnia and Herzegovina	32.0	31.3	15.6	53.1
	Bulgaria	32.0	100.0	0.0	0.0
	Croatia	32.0	31.3	15.6	53.1
	Kosovo	32.0	31.3	15.6	53.1
	Georgia	32.0	31.3	15.6	53.1
	Republic of Macedonia	32.0	31.3	15.6	53.1
	Moldova	32.0	31.3	15.6	53.1
	Montenegro	32.0	31.3	15.6	53.1
	Romania	32.0	100.0	0.0	0.0
	Russia	32.0	31.3	15.6	53.1
	Serbia	32.0	31.3	15.6	53.1
	Slovenia	32.0	92.4	1.4	6.3

[3] According to the data of Austria, the percentage of MSW composting (40.4%) is higher than the the percentage of organic matter present in this fraction (29%). In order to solve that, it was considered that MSW of Austria contains 40.4% of organic matter.

	Ukraine	32.0	31.3	15.6	53.1
Region 5. Extra Europe	EEUU	32.0	31.3	15.6	53.1
	China	32.0	31.3	15.6	53.1
	India	32.0	31.3	15.6	53.1
	Japan	32.0	31.3	15.6	53.1
	Australia	32.0	31.3	15.6	53.1
	Brazil	32.0	31.3	15.6	53.1
	Mexico	32.0	31.3	15.6	53.1

Table 26 End of waste scenario of the prototype pck in each region

Region	Prototype pck landfilled (%)	Prototype pck incinerated (%)	Prototype pck composted (%)
Region 1. Scandinavia + Baltic countries	44.1	26.1	29.8
Region 2. West Europe	29.2	12.0	58.8
Region 3. Central Europe	34.5	27.4	38.1
Region 4. East Europe	39.1	13.8	47.0
Region 5. Extra Europe	31.3	15.6	53.1

The values of Table 26 were multiplied by the values of market share and reported in table 27.

Table27. End of waste scenario of the prototype pck

Scenario	Biowaste landfilled (%)	Biowaste incinerated (%)	Biowaste composted (%)
Basic scenario	**37.4**	**21.3**	**41.3**

- *Results for EPS pck*

The extrapolation described in the methodology was carried out for the different countries (Table 28). Moreover, the weight of the countries was considered in order to calculate the final end of life scenario of household EPS pck in the different regions.

The results of the end of waste scenario of household EPS pck in the different regions were compiled in Table 29.

Table 28 End of waste scenario of household EPS pck in each country

Region	Countries considered	EPS pck recycling (%)	EPS pck landfilled (%)	EPS pck incinerated (%)
Region 1. Scandinavia + Baltic countries	Norway	0.0	22.1	77.9
	Sweden	0.0	37.3	62.7
	Finland	0.0	69.8	30.2
	Estonia	0.0	99.8	0.2
	Latvia	0.0	100.0	0.0
	Lithuania	0.0	100.0	0.0
	TOTAL	0.0	58.5	41.5
Region 2. West Europe	Ireland	0.0	100.0	0.0
	UK	0.0	88.4	11.6
	France	2.5	57.6	39.9
	Spain	0.0	80.7	19.3
	Portugal	0.0	91.4	8.6
	Italy	1.0	57.2	41.8
	Netherlands	0.0	11.5	88.5
	Belgium	0.0	22.9	77.1
	Luxemburg	0.0	16.2	83.8
	Iceland	0.0	59.4	40.6
	Malta	0.0	59.4	40.6
	Greece	0.0	100.0	0.0
	Cyprus	0.0	100.0	0.0
	TOTAL	0.8	67.4	31.8
Region 3. Central Europe	Germany	2.3	8.0	89.7
	Poland	0.0	74.4	25.6
	Czech Republic	0.0	78.2	21.8
	Slovakia	0.0	94.3	5.7
	Hungary	0.0	67.8	32.2
	Denmark	0.0	3.0	97.0
	Austria	0.0	7.0	93.0
	TOTAL	1.2	34.8	64.0
Region 4. East Europe	Albania	0.0	59.4	40.6
	Armenia	0.0	59.4	40.6
	Azerbaijan	0.0	59.4	40.6
	Belarus	0.0	59.4	40.6
	Bosnia and Herzegovina	0.0	59.4	40.6
	Bulgaria	0.0	100.0	0.0
	Croatia	0.0	59.4	40.6
	Kosovo	0.0	59.4	40.6
	Georgia	0.0	59.4	40.6
	Republic of Macedonia	0.0	59.4	40.6
	Moldova	0.0	59.4	40.6
	Montenegro	0.0	59.4	40.6
	Romania	0.0	93.0	7.0
	Russia	0.0	59.4	40.6
	Serbia	0.0	59.4	40.6
	Slovenia	0.0	59.4	40.6
	Ukraine	0.0	59.4	40.6
	TOTAL	0.0	63.3	36.7
Region 5. Extra Europe	EEUU	0.0	59.4	40.6
	China	0.0	59.4	40.6
	India	0.0	59.4	40.6
	Japan	0.0	59.4	40.6
	Australia	0.0	59.4	40.6
	Brazil	0.0	59.4	40.6
	Mexico	0.0	59.4	40.6
	TOTAL	0.0	59.4	40.6

To notice the low recycling rate for EPS pck (figures in bold).

Table 29 End of waste scenario of the household EPS pck in each region.

Region	EPS pck recycling (%)	EPS pck landfilled (%)	EPS incinerated pck (%)
Region 1. Scandinavia + Baltic countries	0.0	58.5	41.5
Region 2. West Europe	0.8	67.4	31.8
Region 3. Central Europe	1.2	34.8	64.0
Region 4. East Europe	0.0	63.3	36.7
Region 5. Extra Europe	0.0	59.4	40.6

The data of Table 29 were multiplied by the values of market share and reported in Table 30.

Table 30 End of waste scenario of the EPS material (basic scenario)

Scenario	EPS pck recycling (%)	EPS pck landfilled (%)	EPS pck incinerated (%)
Basic scenario	**0.5**	**52.1**	**47.4**

- *Sensitivity analysis for packaging disposal*

Beyond the basic scenarios (i.e. the real ones) three further different disposal scenarios were investigated: two "improved" scenarios for EPS pck, where the recycling rate was assumed respectively to be 30% and 50%, and, an "improved" scenario for prototype pck where the biological recycling was set equal to 50%. The remaining streams to incineration and landfill were recalculated maintaining the same proportions.

Table 31 and Table 32 summarized the improved scenarios for EPS pck and prototype one investigated within the sensitivity analysis

Table 31 Improved scenario for EPS pck

Scenario	EPS pck recycling (%)	EPS pck landfilled (%)	EPS pck incinerated (%)
Improved scenario 1	30	36.7	33.3
Improved scenario 2	50	26.2	23.8

Table 32 Improved scenario for prototype pck

Scenario	Biowaste composted (%)	Biowaste incinerated (%)	Biowaste landfilled (%)
Improved scenario	50	18	32

- *Hypothesis and assumption*

Emissions related to the pck systems disposal depend both on the type of treatment technology considered and the physical-chemical characteristics of disposed material like chemical composition, biodegradation in landfill etc. Table 33 reports the characteristics of EPS and prototype materials.

Table 33 Material characteristics

	Unit	Prototype	EPS
Combustion characteristics			
LHV	MJ/kg	17.3	37.3
HHV	MJ/kg	18.6	38.8
Mineralization			
In composting	%	75	Not applicable
In landfill	%	1	1
In incineration	%	100	100
Chemical composition			
Water	%	3	0.2
C-biogenic	%	37.4	---
C-fossil	%	7.11	86.3
Oxigen (without H_2O)	%	45.6	3.86
Hydrogen (without H_2O)	%	6.38	7.76
Chlorine	%	---	0.11
Nitrogen	%	0.017	0.19
Phosphor	%	0.04	---
Bromium	%	---	0.67
Vanadium	%	---	0.028
Zinc	%	---	0.08
Iron	%	---	0.36
Silicon	%	0.094	---
Potassium	%	0.29	---
Magnesium	%	0.06	---
Aluminium	%	---	0.02
Sodium	%	---	0.14
Other elements	%	---	0.282
Total	%	100	100

EPS composition was derived from Ecoinvent 2.2 database whereas for the prototype it was worked out starting from the empirical formula of the raw materials contained in 1 kg of the material itself.

- *Incineration (EPS pck and prototype pck)*

Inventory data for incineration have been calculated using the spreadsheet "Calculation tool for waste disposal in Municipal Solid Waste Incinerator" for Ecoinvent v. 2.1. (2008).

In this study, specific technology encountered in Switzerland in 2000 was considered whose main characteristics are listed below:

- Swiss MSWI plants in 2000 with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% SNCR, 32.2% SCR-high dust, 24.6% SCR-low dust -DeNOx facilities and 13.8% without DeNOx (by burnt waste, according to Swiss average).
- Share of waste incinerated in plants with magnetic scrap separation from slag: 50%.
- Transfer coefficients for modern Swiss MSWI
- Gross electric and thermal efficiencies for municipal waste incineration are 13% and 25.6% respectively.

Electricity and heat produced by the incinerator were calculated considering the Lower Heating Value (LHV) of the incinerated materials. It was calculated using the following empiric formula, based on material's elementary composition:

$$LHV\ [MJ/kg] = HHV - H_20*2.2 - H*2.2*9$$

Where:

$$HHV = -O*9.83 + H*124.27 + C*34.02 + S*19.07 + N*6.28$$

Legend:

HHV = Higher Heating Value

O = oxigen (kg/kg of material)

H = idrogen (kg/kg of material)

C = carbon (kg/kg of material)

N = nitrogen (kg/kg of material)

Electricity and heat produced by the incineration were supposed to replace respectively the European medium voltage electricity mix and heat produced staring from natural gas and heavy fuel oil.

- *Material recycling (EPS pck)*

Recycling is the collection, separation, clean up and processing of waste materials to produce a marketable material or product. It is a matter of fact that the success of recycling is limited by the development of successful strategies for collection and separation. According to Roberts [38] EPS pck is recycled through three different processes: regrind, production of EPS granules by extrusion and plastic mix.

- *Regrind of EPS pck*

Regrind is the more extended mechanical recycling process of EPS pck. Specifically, 28.1% of the EPS pck waste generated in Europe is managed trough this typology of mechanical recycling [38].

Figure 17 Regrind of EPS pck. Source: EnStyro Styrofoam Recycling, 2011 [39]

The energy consumption of the regrind process of EPS pck was available in some commercial LCA databases. According Ecoinvent database, the process "Recycling PS/RER U", which grinds EPS pck for being used instead of virgin bead, presented an energy consumption of 2160 MJ per ton of grinded EPS pck.

According to the database BUWAL 250, in "Recycling PS B250" the energy required for recycling 0.9 kg of EPS pck was 3.78 kWh including 3.5 kWh in order to extrude, purify and granulate the polymer, however, this source resulted quite outdated.

According to Eumeps [37], the process "Material recycling of EPS", which includes the shredding of the material in order to replace virgin pre-expanded PS, presented an energy consumption of 144 kWh (508 MJ). This value was obtained as an average of surveys to 9 European companies.

Reground EPS pck can be used in different applications as new remoulded packaging or building blocks, sheets or pieces.

- *Extrusion of EPS pck*

EPS pck waste can be extruded into granules which can be subsequently remoulded in new products. Currently, 11.1% of the EPS pck waste generated in Europe is managed through this typology of mechanical recycling [38]. No representative inventory data were found out in databases about energy consumptions.

Extruded EPS pck can be re-used in different applications like to make CD cases, plant pots, office items, etc.

- *Extrusion of EPS mixed with other plastic wastes*

After the separation of the recyclables and compostable waste included in the fraction of MSW it remains a fraction of mixed plastics which includes EPS pck. This fraction can be extruded into granules which can be remoulded afterwards to be used in different applications. This recovery option has not significant relevance to the management of EPS pck waste in Europe (2.6%). Mixed plastic, including EPS pck can be extruded into granules and used in several applications including park benches, fence posts and road signs.

In this study it was assumed that the recycling of 1 kg of collected EPS pck replaced 0.9 kg of virgin EPS pck granule produced in EU. The residual difference (10%) was considered to be incinerated in the MSWI. The specific electricity consumption was assumed equal to 0.5 MJ/kg EPS pck according to Eumeps study. No further inventory data like direct emissions, other utilities consumptions related to the recycling process were accounted for since not available (Table 40).

- *Landfill (EPS pck and prototype pck)*

Environmental impacts of landfill were calculated using spreadsheet "Calculation tool for waste disposal in Municipal Sanitary Waste Landfill" for Ecoinvent v. 2.1. (2008). The mineralization in landfill for prototype material has been considered to be 1% within a time frame of 100 years (Table 33).

In this study the specific technology considered for landfill was that encountered in Switzerland in 2000 whose main characteristics are listed below:

- Landfill includes base seal, leachate collection system, treatment of leachate in municipal wastewater treatment plant
- Composition of biogas from degradable carbon: 56% C-CH_4 and 44% C-CO_2.
- The rate of gas emitted into atmosphere is 53%
- The landfill gas collection rate is 47%, of which 66% is recovered for energy, while the rest (34%) is flared.

- *Composting (prototype pck)*

The bio-waste (average water content 50% by weight) is normally shredded, mixed and placed into windrows along a non permeable surface. In order to ensure aerobic conditions, regulate temperature and moisture, the windrows are tuned several times during the composting process, which takes on average 4 months [40]. Finally the compost is screened to remove contaminants (such as plastics and metals) and oversized materials which can be reprocessed until their complete degradation. The level of biodegradation achieved during composting is also very much determined by the particle size of product. In laboratory testing, biodegradation is tested on samples after milling in order to reach high levels of biodegradation as fast as possible. This means that in reality, biodegradation levels reached at the end of composting cycle will be lower. In this study the mineralization of prototype pck has been considered to be 75%. The 75% of the carbon present in initial waste is emitted into air, mainly as carbon dioxide (74.9%) and methane (0.1%) [41]. The remaining part is transformed into compost, a humified organic substrate.

In reference to this technology, a closed system with collection and treatment of process air, turning the ground during the intensive phase, forced ventilation and recycling of leachate was considered.

The methodological approach applied for composting treatment and compost utilization is described in the following paragraph.

- *Methodological approach for composting and compost utilization ("combined perspective")*

Biologic recycling (i.e. composting) for prototype pck was dealt with considering that the compost obtained from prototype material had the average characteristics of compost obtained from bio-waste (Table 34). Such a choice was done simply because composting process is the result of the treatment of different compostable materials in input (i.e. bio-waste), whereas compostable materials, treated individually (e.g. banana peel), in a composting industrial plant do not allow to get compost. However, if on one hand average compost characteristics were assumed (e.g. nutrient content humic carbon etc.) and related benefits associated to its utilization, on the other hand average emissions from compost process were accounted for prototype pck. It meant, for example, that emissions to air like N_2O, NH_3 during the composting process were allocated to prototype material as well. To notice that such emissions from prototype material would be in the reality negligible since the nitrogen content in the prototype material is negligible (~0.01%).

The average inventory data for composting process were derived from Ecoinvent 2.2 dataset ("Compost, at plant CH/U"). However, as the prototype material (may) contain both biogenic and fossil carbon (Table 33), it was decided to consider only for CO_2 and CH_4, the individual material-specific emissions. From here the name "Combined perspective". This choice ("combined perspective") was dictated by the fact that these emissions affected the prototype carbon footprint (i.e. GWP) and biogenic carbon balance therefore they were accounted reflecting as more as possible the reality.

Table 34 Average compost characteristics (different sources)

Characteristics				
Parameter	**Unit**	**Range**	**Representative value (used criteria)**	**Reference**
Dry Matter (DM)	% on wet compost	28% - 73%	**60%** (most representative - fixed)	[42][43][44][45][46]
Organic carbon (OC)	% on DM	19% - 47%	**25%** (preventive assumption)	[42][47][45]
Humus factor (Humus –C)	% on OC	51%	**51%** (literature)	[41]
N	% on DM	0.9% - 2.8%	**1.8%** (average MIN/MAX)	[42][47][43][44][45][46]
P (as P_2O_5)	% on DM	0.4% - 2.1%	**1.3%** (average MIN/MAX)	[42][47][43][44][45][46]
K (as K_2O)	% on DM	0.4% - 3.0%	**1.7%** (average MIN/MAX)	[42][47][43][44][45][46]
Ca (as CaO)	% on DM	3.4% - 11.8%	**7.6%** (average MIN/MAX)	[42][43]
Mg (as MgO)	% on DM	0.6% - 1.7%	**1.2%** (average MIN/MAX)	[42][43]

The average yield for composting process was about 40%, therefore 0.4 kg of compost (moisture 40%) were obtained for each kg of prototype pck in input.

High quality compost can be used in horticultural sector in substitution of peat, or in agricultural sector, thus reducing fertilizers utilization by farmers. Nevertheless, it is worth to point out that there are other many benefits (i.e. increase biodiversity, protection to erosion etc.) which are currently not properly accounted within LCA framework due to the limits of the methodology itself. A brief description of the environmental benefits that were considered for compost utilization was reported in the paragraphs below.

Compost use in growing media: peat replacement

The equivalence between compost and peat has been made on the basis of the carbon present in the two matrices that contributed to the formation of humus. On the basis of the average characteristics of compost (see Table 34) and peat (Table 35), 1 kg of compost replaced about 1 kg of peat.

Table 35 Average characteristics of peat

Peat characteristics	Unit	Selected Value	Source
Dry Matter (DM)	% on FM	70%	[41]
Carbon (C)	% on DM	53%	[41]
Humus factor	% on C	21%	[41]

The avoided impacts considered for the scenario where compost replaced peat are summarized in Table 36.

Table 36 Inventory data of peat use

Benefits	Unit	Selected value (used criteria)		Source
Peat excavation	kg/kg wet compost(d)	1	(average)	[47][48][49]
Peat transport	km	2000	(assumption)	[48]
Peat use (mineralization of fossil-C)	kg fossil CO_2 /kg	1.36	(based on C content in 0.82 kg peat, 100% mineralization in 100 y)	[41]

Average data for peat excavation ("peat at mine/NORDEL) came from Ecoinvent 2.2 database and they reported only diesel consumed by the excavation machineries. No greenhouse gas emissions coming from land use change (LUC) were accounted for.

Compost use: agriculture sector

The compost is suitable to be use also in agriculture to reduce fertilizer use and improve soil quality. On average about 16 t/ha*year of high quality compost can be applied to agricultural soils. Crops as grain, maize, barley, sunflower, potatoes can safely cultivated by applying compost. Compost benefits accounted in the LCA model were summarized in Table 37.

Table 37 Inventory data for compost use in agriculture

Compost used on land (Unit/t wet compost)								
Benefits			Unit	Range		Selected value (used criteria)		Reference
Nutrients supply	N	Supply	kg/t wet compost [(d)]	5.2	16.8	11	(e)	
	P_2O_5	Supply	kg/t wet compost [(d)]	2.3	12.8	7.6	(e)	
	K_2O	Supply	kg/t wet compost [(d)]	2.46	18.2	10.4	(e)	
	CaO	Supply	kg/t wet compost [(d)]	20.3	70.7	45.5	(e)	
	MgO	Supply	kg/t wet compost [(d)]	3.6	10.3	6.95	(e)	
C-bio not-degrade after 100 years (C-sink)			% on total OC			10%	(assumption)	[47] [50]
N_2O emissions reduction			g/t wet compost	-20	-201	-110	(average MIN/MAX)	[47]

(d) Compost as such: 40% water content; (e) in agreement with average characteristics reported in Table 34

The N_2O emission reduction depends from the substitution of mineral nitrogen with organic nitrogen (compost) that has a slower release [47].

The environmental impacts associated to the production of various chemical fertilizers can vary greatly (Ecoinvent database). For this reason, the scenario of replacement of fertilizers was defined on the basis of the quantities consumed on average in Europe [51] [52] [53], except for phosphate fertilizers for which an equal mix of all fertilizers available in the database was assumed. Table 38 summarizes the mix for chemical fertilizers. All data relating to the impacts "cradle to gate" of the fertilizer came from the Ecoinvent 2.2 database.

Table 38 Replacement scenarios for N, P and K fertilizers.

Nitrogenous fertilizers		
Dataset used	**Market share [%]**	**N content [%]**
Urea, as N, at regional storehouse/RER	30.3	46
Ammonium nitrate, as N, at regional storehouse/RER	26.8	33
Calcium ammonium nitrate, as N, at regional storehouse/RER	32.6	27
Ammonium sulphate, as N, at regional storehouse/RER	10.3	21
Total	100%	
Phosphoric fertilizers (P_2O_5)		
Dataset used	**Market share – assumption [%]**	**P_2O_5 content [%]**
Ammonium nitrate phosphate, as P_2O_5, at regional storehouse/RER	20%	52%
Diammonium phosphate, as P_2O_5, at regional storehouse/RER	20%	46%
Monoammonium phosphate, as P_2O_5, at regional storehouse/RER	20%	52%
Single superphosphate, as P_2O_5, at regional storehouse/RER	20%	20%
Triple superphosphate, as P_2O_5, at regional storehouse/RER S	20%	46%
Total	100%	-
Potassic fertilizers (K_2O)		
Dataset used	**Market share [%]**	**K_2O content [%]**
Potassium Chloride, as K_2O, at regional storehouse/RER	95%	60%
Potassium Nitrate, as K_2O, at regional storehouse/RER	5%	46%
Total	100%	-

The emissions of fossil CO_2 were considered for the nitrogenous fertilizer (urea) and these were about 0.8 kg CO_2 eq./kg of N [41].

- *Inventory of end-of-life treatments*

Table 39 reports the inventory data for prototype pck disposal (basic scenario).

Table 39 Inventory data for prototype pck disposal (basic scenario).

Resources/Processes	U.M.	Composting (41.3%)	Incineration (21.3%)	Landfill (37.4%)
Prototype pck (F.U. = 2.4 kg)	kg	**0.991**	**0.511**	**0.898**
Materials/fuels				
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	kg		$7.31x10^{-7}$	$5,89x10^{-10}$
Quicklime, milled, packed, at plant/CH U	kg		$1.30x10^{-7}$	$1,07x10^{-10}$
Hydrochloric acid, 30% in H2O, at plant/RER U	kg		$4.63x10^{-7}$	$1,19x10^{-11}$
Chemicals inorganic, at plant/GLO U	kg		$7.72x10^{-7}$	$1,99x10^{-11}$
Cement, unspecified, at plant/CH U	kg		$6.21x10^{-4}$	$1,40x10^{-7}$
Transport, freight, rail/RER U	tkm		$7.51x10^{-5}$	$1,54x10^{-6}$
Transport, lorry 20-28t, fleet average/CH U	tkm		$2.84x10^{-4}$	$2,55x10^{-6}$
Ammonia, liquid, at regional storehouse/CH U	kg		$4.44x10^{-6}$	$5,42x10^{-9}$
Natural gas, burned in industrial furnace low-NOx >100kW/RER U	MJ		$4.32x10^{-4}$	$5,29x10^{-7}$
Titanium dioxide, production mix, at plant/RER U	kg		$1.27x10^{-7}$	$1,55x10^{-10}$
Chromium oxide, flakes, at plant/RER U	kg		$2.59x10^{-9}$	$3,17x10^{-12}$
Iron (III) chloride, 40% in H2O, at plant/CH U	kg			$1,30x10^{-6}$
Aluminium sulphate, powder, at plant/RER U	kg			$2,58x10^{-7}$
Iron sulphate, at plant/RER U	kg			$9,52x10^{-7}$
Electricity, low voltage, at grid/CH U	kWh			0.00015
Light fuel oil, burned in boiler 100kW, non-modulating/CH U	MJ			$3,14x10^{-5}$
Natural gas, burned in boiler modulating >100kW/RER U	MJ			$4,25x10^{-5}$
Electricity/heat				
Municipal waste incineration plant/CH/I U	p		$1.28x10^{-10}$	$1.72x10^{-14}$
Slag compartment/CH/I U	p		$8.43x10^{-12}$	$4.94x10^{-15}$
Residual material landfill facility/CH/I U	p		$3.23x10^{-12}$	$7.28x10^{-16}$
Electricity from waste, at municipal waste incineration plant/CH U	kWh			$9.97x10^{-6}$
Heat from waste, at municipal waste incineration plant/CH U	MJ			$5.79x10^{-5}$
Sewer grid, class 3/CH/I U	km			$4.89x10^{-10}$
Wastewater treatment plant, class 3/CH/I U	p			$1.28x10^{-11}$
Sanitary landfill facility/CH/I U	p			$4.99x10^{-10}$
Diesel, at regional storage/CH U	Kg	$1.39x10^{-3}$		
Electricity, low voltage, production UCTE, at grid/UCTE U	kWh	$6.14x10^{-3}$		
Compost plant, open/CH/I U	p	$2.97x10^{-9}$		
Emissions to air				
NMVOC, non-methane volatile organic compounds, unspecified origin	kg			$2.97x10^{-9}$
Carbon monoxide, biogenic	kg		$9.57x10^{-5}$	$1.80x10^{-7}$
Carbon monoxide, fossil	kg	$6.64x10^{-5}$	$1.82x10^{-5}$	$3.44x10^{-8}$
Carbon dioxide, biogenic	kg		$6.93x10^{-1}$	$2.81x10^{-4}$
Carbon dioxide, fossil	kg		$1.32x10^{-1}$	$5,35x10^{-5}$
Carbon dioxide, biogenic (from composting process)	kg	1.02		
Carbon dioxide, fossil (from composting process)	kg	$1.93x10^{-1}$		
Carbon dioxide, biogenic (compost use peat replacement)	kg	$1.13x10^{-1}$		
Carbon dioxide, fossil (compost use peat replacement)	kg	$2.15x10^{-2}$		
Carbon dioxide, biogenic (compost use agriculture sector)	kg	$2.03x10^{-1}$		
Carbon dioxide, fossil (compost use agriculture sector)	kg	$3.86x10^{-2}$		
Carbon dioxide (C-Sink)	kg	$-2.30x10^{-2}$		-1.22
Methane, biogenic (high. pop.)	kg	$3.96x10^{-4}$	$2.74 x10^{-6}$	$5.50x10^{-7}$
Methane, fossil (high. pop.)	kg		$5.22x10^{-7}$	$1.05x10^{-7}$
Nitrogen oxides (high. pop.)	kg	$2.38x10^{-4}$	$2.80x10^{-6}$	$3.37x10^{-8}$
Ammonia (high. pop.)	kg	$4.96x10^{-4}$	$6.96x10^{-8}$	$3.44x10^{-9}$
Dinitrogen monoxide (high. Pop.)	kg	$1.49x10^{-4}$	$3.71x10^{-7}$	$9.52x10^{-9}$
Hydrogen sulfide (high. pop.)	kg	$2.77x10^{-4}$		

Cyanide (high. Pop.)	kg		$7.91x10^{-8}$	$9.70x10^{-11}$
Phosphorus (high. Pop.)	kg		$2.04x10^{-7}$	$1.28x10^{-10}$
Silicon (high. pop.)	kg		$1.12x10^{-6}$	$9.25x10^{-10}$
Potassium (high. pop.)	kg		$4.47 x10^{-6}$	
Magnesium (high. Pop.)	kg		$4.25x10^{-7}$	$4.52x10^{-10}$
Heat, waste (high. Pop.)	MJ	3.44	1.29	$1.30x10^{-3}$
Iron (high. pop.)	kg			$2.67x10^{-11}$
Aluminium (high. Pop.)	kg			$6.35x10^{-11}$
Carbon dioxide, biogenic (high. pop.)	kg			$8.41x10^{-3}$
Carbon dioxide, fossil (high. pop.)	kg			$1.60x10^{-3}$
Carbon monoxide, biogenic (high. pop.)	kg			$4.77x10^{-7}$
Carbon monoxide, fossil (high. pop.)	kg			$9.07x10^{-8}$
Methane, biogenic (high. pop.)	kg			$1.29x10^{-3}$
Methane, fossil (high. pop.)	kg			$2.46x10^{-4}$
NMVOC, non-methane volatile organic compounds, unspecified origin (high. pop.)	kg			$1.08x10^{-8}$
Particulates, < 2.5 um (high. Pop.)	kg			$1.90x10^{-7}$
Nitrogen oxides (high. pop.)	kg			$9.97x10^{-10}$
Silicon (high. pop.)	kg			$1.05x10^{-10}$
Potassium (high. pop.)	MJ			$4.76x10^{-9}$
Magnesium (high. Pop.)	kg			$8.37x10^{-10}$
Heat, waste	MJ			$5.45x10^{-2}$
Emissions to water				
Ammonium, ion (river)	kg			$1.87x10^{-6}$
Nitrite (river)	kg			$3.92x10^{-8}$
Nitrogen (river)	kg			$5.06x10^{-8}$
BOD5, (river)	kg		$8.52x10^{-6}$	$2.31x10^{-5}$
COD, (river)	kg		$1.52x10^{-5}$	$7.35x10^{-5}$
TOC, (river)	kg		$6.24x10^{-6}$	$1.86x10^{-5}$
DOC, (river)	kg		$6.24x10^{-6}$	$1.79x10^{-5}$
Sulfate (river)	kg			$8.19x10^{-7}$
Nitrate (river)	kg		$1.12x10^{-6}$	$6.81x10^{-6}$
Phosphate (river)	kg		$4.00x10^{-8}$	$2.16x10^{-7}$
Chloride (river)	kg			$8.54x10^{-7}$
Silicon (river)	kg		$1.02x10^{-7}$	$2.54x10^{-8}$
Iron, ion (river)	kg			$2.73x10^{-10}$
Aluminium (river)	kg			$3.39x10^{-12}$
Potassium, ion (river)	kg		$2.57x10^{-4}$	$1.90x10^{-5}$
Magnesium (river)	kg		$1.08x10^{-6}$	$3.02x10^{-6}$
BOD5,(groundwater, long-term)	kg		$1.84x10^{-3}$	0.0263
COD (groundwater, long-term)	kg		0.00562	0.111
TOC, Total Organic Carbon (groundwater, long-term)	kg		0.00222	0.102
DOC, Dissolved Organic Carbon (groundwater, long-term)	kg		0.00222	0.102
Ammonium, ion (groundwater, long-term)	kg			$6.14x10^{-5}$
Nitrogen, organic bound (groundwater, long-term)	kg			0.001
Nitrite (groundwater, long-term)	kg			$3.34x10^{-6}$
Nitrate (groundwater, long-term)	kg		$3.16x10^{-6}$	$6.47x10^{-6}$
Phosphate (groundwater, long-term)	kg		$2.39x10^{-5}$	$7.45x10^{-6}$
Silicon (groundwater, long-term)	kg		$4.17x10^{-5}$	$1.62x10^{-5}$
Iron, ion (groundwater, long-term)	kg			$3.74x10^{-7}$
Aluminium (groundwater, long-term)	kg			$3.01x10^{-8}$
Potassium, ion (groundwater, long-term)	kg		0.00122	0.00259
Magnesium (groundwater, long-term)	kg		$2.85x10^{-4}$	$5.39x10^{-4}$
Heat, waste (river)	MJ		1.29	0.00213
Heat, waste (groundwater, long-term)	MJ			16.5

Emission to soil				
Heat, waste (industrial)	MJ			0.0782
Waste to treatment				
Process-specific burdens, municipal waste incineration/CH U	kg		0.511	$6.91x10^{-5}$
Process-specific burdens, slag compartment/CH U	kg		0.00474	$2.77x10^{-6}$
Process-specific burdens, residual material landfill/CH U	kg		0.00155	$3.49x10^{-7}$
Disposal, cement, hydrated, 0% water, to residual material landfill/CH U	kg		0.00155	$3.50x10^{-7}$
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH U	kg	$9.61x10^{-6}$		
Treatment, sewage, to wastewater treatment, class 2/CH U	m^3	$3.96x10^{-4}$		
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	kg			$3.48x10^{-5}$
Disposal, paper, 11.2% water, to municipal incineration/CH U	kg			$3.49x10^{-5}$
Process-specific burdens, sanitary landfill/CH U	kg			0.898
Avoided products				
Heat, unspecific, in chemical plant/RER U	MJ		2.434	
Electricity, medium volt<ge, production UCTE, at grid/UCTE U	MJ		1.236	
Compost 40% H_2O (peat replacement, 33%)	kg	0.132		
Compost 40% H_2O (agriculture use, 66%)	kg	0.265		

p= “part” of infrastructure needed to fulfil the treatment of the F.U.

Average emissions from industrial composting (“combined perspective”)

Material specific (“combined perspective”)

The biogenic carbon mass balance for prototype pck system is provided in Figure 18. Figures were related to the FU and they were extrapolated from Table 33. To notice that a C-sink effect occurred in compost utilization in agricultural sector and when the prototype pck is disposed in landfill [54].

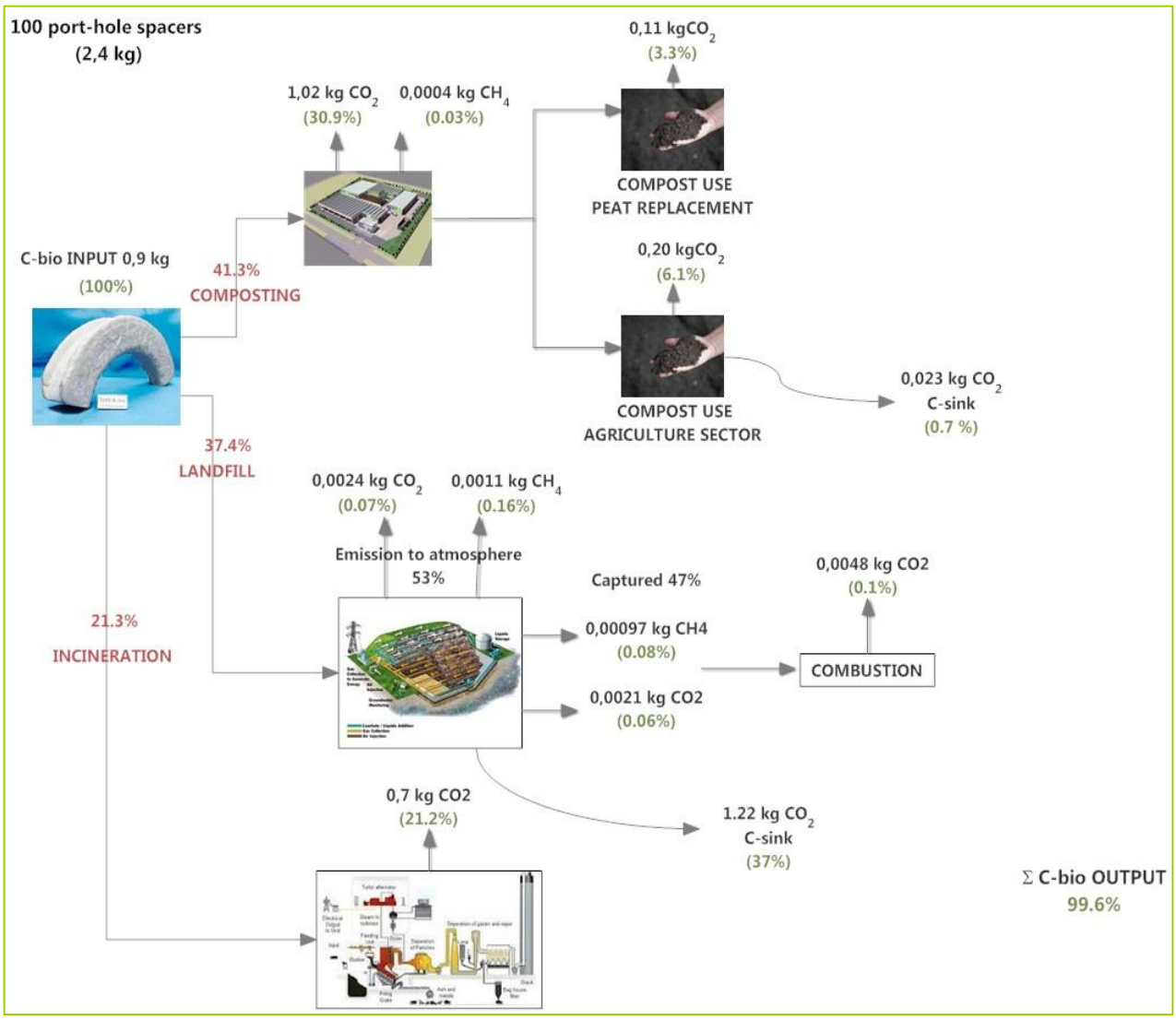


Figure 18 Biogenic carbon mass balance for prototype pck. Figures related to F.U. (2.4 kg)

Table 40 shows the inventory data for EPS pck disposal.

Table 40 Inventory of end of life EPS pck

Resources/Processes	U.M.	Recycling (0.5%)	Incineration (47.4%)	Landfill (52.1%)
EPS pck (F.U. = 1.2 kg)	kg	**0.006**	**0.569**	**0.625**
Materials/fuels				
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	kg		$7.74x10^{-4}$	$2.12x10^{-9}$
Quicklime, milled, packed, at plant/CH U	kg		$1.12x10^{-4}$	$3.84x10^{-10}$
Hydrochloric acid, 30% in H2O, at plant/RER U	kg		$1.52x10^{-6}$	$9.13x10^{-11}$
Chemicals organic, at plant/GLO U	kg		$5.38x10^{-5}$	$4.00x10^{-8}$
Chemicals inorganic, at plant/GLO U	kg		$2.54x10^{-6}$	$1.52x10^{-10}$
Cement, unspecified, at plant/CH U	kg		0.0016	$2.46x10^{-7}$
Transport, freight, rail/RER U	tkm		$2.16x10^{-3}$	$3.31x10^{-7}$
Transport, lorry 20-28t, fleet average/CH U	tkm		$7.85x10^{-4}$	$2.84x10^{-6}$
Ammonia, liquid, at regional storehouse/CH U	kg		$5.58x10^{-5}$	$4.26x10^{-8}$
Natural gas, burned in industrial furnace low-NOx >100kW/RER U	MJ		$5.44x10^{-3}$	$4.16x10^{-6}$
Titanium dioxide, production mix, at plant/RER U	kg		$1.60x10^{-6}$	$1.22x10^{-9}$
Chromium oxide, flakes, at plant/RER U	kg		$3.26x10^{-8}$	$2.49x10^{-11}$
Iron (III) chloride, 40% in H2O, at plant/CH U	kg		$6.03x10^{-5}$	$2.63x10^{-8}$
Electricity, low voltage, at grid/CH U	kWh			$2.81x10^{-4}$
Light fuel oil, burned in boiler 100kW, non-modulating/CH U	MJ			$2.38x10^{-5}$
Natural gas, burned in boiler modulating >100kW/RER U	MJ			$3.21x10^{-5}$
Electricity/heat				
Electricity, medium voltage, production UCTE, at grid/UCTE U	MJ	$3.05x10^{-3}$		
Municipal waste incineration plant/CH/I U	p		$1.42x10^{-10}$	$2.39x10^{-14}$
Slag compartment/CH/I U	p		$1.67x10^{-11}$	$4.43x10^{-15}$
Residual material landfill facility/CH/I U	p		$8.36x10^{-12}$	$1.28x10^{-15}$
Electricity from waste, at municipal waste incineration plant/CH U	kWh			$1.38x10^{-5}$
Heat from waste, at municipal waste incineration plant/CH U	MJ			$8.00x10^{-5}$
Sewer grid, class 3/CH/I U	km			$3.41x10^{-10}$
Wastewater treatment plant, class 3/CH/I U	p			$8.88x10^{-12}$
Sanitary landfill facility/CH/I U	p			$3.48x10^{-10}$
Emissions to air				
NMVOC, non-methane volatile organic compounds, unspecified origin	kg			$4.04x10^{-9}$
Carbon monoxide, fossil (high. pop.)	kg		$1.3x10^{-4}$	$2.92x10^{-7}$
Carbon dioxide, fossil (high. pop.)	kg		1.8	$4.54x10^{-4}$
Methane, fossil (high. pop.)	kg		$3.6x10^{-6}$	$8.88x10^{-7}$
Nitrogen oxides (high. pop.)	kg			$2.64x10^{-7}$
Ammonia (high. pop.)	kg			$2.71x10^{-8}$
Sulfur dioxide (high. pop.)	kg		$1.6x10^{-6}$	
Dinitrogen monoxide (high. Pop.)	kg		$4.7x10^{-6}$	$7.44x10^{-8}$
Cyanide (high. pop.)	kg		$1.0x10^{-6}$	$7.63x10^{-10}$
Hydrogen chloride (high. pop.)	kg		$7.2x10^{-9}$	
Bromine (high. pop.)	kg		$1.5x10^{-6}$	
Hydrogen fluoride (high. pop.)	kg		$4.3x10^{-9}$	

Arsenic (high. pop.)	kg		$1.1x10^{-14}$	$5.82x10^{-13}$
Barium (high. pop.)	kg		$1.0x10-^{7}$	$1.22x10^{-9}$
Cadmium (high. pop.)	kg		$7.3x10^{-10}$	$7.00x10-^{13}$
Cobalt (high. pop.)	kg		$5.5x10^{-13}$	$9.63x10^{-16}$
Chromium (high. pop.)	kg		$1.7x10^{-12}$	$1.03x10^{-16}$
Copper (high. pop.)	kg		$4.5x10^{-10}$	$1.80x10^{-14}$
Mercury (high. pop.)	kg		$1.6x10^{-14}$	$5.97x10-^{16}$
Manganese (high. Pop.)	kg		$2.4x10^{-13}$	$1.49x10^{-15}$
Nickel (high. pop.)	kg		$4.9x10^{-13}$	$1.23x10^{-16}$
Lead (high. Pop.)	kg		$3.2x10^{-10}$	$1.82x10^{-14}$
Antimony (high. pop.)	kg		$9.2x10^{-14}$	$1.35x10^{-12}$
Selenium (high. pop.)	kg		$5.8x10^{-15}$	$3.13x10^{-18}$
Tin (high. pop.)	kg		$1.9x10^{-8}$	$7.25x10^{-13}$
Vanadium (high. pop.)	kg		$1.6x10^{-8}$	$9.06x10^{-12}$
Zinc (high. pop.)	kg		$7.7x10^{-9}$	$2.79x10^{-12}$
Beryllium (high. pop.)	kg		$2.8x10^{-10}$	$8.69x10^{-14}$
Strontium (high. pop.)	kg		$4.9x10^{-9}$	$1.54x10^{-12}$
Titanium (high. pop.)	kg		$5.5x10^{-7}$	$1.49x10^{-10}$
Thallium (high. pop.)	kg		$2.2x10^{-10}$	$6.94x10^{-14}$
Iron (high. pop.)	kg		$6.9x10^{-8}$	$5.10x10^{-12}$
Aluminium (high. Pop.)	kg		$1.7x10^{-7}$	$8.88x10^{-11}$
Sodium (high. pop.)	kg		$7.6x10^{-6}$	
Heat, waste (high. Pop.)	MJ		17	$2.03x10^{-3}$
Carbon dioxide, fossil (low. Pop.)	kg			$1.36x10^{-2}$
Carbon monoxide, fossil (low. Pop.)	kg			$7.69x10^{-7}$
Methane, fossil (low. pop.)	kg			$2.08x10^{-3}$
NMVOC, non-methane volatile organic compounds, unspecified origin (high. pop.)	kg			$1.46x10^{-8}$
Particulates, < 2.5 um (low. Pop.)	kg			$2.59x10^{-7}$
Sulfur dioxide (low. Pop.)	kg			$5.54x10^{-7}$
Nitrogen oxides (low. pop.)	kg			$7.81x10^{-9}$
Hydrogen chloride (high. pop.)	kg			$2.57x10^{-7}$
Bromine (low. pop.)	kg			$1.94x10^{-7}$
Hydrogen fluoride (low. pop.)	kg			$3.55x10^{-8}$
Arsenic (low. pop.)	kg			$2.90x10^{-11}$
Barium (low. pop.)	kg			$3.24x10^{-10}$
Cadmium (low. pop.)	kg			$1.71x10^{-10}$
Cobalt (low. pop.)	kg			$1.54x10^{-11}$
Chromium (low. pop.)	kg			$7.06x10^{-13}$
Copper (low. pop.)	kg			$9.38x10^{-13}$
Mercury (low. pop.)	kg			$1.41x10^{-10}$
Manganese (low. pop.)	kg			$1.39x10^{-10}$
Nickel (low. Pop.)	kg			$1.81x10^{-12}$
Lead (low. pop.)	kg			$1.83x10^{-13}$
Antimony (low. pop.)	kg			$6.88x10^{-12}$
Selenium (low. pop.)	kg			$3.36x10^{-13}$
Tin (low. pop.)	kg			$2.34x10^{-13}$

Vanadium (low. pop.)	kg			$4.60x10^{-11}$
Zinc (low. pop.)	kg			$5.49x10^{-11}$
Beryllium (low. pop.)	kg			$4.40x10^{-14}$
Strontium (low. pop.)	kg			$7.81x10^{-12}$
Titanium (low. pop.)	kg			$7.56x10^{-11}$
Thallium (low. pop.)	kg			$3.53x10^{-14}$
Iron (low. pop.)	kg			$7.75x10^{-11}$
Aluminium (low. pop.)	kg			$1.51x10^{-11}$
Sodium (low. pop.)	kg			$9.19x10^{-9}$
Heat, waste (low. pop.)	MJ			$7.38x10^{-2}$
Emissions to water				
Ammonium, ion (river)	kg			$1.47x10^{-5}$
Nitrite (river)	kg			$3.09x10^{-7}$
Nitrogen (river)	kg			$3.98x10^{-7}$
BOD5, Biological Oxygen Demand (river)	kg		$1.85x10^{-5}$	$3.14x10^{-5}$
COD, Chemical Oxygen Demand (river)	kg		$3.30x10^{-5}$	$1.00x10^{-4}$
TOC, Total Organic Carbon (river)	kg		$1.35x10^{-5}$	$2.53x10^{-5}$
DOC, Dissolved Organic Carbon (river)	kg		$1.35x10^{-5}$	$2.42x10^{-5}$
Sulfate (river)	kg		$1.88x10^{-4}$	$4.83x10^{-6}$
Nitrate (river)	kg		$1.41x10^{-5}$	$5.35x10^{-5}$
Chloride (river)	kg		$6.32x10^{-4}$	$1.78x10^{-5}$
Bromine (river)	kg		$4.14x10^{-4}$	$1.39x10^{-5}$
Fluoride (river)	kg		$6.26x10^{-7}$	$6.56x10^{-9}$
Arsenic, ion (river)	kg		$4.72x10^{-7}$	$1.83x10^{-9}$
Barium (river)	kg		$1.42x10^{-8}$	$7.75x10^{-8}$
Cadmium, ion (river)	kg		$6.03x10^{-9}$	$1.30x10^{-8}$
Cobalt (river)	kg		$2.98x10^{-9}$	$3.13x10^{-8}$
Chromium VI (river)	kg		$7.34x10^{-7}$	$1.48x10^{-9}$
Copper, ion (river)	kg		$2.49x10^{-9}$	$8.56x10^{-10}$
Mercury (river)	kg		$5.01x10^{-9}$	$1.11x10^{-10}$
Manganese (river)	kg		$2.46x10^{-9}$	$2.81x10^{-7}$
Nickel, ion (river)	kg		$7.11x10^{-9}$	$4.40x10^{-9}$
Lead (river)	kg		$2.37x10^{-10}$	$6.04x10^{-11}$
Antimony (river)	kg		$8.25x10^{-6}$	$1.86x10^{-8}$
Selenium (river)	kg		$3.77x10^{-7}$	$8.94x10^{-10}$
Tin, ion (river)	kg		$5.36x10^{-10}$	$3.91x10^{-10}$
Vanadium, ion (river)	kg		$1.07x10^{-7}$	$9.38x10^{-8}$
Zinc, ion (river)	kg		$8.71x10^{-8}$	$7.63x10^{-8}$
Beryllium (river)	kg		$1.71x10^{-10}$	$8.94x10^{-11}$
Strontium (river)	kg		$3.07x10^{-8}$	$1.58x10^{-8}$
Titanium, ion (river)	kg		$2.66x10^{-9}$	$1.54x10^{-7}$
Thallium (river)	kg		$1.35x10^{-10}$	$7.13x10^{-11}$
Iron, ion (river)	kg		$7.06x10^{-7}$	$1.58x10^{-7}$
Aluminium (river)	kg		$9.16x10^{-9}$	$3.64x10^{-9}$
Sodium, ion (river)	kg		$1.75x10^{-4}$	$3.68x10^{-5}$
Chromium, ion (river)	kg		$7.17x10^{-8}$	$4.43x10^{-12}$

BOD5, Biological Oxygen Demand (groundwater, long-term)	kg		$3.99x10^{-3}$	$3.57x10^{-2}$
COD, Chemical Oxygen Demand (groundwater, long-term)	kg		$1.22x10^{-2}$	$1.51x10^{-1}$
TOC, Total Organic Carbon (groundwater, long-term)	kg		$4.83x10^{-3}$	$1.38x10^{-1}$
DOC, Dissolved Organic Carbon (groundwater, long-term)	kg		$4.83x10^{-3}$	$1.38x10^{-1}$
Sulfate (groundwater, long-term)	kg		$9.67x10^{-4}$	$1.18x10^{-3}$
Hydrogen sulfide (groundwater, long-term)	kg			$3.08x10^{-5}$
Ammonium, ion (groundwater, long-term)	kg			$4.83x10^{-4}$
Nitrogen, organic bound (groundwater, long-term)	kg			$7.88x10^{-4}$
Nitrite (groundwater, long-term)	kg			$2.63x10^{-5}$
Nitrate (groundwater, long-term)	kg		$3.97x10^{-5}$	$5.08x10^{-5}$
Chloride (groundwater, long-term)	kg		$1.52x10^{-5}$	$6.88x10^{-4}$
Bromine (groundwater, long-term)	kg		$8.76x10^{-5}$	$5.38x10^{-4}$
Fluoride (groundwater, long-term)	kg		$7.23x10^{-6}$	$8.88x10^{-6}$
Arsenic, ion (groundwater, long-term)	kg		$5.75x10^{-7}$	$1.15x10^{-6}$
Barium (groundwater, long-term)	kg		$9.10x10^{-5}$	$1.13x10^{-4}$
Cadmium, ion (groundwater, long-term)	kg		$1.33x10^{-7}$	$1.46x10^{-5}$
Cobalt (groundwater, long-term)	kg		$1.52x10^{-5}$	$1.91x10^{-5}$
Chromium VI (groundwater, long-term)	kg		$2.38x10^{-6}$	$1.13x10^{-7}$
Copper, ion (groundwater, long-term)	kg		$4.94x10^{-5}$	$6.75x10^{-5}$
Mercury (groundwater, long-term)	kg		$2.44x10^{-8}$	$5.14x10^{-7}$
Manganese (groundwater, long-term)	kg		$3.80x10^{-5}$	$4.71x10^{-5}$
Nickel, ion (groundwater, long-term)	kg		$1.06x10^{-5}$	$1.25x10^{-5}$
Lead (groundwater, long-term)	kg		$6.03x10^{-7}$	$9.31x10^{-6}$
Antimony (groundwater, long-term)	kg		$1.51x10^{-5}$	$2.62x10^{-6}$
Selenium (groundwater, long-term)	kg		$7.80x10^{-7}$	$3.59x10^{-7}$
Tin, ion (groundwater, long-term)	kg		$7.28x10^{-6}$	$1.59x10^{-5}$
Vanadium, ion (groundwater, long-term)	kg		$2.73x10^{-5}$	$5.08x10^{-5}$
Zinc, ion (groundwater, long-term)	kg		$7.34x10^{-6}$	$4.31x10^{-4}$
Beryllium (groundwater, long-term)	kg		$2.22x10^{-7}$	$3.03x10^{-7}$
Strontium (groundwater, long-term)	kg		$4.88x10^{-5}$	$5.36x10^{-5}$
Titanium, ion (groundwater, long-term)	kg		$1.65x10^{-4}$	$6.06x10^{-4}$
Thallium (groundwater, long-term)	kg		$1.29x10^{-7}$	$2.43x10^{-7}$
Iron, ion (groundwater, long-term)	kg		$9.62x10^{-4}$	$1.58x10^{-4}$
Aluminium (groundwater, long-term)	kg		$8.14x10^{-5}$	$1.21x10^{-4}$
Sodium, ion (groundwater, long-term)	kg		$6.26x10^{-4}$	$8.50x10^{-4}$
Heat, waste (groundwater, long-term)	MJ		2.81	$2.89x10^{-3}$
Heat, waste (groundwater, long-term)	MJ			24.1
Emissions to soil				
Heat, waste)industrial	MJ			$1.23x10^{-1}$
Waste to treatment				
Process-specific burdens, municipal waste incineration/CH U	kg		$5.69x10^{-1}$	$9,56x10^{-5}$
Process-specific burdens, slag compartment/CH U	kg		$9.39x10^{-3}$	$2,49x10^{-6}$
Process-specific burdens, residual material landfill/CH U	kg		$4.01x10^{-3}$	$6,14x10^{-7}$
Disposal, cement, hydrated, 0% water, to residual material landfill/CH U	kg		$4.01x10^{-3}$	$6,14x10^{-7}$
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	kg			$2,43x10^{-5}$

Disposal, paper, 11.2% water, to municipal incineration/CH U	kg			$2{,}43x10^{-5}$
Process-specific burdens, sanitary landfill/CH U	kg			$6.25x10^{-1}$
Disposal, polystyrene, 0.2% water, to municipal incineration/CH U	kg	$6.00x10^{-4}$		
Avoided products				
EPS granule	kg	$5.40x10^{-3}$		
Heat, unspecific, in chemical plant/RER U	MJ		5.7	
Electricity, medium voltage, production UCTE, at grid/UCTE U	MJ		2.9	

* average emissions

p= “part” of infrastructure needed to fulfil the treatment of the F.U.

4 IMPACT ASSESSMENT AND INTERPRETATION

The impact indicators represent, as far as possible, environmental issues of concern to which Life Cycle Inventory (LCI) results may be assigned. These categories can provide indicators of potential impacts (i.e. emission or resources related categories) or directly the consumption of resources like non renewable resources, water etc. (i.e. inventory level categories). Potential impacts are typically characterized using the following equation:

Potential impact = inventory data x characterization factors

An example of "characterization" process is shown in Figure 19, where some characterization factors for Eco-Indicator 95 Method are shown.

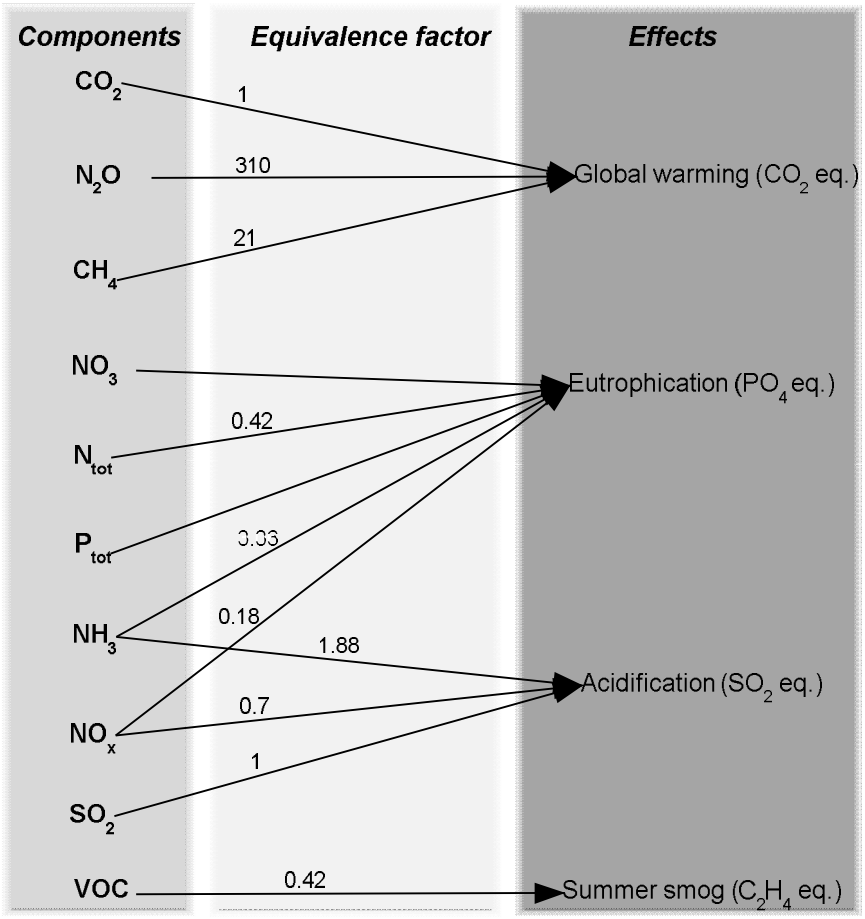


Figure 19 Example of characterization process of inventory data (adapted from Eco-Indicator 95 Method)

For example, all greenhouse gases shown in Figure 19 (i.e. CO_2, N_2O and CH_4) can be expressed in terms of CO_2 equivalents by multiplying the relevant LCI results by a CO_2 characterization factor and then combining the resulting impact indicators (or categories) to provide an overall indicator of global warming potential [55] The link between a substance and one or more impact categories depends on the knowledge of cause – environmental effect relation of the substance itself. A substance can contribute to more than one impact category like NH_3 which contributes for Eutrophication and Acidification.

The considered impact categories are shown in Table 41.

Table 41 Impact categories

Impact categories	Midpoint reference substance or indicator (unit)	Abbreviation
Inventory level categories		
Non renewable Energy Resource consumption	MJ eq.	NRER
Renewable Energy Resource consumption	MJ eq.	RER
Water consumption	m^3	WC
Land occupation	m^2/y	LO
Emission-related categories		
Global Warming Potential (100 years)	kg CO_2 eq.	GWP
Eutrophication	kg PO_4 eq.	EP
Acidification	kg SO_2 eq.	AP
Stratospheric Ozone Depletion	kg CFC-11 eq.	OD
Photochemical Ozone Formation	Kg C_2H_4 eq.	POF
Resource-related categories		
Depletion of abiotic resources	kg Sb eq.	AD

LCA results are presented in this section in graphical format as bar charts which are broken down to individual life cycle steps. These were:

- Granule production
- Granule expansion (packaging production)
- End of life (packaging disposal)
- Credits coming from energy (i.e. electricity & heat replacement) and material recovery (i.e. virgin EPS or peat/fertilizers replacement) according to system expansion.
- Net results

Each bar chart is followed by the contribution analysis results (i.e. pie charts). All presented results were related to the F.U. of the study (i.e. 100 port-hole spacers).

GLOBAL WARMING POTENTIAL

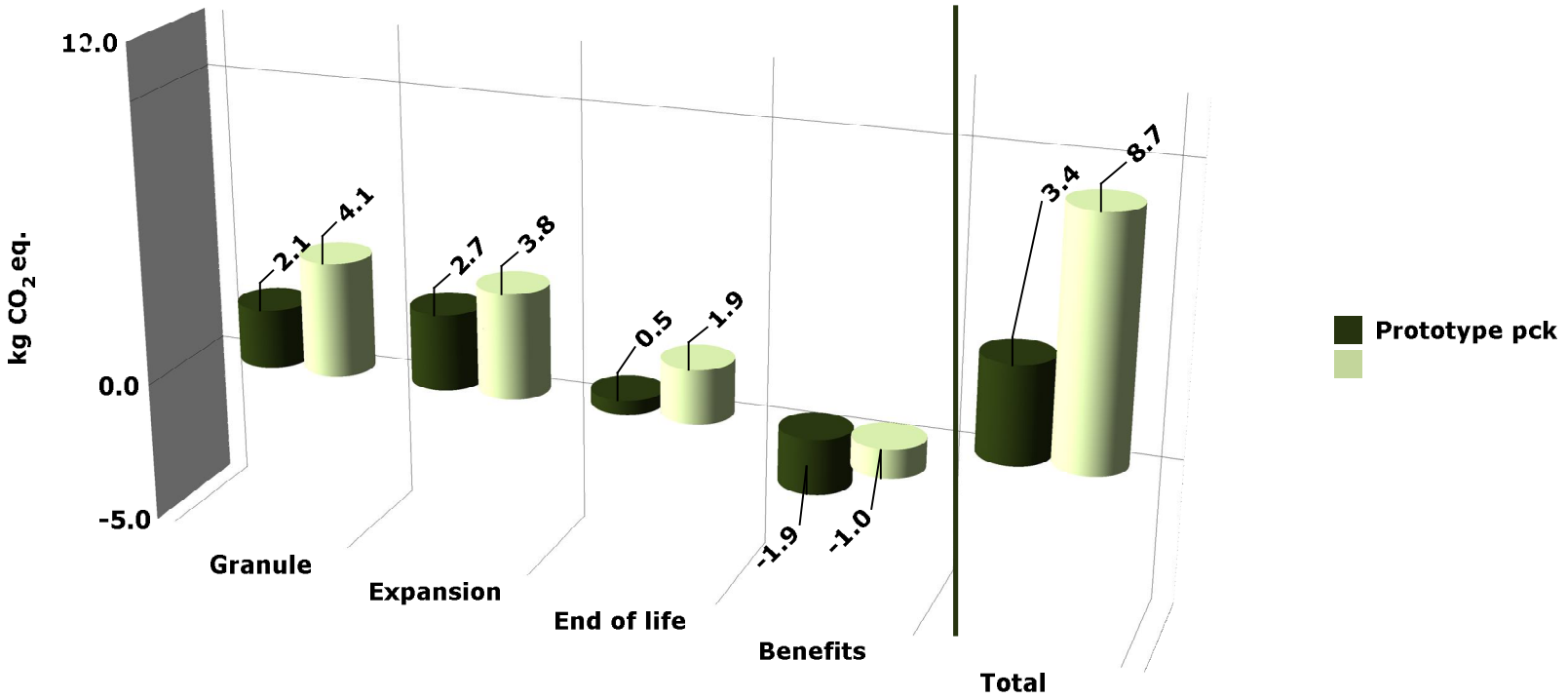
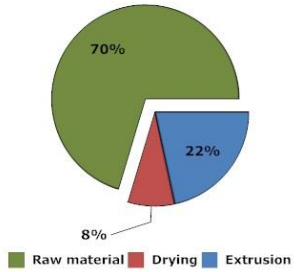
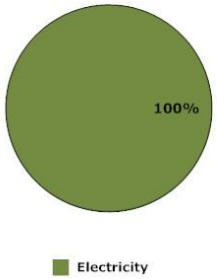
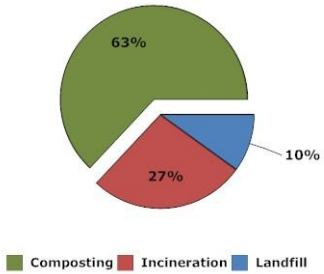
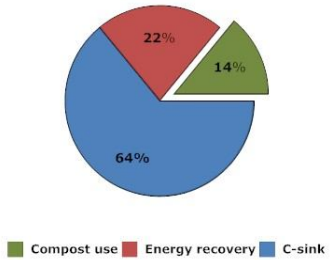
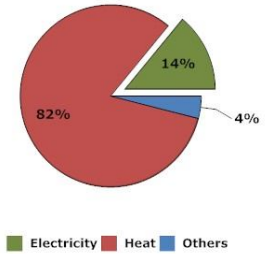
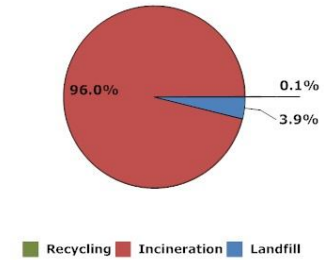
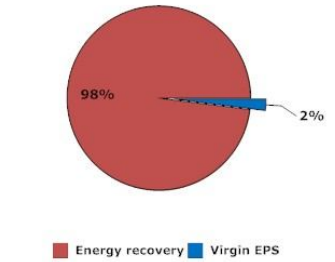


Figure 20 Global Warming Potential for EPS pck and prototype pck (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

As can be noticed the granule production and expansion steps represented the most relevant greenhouse gases (GHG) sources for both pck systems. For EPS pck also the End of life step was relevant due to EPS incineration (share 47%) that emits in the atmosphere fossil CO_2. This was clearly recognizable from the contribution analysis (Table 42). To notice that for the prototype pck the GHG emissions coming from expansion were those associated to the electricity consumption only, whereas, for EPS, the major contribution was related to the heat production rather than electricity. For EPS pck heat is required for producing steam, which in turn is used in the expansion process.

Table 42 Contribution Analysis for Global Warming Potential

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

The GHG emissions for the prototype granule were mainly due to raw material production (i.e.70%). Such emissions took into account also the N_2O, fossil CO_2 emissions coming from agricultural practices like tapioca cultivation.

NON RENEWABLE ENERGY RESOURCE CONSUMPTION

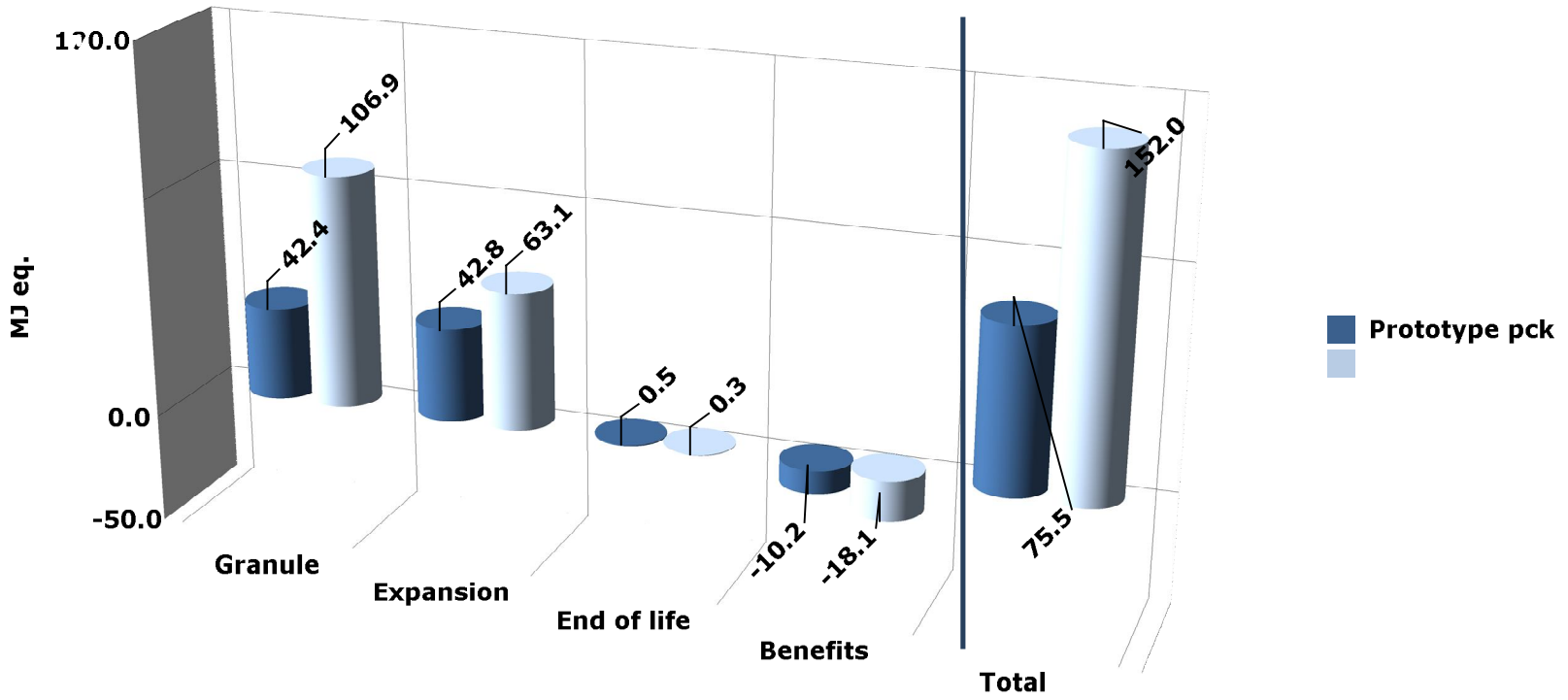
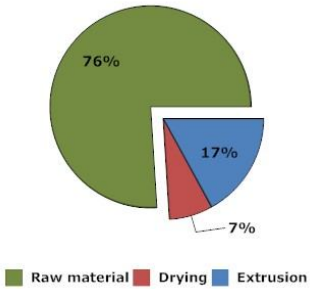
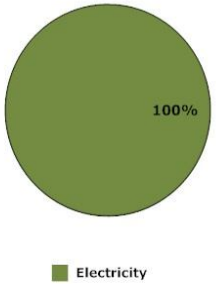
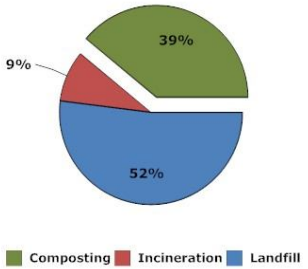
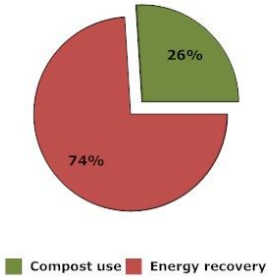
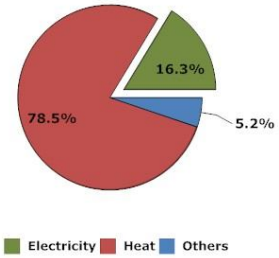
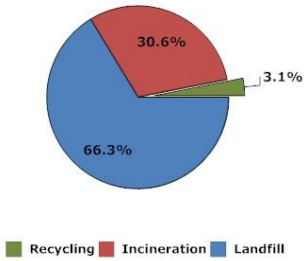
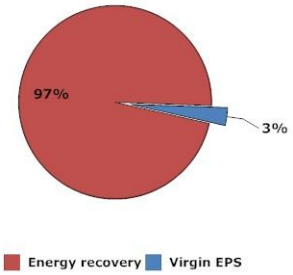


Figure 21 Non Renewable Energy Resource Consumption for EPS pck and prototype pck (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

Again the granule production and expansion steps dominated the overall results for both pck systems. In particular EPS granule production was characterized by a high consumption due to the use of a non renewable feedstock (i.e. oil and natural gas) for its production. For the expansion process the contribution was mainly due to the fact that Italian (for the prototype) and European (for EPS) electricity mixes and fuels used for producing steam were based totally or on a large extend on fossil resources.

Table 43 Contribution Analysis for Non Renewable Energy Resource Consumption

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

For the prototype granule production the main cause of non renewable resources consumption was the production of the polymer.

RENEWABLE ENERGY RESOURCE CONSUMPTION

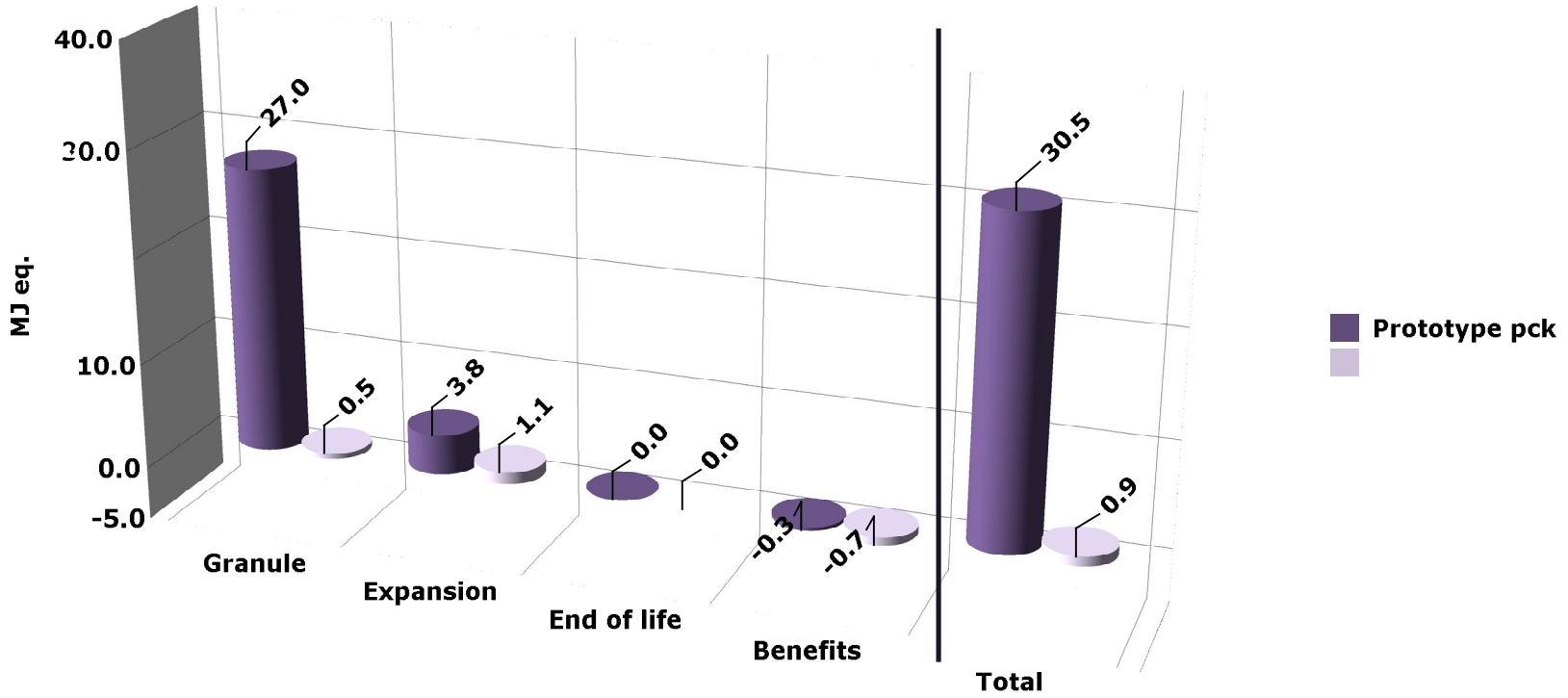
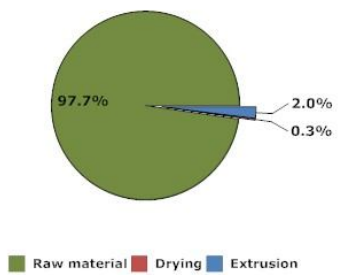
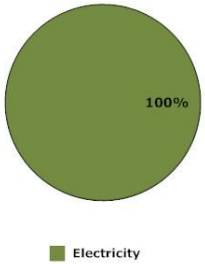
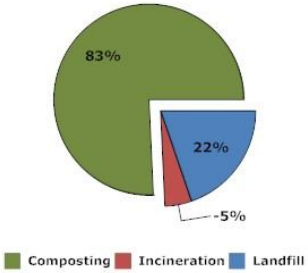
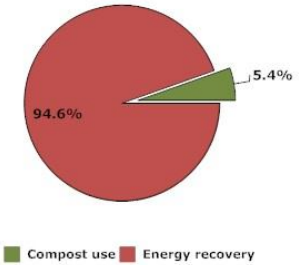
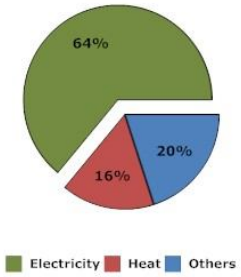
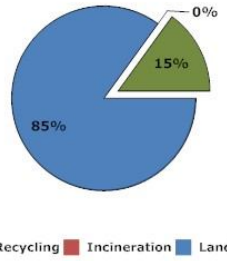
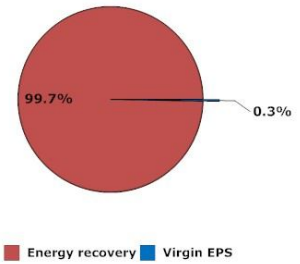


Figure 22 Renewable Energy Resource Consumption for EPS pck and prototype pck (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

The prototype granule production got the highest contribution for RER indicator (88%) due to the consumption of a renewable feedstock (starch). The other contributions within the expansion step for example were due the fact that Italian and European electricity mixes are based also on renewable sources (e.g. hydropower etc.).

Table 44 Contribution Analysis for Renewable Energy Resource Consumption

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

EUTROPHICATION

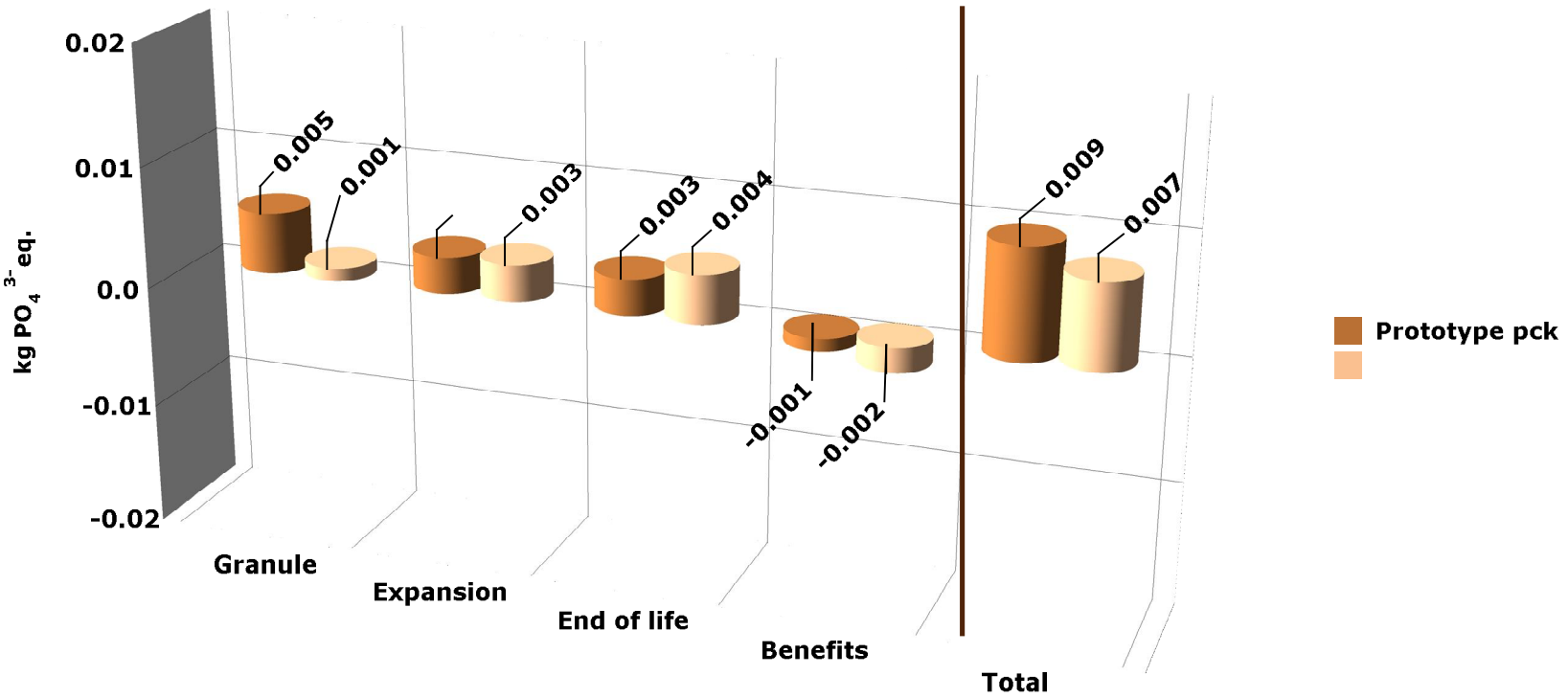
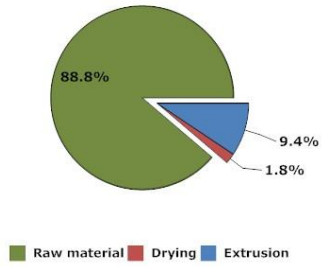
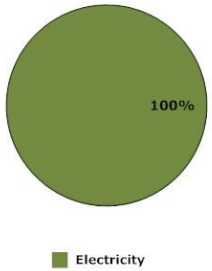
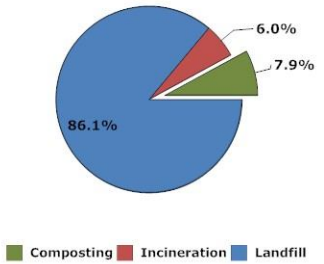
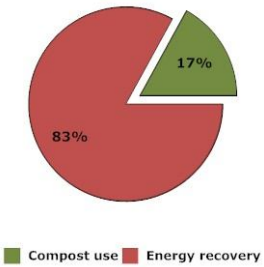
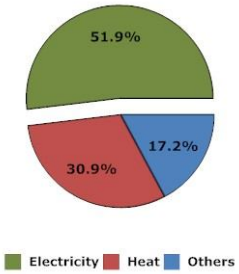
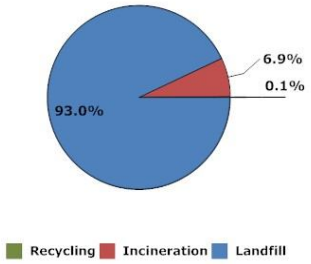
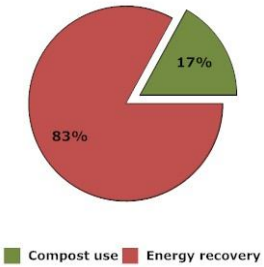


Figure 23 Eutrophication for EPS and prototype pck systems (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

For eutrophication the prototype pck has a greater impact than EPS one due to the raw material production phase (use of fertilizers), however, also emissions coming from End of Life treatments were relevant, especially from landfill (Table 45). For expansion step the main cause for both pck system was the electricity produced in coal-based power plants.

Table 45 Contribution Analysis for Eutrophication

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

ACIDIFICATION

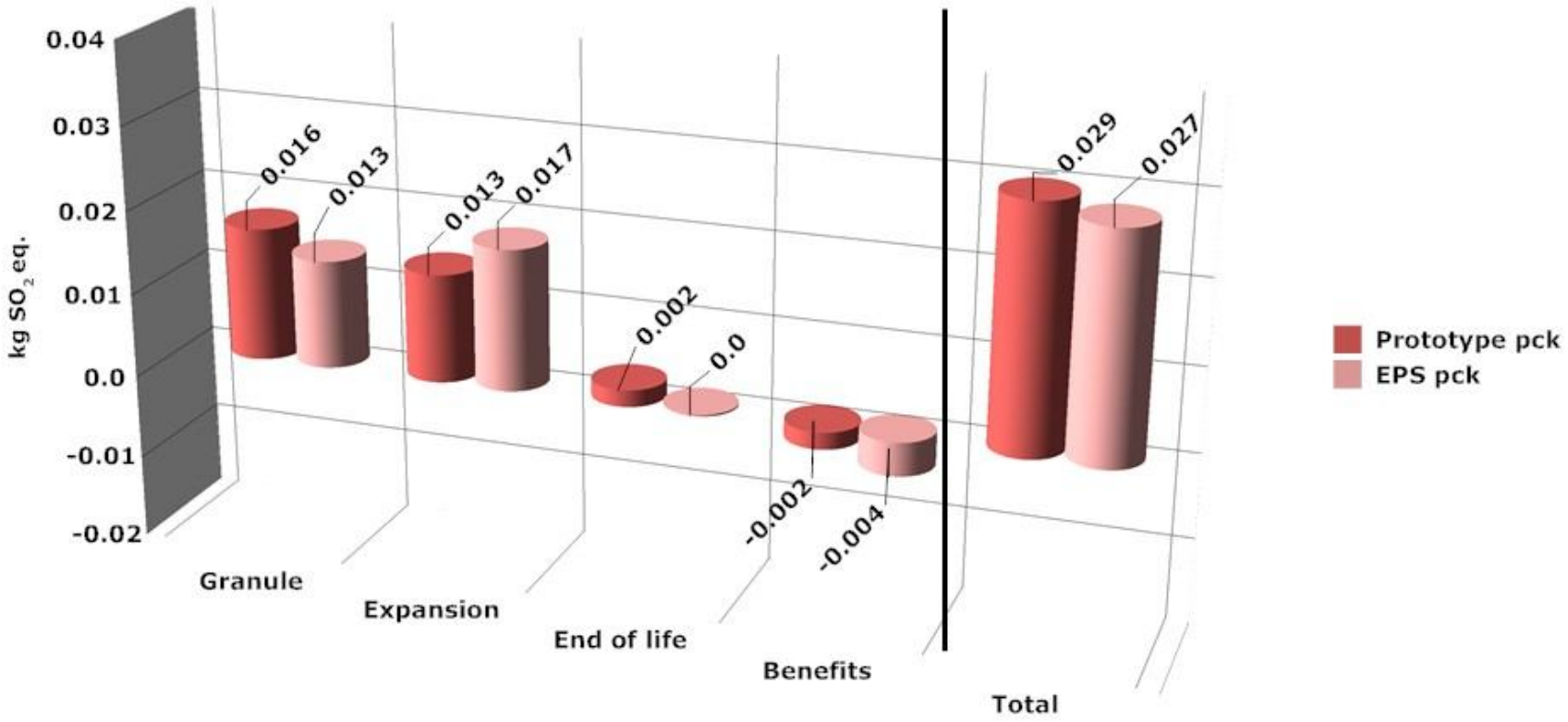
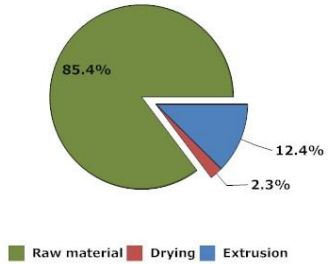
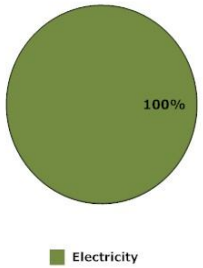
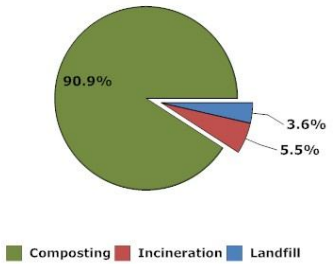
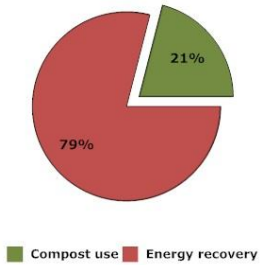
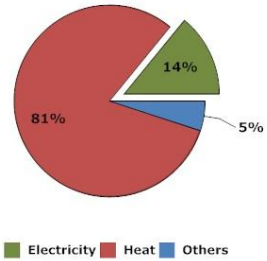
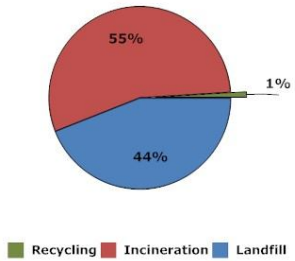
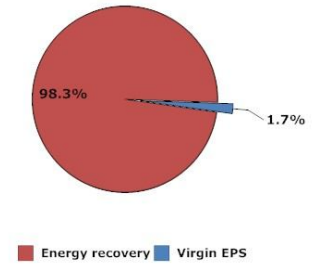


Figure 24 Acidification for EPS and prototype pck systems (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

Acidification substances like NOx, SO_2 etc. were particularly relevant for granule and expansion steps. For the prototype pck the main sources were amenable to the electricity production from oil and coal power plants (Italian electricity mix) followed by tapioca transport that represented about 20% of the overall impact. For EPS pck the main sources were related to electricity (European electricity mix) and heat production.

Table 46 Contribution Analysis for Acidification

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

STRATOSPHERIC OZONE DEPLETION

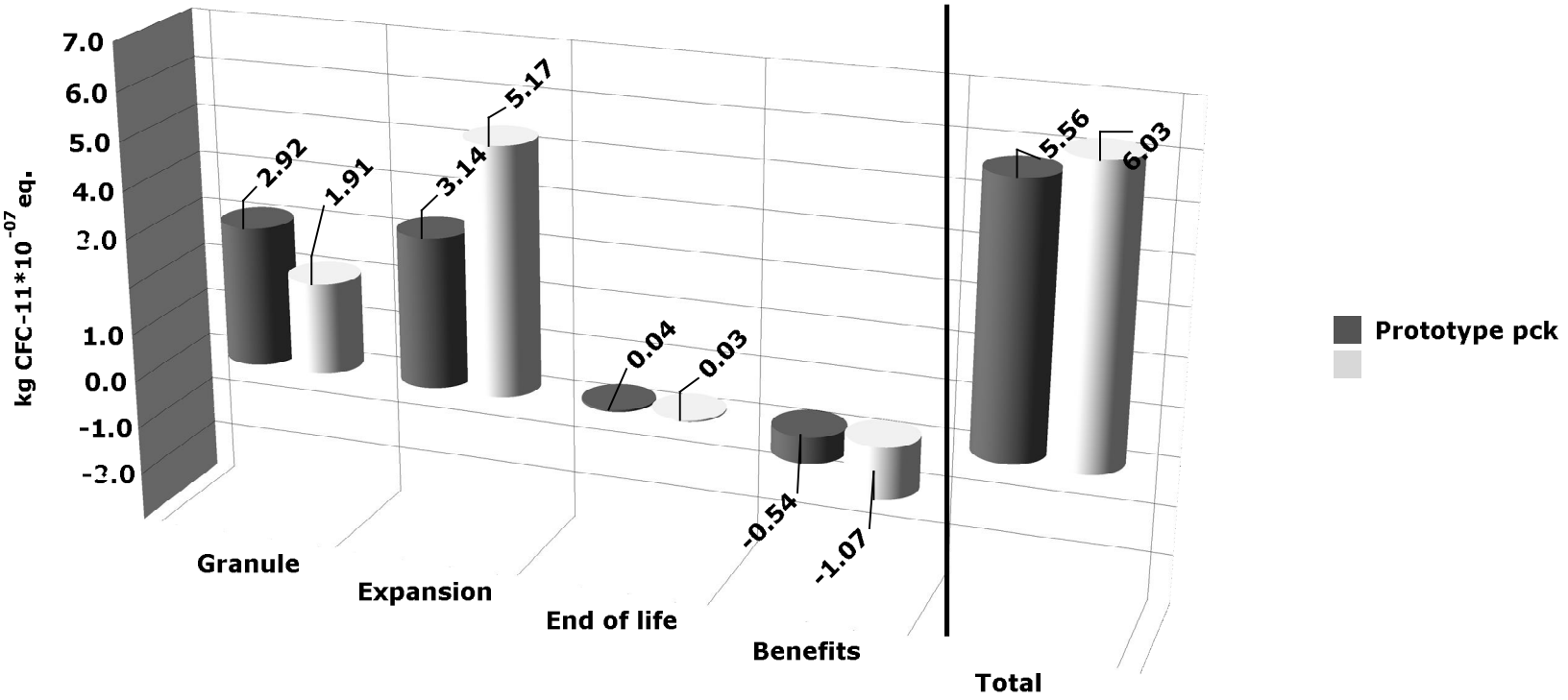
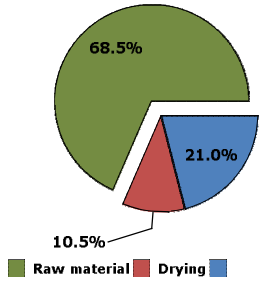
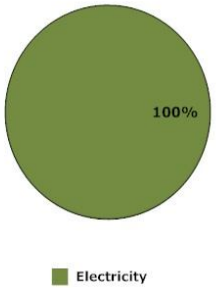
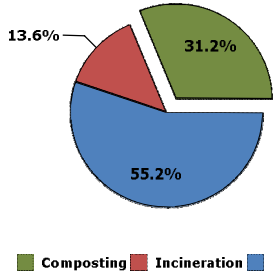
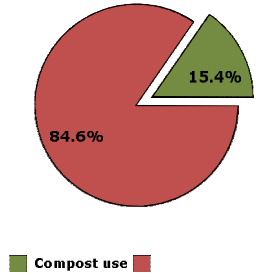
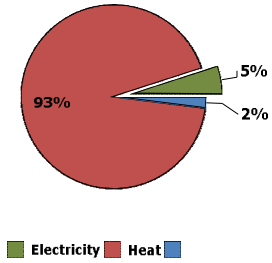
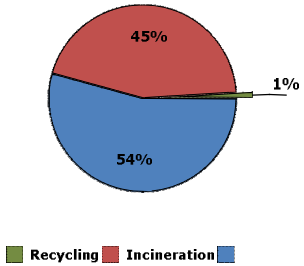
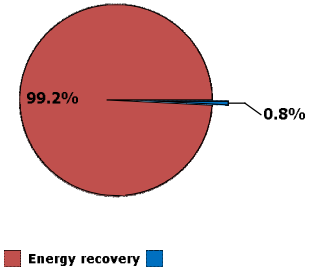


Figure 25 Stratospheric Ozone Depletion for EPS pck and prototype pck (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

Ozone depleting substances were mainly associated to the electricity (for the prototype) and heat (for EPS) production. In particular, it was observed that natural gas losses occurring in its transportation (i.e. pipes) was the main cause of impacts for this impact category.

Table 47 Contribution Analysis for Stratospheric Ozone Depletion

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

PHOTOCHEMICAL OZONE FORMATION

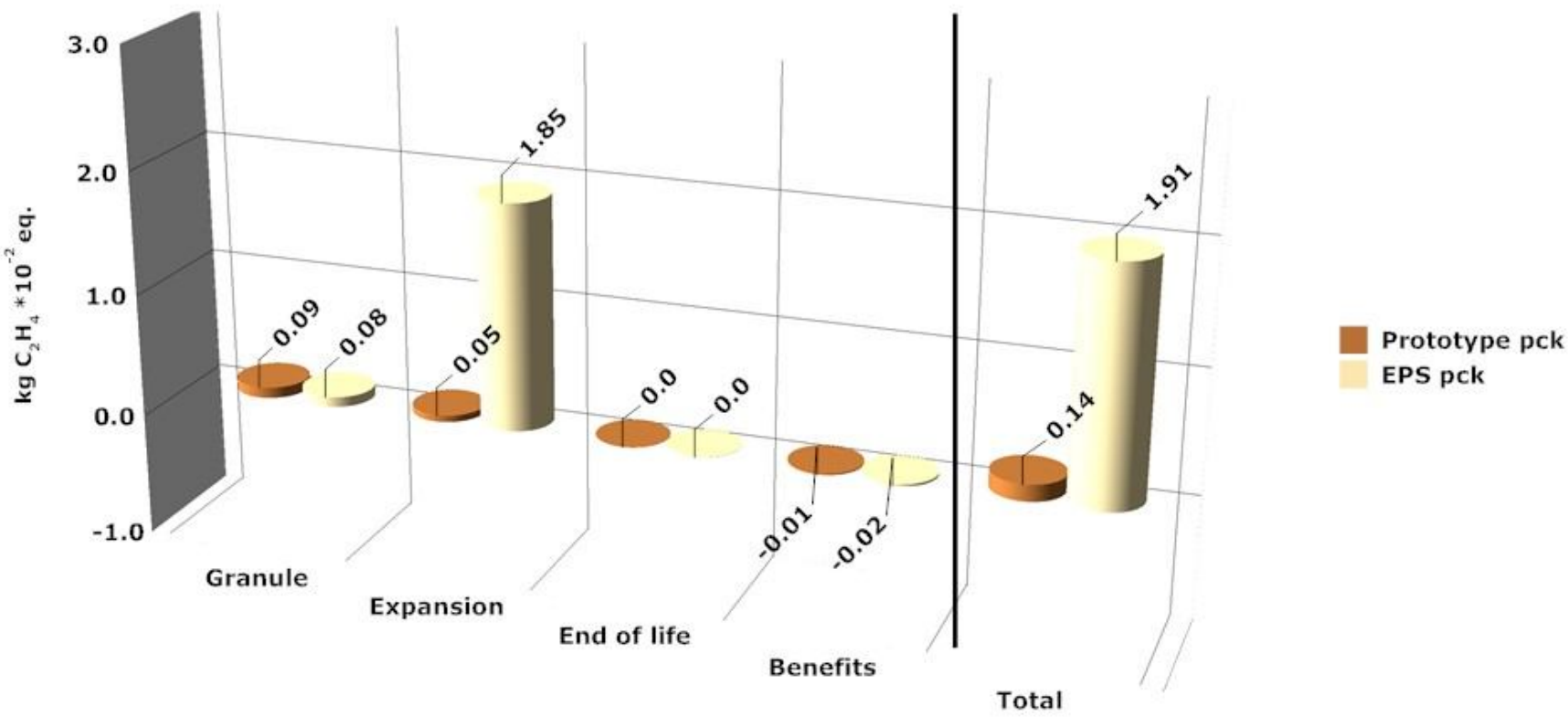
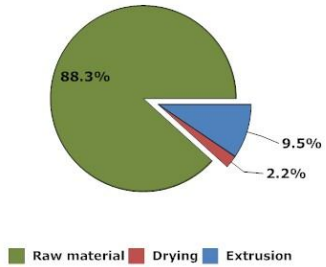
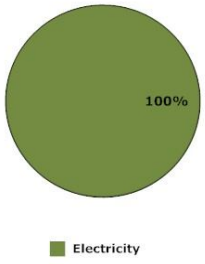
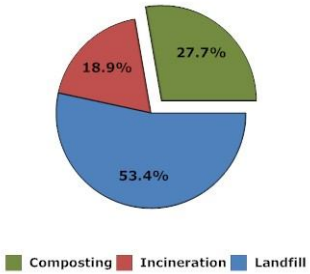
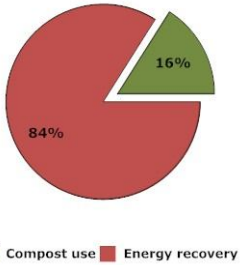
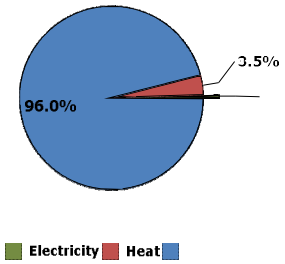
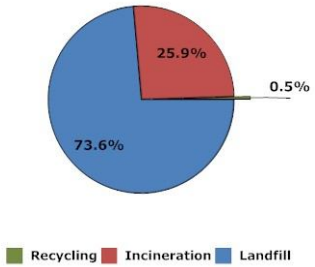
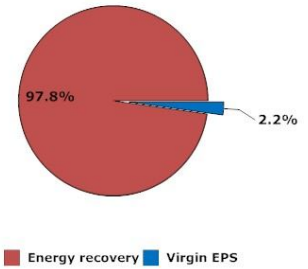


Figure 26 Photochemical Ozone Formation for EPS and prototype pck systems (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

For this impact category the expansion process for EPS pck was by far the most relevant step. The reason of that was amenable to the pentane emissions during the expansion process since pentane is used as expansion agent. The remaining contributions like those coming from granule step were mainly due to Volatile Organic Compounds (VOC) emissions.

Table 48 Contribution Analysis for Photochemical Ozone Formation

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

DEPLETION OF ABIOTIC RESOURCES

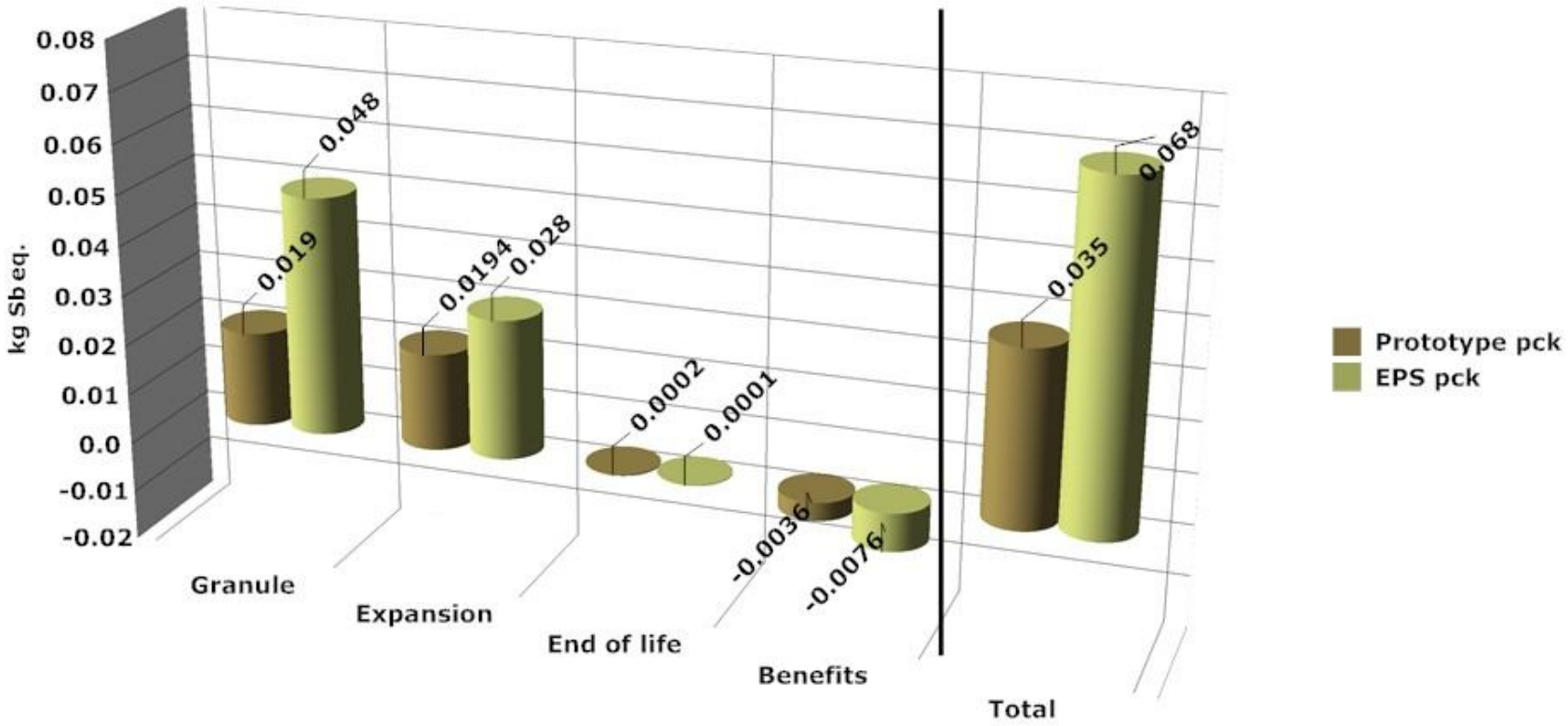
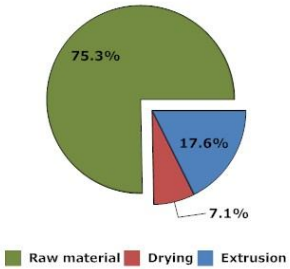
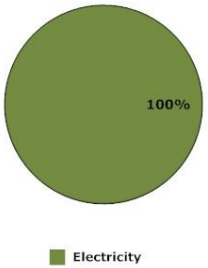
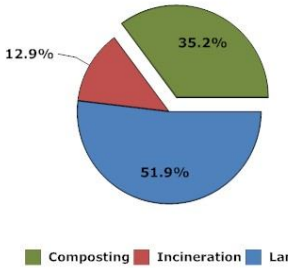
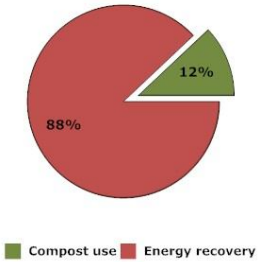
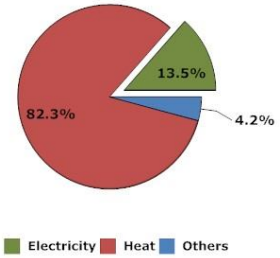
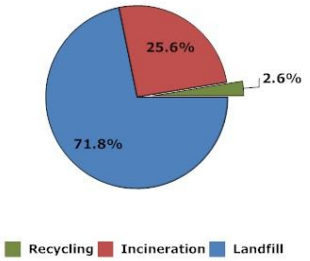
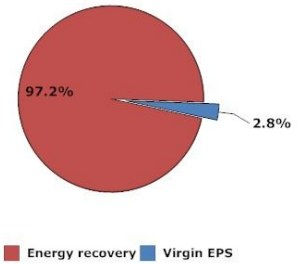


Figure 27 Depletion Abiotic Resources for EPS and prototype pck systems (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

Abiotic resources consumption (e.g. oil, minerals etc.) was relevant for granule production, in particular for EPS due to its nature 100% non renewable. Also the expansion steps were important due to the consumption of fossil fuels largely used for producing electricity and heat.

Table 49 Contribution Analysis for Depletion Abiotic Resources

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

WATER CONSUMPTION

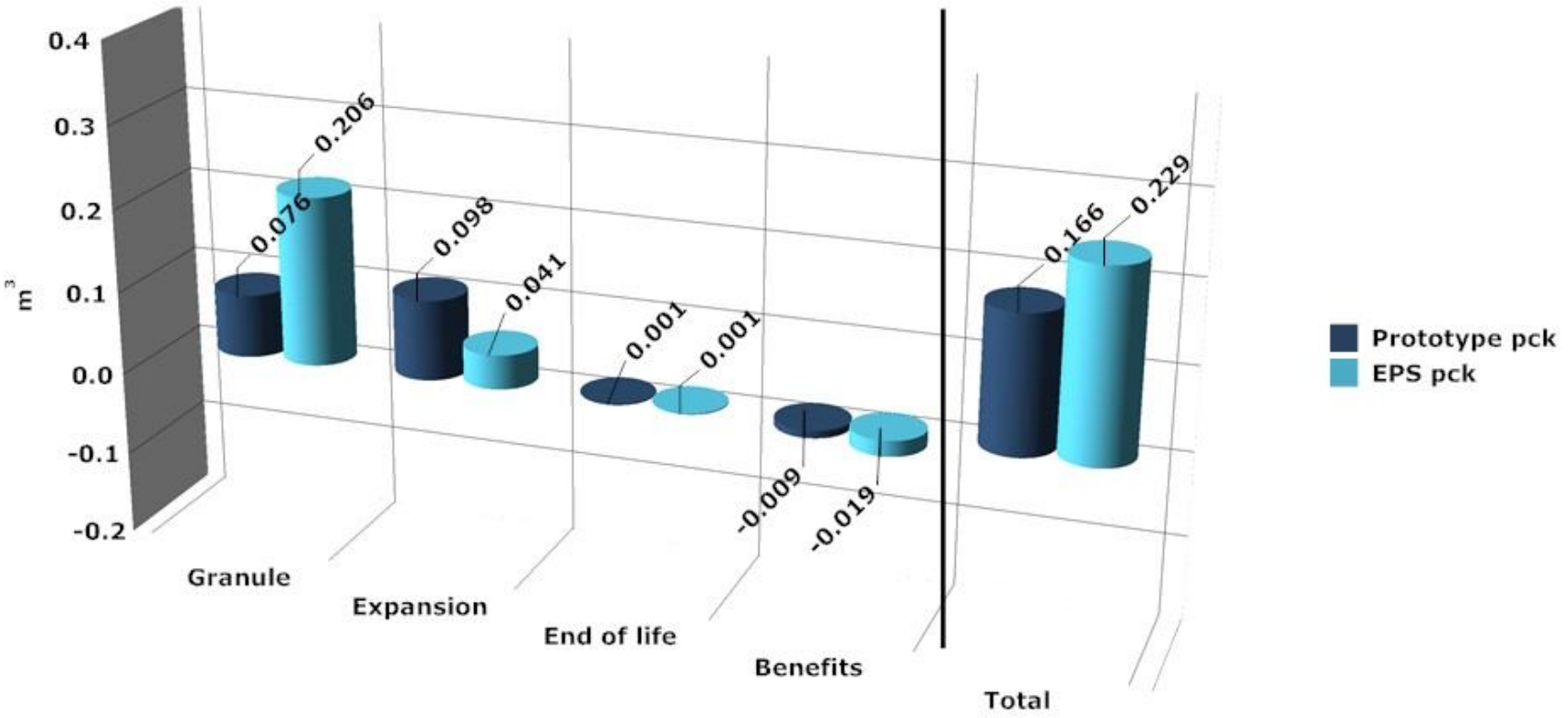
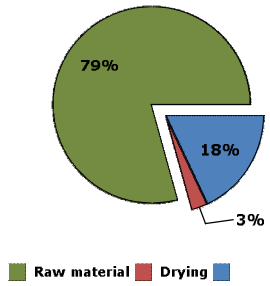
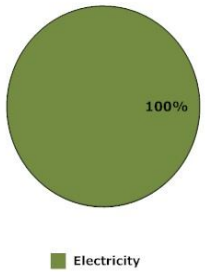
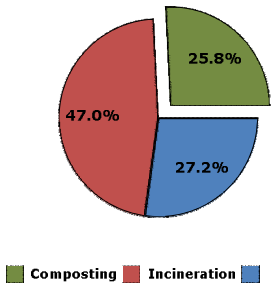
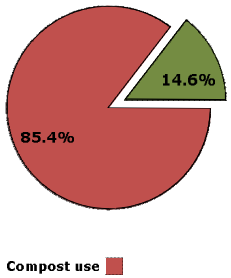
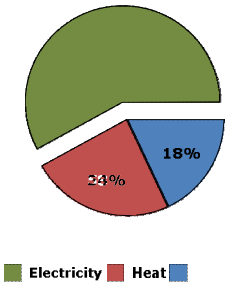
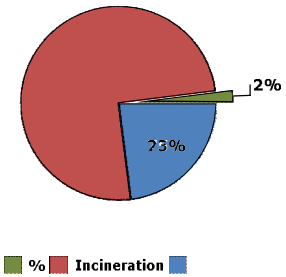
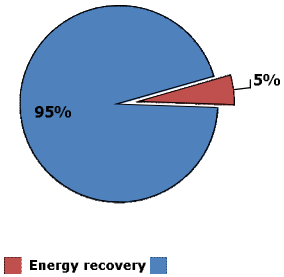


Figure 28 Water Consumption Formation for EPS and prototype pck systems (Values related to F.U. 2.4 kg prototype pck and 1.2 kg EPS pck)

Regarding water consumption, EPS granule production resulted to have the highest impact; however, due to lack of information it was not possible to trace the cause of that. For the prototype pck the main causes were the tapioca cultivation (granule) and electricity production from oil power plants (expansion).

Table 50 Contribution Analysis for Water Consumption

	GRANULE	EXPANSION	END OF LIFE	BENEFITS
Prototype pck				
EPS pck	N.A.			

N.A. = Not Available

LAND OCCUPATION

The land occupation for prototype pck (basic scenario) was about 1.7 m^2/year

- *Use of agricultural resources for bioplastic production*

Food and feed represent the predominant markets of goods coming from agriculture sector, however, substantial amounts of cropland are also dedicated to the production of crops for industrial products such as starches (e.g. paper industry), cotton, tobacco, lubricants, etc. and, to a larger extent, for fuels [56]. Bioplastics constitute another relatively small but growing segment in this big market of bio-products [57].

In Europe about 10 million t of protective transport packaging materials are annually produced [58]. Assuming to replace 30% (i.e. ~3 million t) of them with pck systems made of prototype material, a preliminary estimation of the magnitude of the use of starch was performed. As some renewable raw materials are produced predominantly outside of Europe like tapioca, the calculation considered the World production of maize, potato and tapioca [18]. For prototype material a density of 40 kg/m^3 was considered whereas for traditional pck systems a density of 30 kg/m^3 (assumption), since many different oil-based materials are used in protective transport pck.

Table 51 World production of tapioca, maize and potatoes in 2008 (FAOSTAT)

Parameter	U.M.	Tapioca	Maize	Potatoes	Total
Area harvested	Ha	18,394,349	161,203,204	18,159,000	197,756,553
Renewable feedstock	T	232,143,136	827,489,803	327,509,778	1,387,142,717
Starch content (on fresh matter)	%	25%	64%	20%	

According to the densities assumed for the prototype and traditional pck materials and, considering the prototype pck material entirely made of starch (conservative assumption), about 4 million t of starch would be needed to produce a bio-based and biodegradable pck material able to replace 30% of oil-based pck materials consumed annually in EU. Such amount of starch would correspond to about 0.6% of the total World production of tapioca, maize and potato in 2008.

4.1 NORMALISATION

In order to facilitate the interpretation of results a normalization process was carried out. Normalized LCA results give for each environmental impact the relative share of the impact of the analyzed system in the total impact of this category per average citizen or globally per country. In other words it tells us how important a certain value is. Within this study the LCA results were normalized respect to an equivalent person of Europe in 1995 (Table 52).

Table 52 Normalised LCA results

Impact category	Unit	EPS pck (basic scenario)	Prototype pck (basic scenario)
NRER	Equivalent person	$1.67x10^{-3}$	$8.31x10^{-4}$
AP		$7.54x10^{-4}$	$7.98x10^{-4}$
EP		$1.05x10^{-3}$	$1.46x10^{-3}$
POF		$5.13x10^{-3}$	$3.63x10^{-4}$
AD		$1.87x10^{-3}$	$9.62x10^{-4}$
GWP 100		$7.77x10^{-4}$	$3.06x10^{-4}$
OD		$1.36x10^{-5}$	$1.25x10^{-5}$

Figures in Table 52 were graphically reported in Figure 29 (a logarithmic scale was used for the y-axis)

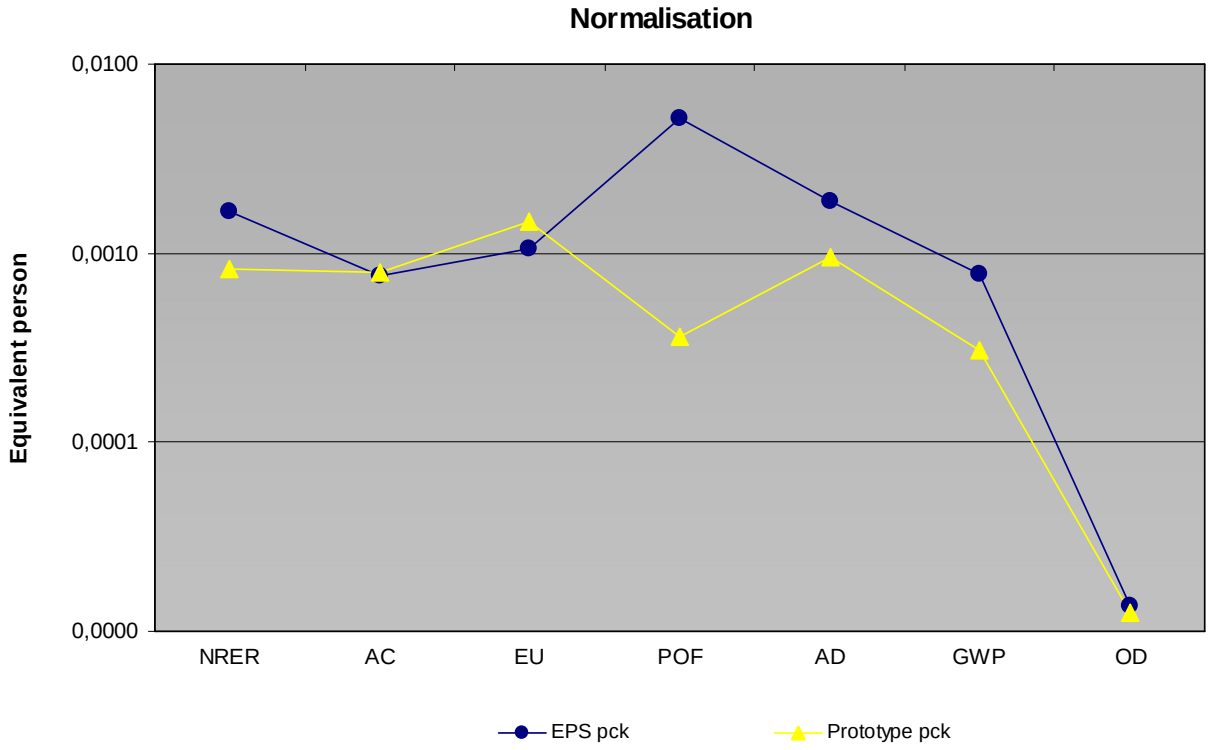


Figure 29 Normalised LCA results for EPS pck and prototype pck (basic scenarios)

Basically, it was observed that NRER, AC, EU, POF, AD and GWP impact categories were characterized by the same magnitude or relative importance, whereas, the magnitude for OD was about two orders of magnitude lower compared to them.

4.2 ESTIMATION OF UNCERTAINTY

In LCA it is important to know to what extent the outcome of the analysis is affected by various types of uncertainty, such as parameter, scenario and model uncertainty [59]. Questions like: "How reliable are the LCA results?" "Does product A really score better than product B?" represent the root topics of the result interpretation (i.e. 4° step of an LCA). Further, the information on the uncertainty of the model outcomes, beyond to provide useful aids on reliability of results, they guide to further research towards reducing uncertainty. There are many ways of classifying the uncertainty in LCA, but without going into the details, we opted for a less rigorous but more pragmatic division (Table 53). For each uncertainty source, the tool adopted in this study so as to manage it was reported as well.

Table 53 Sources of uncertainties generally encountered in LCAs (author division)

Source of uncertainty	Example	Tool (adopted in this study)
• **Inventory data quality and modelling**	Neglecting important flows. Data unavailable (e.g. a CFC emission to air from a unit process) or wrong, or unreliable. Data unavailable approximated with data available but not representative enough. Level of details. Consistency of the LCA model.	**Data quality checks**: completeness, consistency, representativeness etc. **Peer review** (expected)
• **Statistic uncertainty of inventory**	Data is available but it is affected by variability and stochastic error due to e.g. measurement uncertainty, process specific variations, temporal variation, etc.	**Monte Carlo simulation**: calculate the correlation between model input and total model output
• **Parameters**	System boundaries, allocation, process technology, raw materials, biodegradation rate of material, indirect effects (e.g. LUC), End of Life treatments etc.	**Sensitivity analysis**: setting one or more sensitivity scenarios for each key parameter.

Figure 30 reports the "Cradle to grave" LCA results for the prototype pck normalized to those obtained for the EPS one.

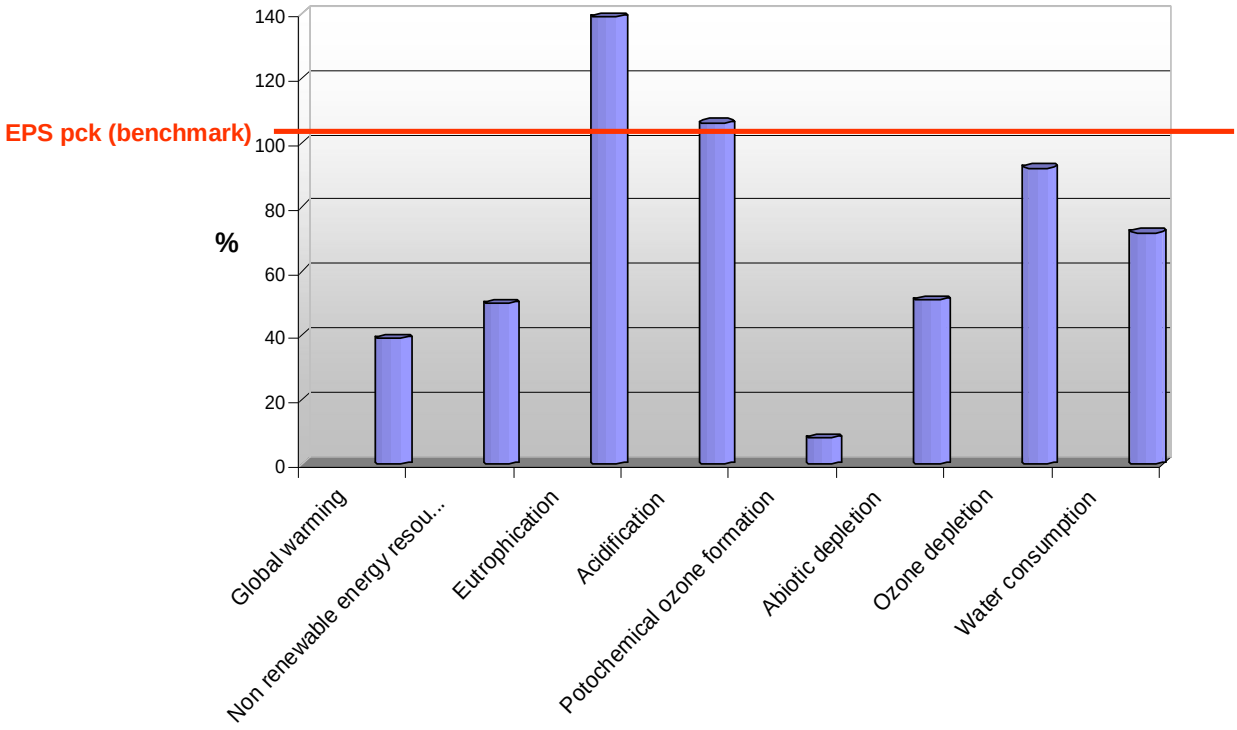


Figure 30 LCA results for the prototype pck normalized to EPS pck (=100%). Basic scenarios.

This graphical representation clearly shows that prototype pck scored better for GWP, NRER, POF, AD, OD and WC, worse for EU and comparable for AC but, how reliable are these results? What is their variation in function of the variation of the key parameters?

Actually, for the reasons explained in Table 53, these figures could be empty of meaning, without an estimation of uncertainty and, without a carefully check of inventory data quality. In the following paragraphs each source of uncertainty was addressed.

4.2.1 Data quality check

In reference to granule production, average industrial data (i.e. secondary data) were used for EPS whereas for the prototype, primary and secondary data were used. Primary (or foreground) data were those related to the processes under operational control by the project partners like granules production and granules expansion. For EPS expansion both primary data and literature data were used. Regarding the End of Life disposal, the end user of the packaging system (another project partner), provided valuable data about washing machines distribution thanks to which was possible to define a quite realistic end of life scenario both for EPS pck and prototype pck. All background inventory data (e.g. electricity production, transports, chemicals, fertilizers production etc.) came from Ecoinvent 2.2 database, one of the most used database at worldwide level that provides consistent, validated and transparent inventory data. Finally, all inventory data like emissions to air, water and soil coming from pck system disposal (e.g. incineration, composting etc.) were elaborated using the Ecoinvent tool for waste treatment (see Table 39 and Table 40 for details) and literature sources.

The quality of inventory data is shown in Table 54.

Table 54 Inventory data quality

Life cycle stage	Geographical coverage	Time period	Data Origin	Completeness	Representativity	Source of information
Prototype bio-based granule	IT	2008-2012	++/+/O	+	+/O	Project partners and specific literature
EPS granule	EU	2005	O	+	+	Ecoinvent 2.2 database based on avg. industrial data (PlasticsEurope)
Prototype expansion	IT	2012	++/+/-	+	+	Project partners
EPS expansion	EU	1998-2011	++/O	+	+	Ecoinvent 2.2 database, literature, EPS pck producers
End of Life scenarios	EU/extra EU	2008	O/+	not applicable	+	Statistic data (EUROSTAT 2008)
Waste treatments	EU	no longer than 10 years	+/O	++/+	+	Project partners for EoL scenarios and Ecoinvent tool for inventory data elaboration
Compost utilization	EU	2008	O/+	+	+	Literature
Background data: e.g. electricity production, transports, fertilizers, chemicals, other materials etc	EU	no longer than 10 years	O	+	+/O	Ecoinvent 2.2 database

Data origin:
+ + : Measured
+ : Calculated
O : Literature
- : Estimated

Completeness:
+ + : All flows captured
+ : All relevant flows captured
O : Individual relevant flows captured
- : Some relevant flows not captured

Representativeness:
+ : Completely representative
O : Partly representative
- : Not representative

As can be noticed the completeness and representativeness of data in input was quite good. To notice also that for the prototype pck almost all used data were derived from direct measurements (e.g. electricity consumptions) and/or calculated. They reflected the best trial outcomes.

Anyhow, so as to make the prototype and EPS pck systems as more consistent and realistic as possible further choices were done:

- Use an attributional approach for upstream processes (i.e. granule production) so as to maintain homogeneous the compared systems → see § 3
- Elaboration of a new dataset reflecting the Thai electricity mix for tapioca starch production since in Ecoinvent 2.2 no data for Thai mix were available. This was done to adhere as more as possible to reality → see Table 11
- Several emissions to air from EPS expansion process, with exception of pentane, were reported in the inventory for the sake of clarity but, not taken into account in the impact assessment since their level of detail was higher compared to that of the prototype expansion process. In this way, we opted to underestimate impacts from expansion in favour to maintain systems homogeneous → see Table 16
- Consistency checks of energy consumption for EPS expansion process: primary data coming from three different sources were compared with literature ones to verify their consistency, and to define a representative consumption → see Table 16
- End of Life scenarios. So as to define as more real as possible the fate of EPS pck and that of a hypothetical compostable pck, washing machines distribution data were collected and matched with statistic data about MSW management. This has permitted to estimate with a acceptable approximation the real fate of the pck systems reducing the number of hypothesis and assumption → § 4.2.3
- Mass balance checks. In order to verify that no errors occurred in the elaboration of inventory and in the model, some balance checks were performed like that reported in Figure 18 related to the biogenic-C balance for the prototype pck.

Once data quality checks were finalized, how the statistic uncertainty of the inventory data affected the LCA results was investigated.

4.2.2 Monte Carlo simulation

Monte Carlo analysis is a probabilistic simulation and represents a simple and efficient tool for dealing with statistic uncertainty of LCA results as long as the statistical distribution of data in input (inventory) is know. For each input parameter (e.g. emission of SO_2 from an oil fired furnace), a compiuter algorithm creates a random number according to its distribution and it executes the calculation. The result is stored. Next the calculation is repeated taking different random numbers always within the defined uncertainty range, and also this result is stored. After repeating the procedure for instance 1000 times, we get 1000 different LCA results. These results are then evaluated to get information about their statistical distribution (e.g. mean, standard deviation etc.).

In the used software four different distributions can be used: Range (min and max), Triangular, Normal distribution and Lognormal distribution. Almost all unit processes of Ecoinvent database have a lognormal distribution [60].

Important aspects in Monte Carlo analysis are correlations. Suppose our LCA model contains several processes that refer to the same electricity process, then for each Monte Carlo run simulation, the software considers for it the same uncertainty. If it would not do so, then the result uncertainty would be overestimated. This is very important also in comparative analysis, in fact, for each Monte Carlo run the software considers for all the same processes used by product A and product B the same uncertainty.

A further important aspect in comparative analysis is that the software does not provide the distribution of LCA results for product A and product B because it could happen that the two distributions are quite or almost overlapped with the impression that it is impossible to determine if product A is preferable to product B. For this reason the software avoids to show overlapping distributions rather it shows how many times the Monte Carlo simulation shows that product A is better than product B, thus only the distribution of the difference (A-B) is showed along with statically information (e.g. meas, standard deviation etc). If difference for a given impact category is largely positive it will mean that A>B; if the outcome is largely negative B>A.

It is worth to point out that Monte Carlo simulation address only the uncertainty in the inventory. Other sources of uncertainty relied in the methods used for characterizing pollutant emissions in potential impact or even forward in the damage evaluation.

Generally, for obtaining a quick impression of statistical distribution of LCA results, a standard error of mean below 0.01 is quite acceptable Since the standard error of mean indicates how much the mean is changed by the last Monte Carlo run, the lower it is, the more reliable the results are. In general such a level (0.01) is reached in about 50 - 100 runs [61].

However so as to have a really good impression of the standard deviation of the difference (A-B), at least 1000 runs are needed. The statistics of the Monte Carlo simulation performed for prototype and EPS pck systems were given in Table 55 whereas Figure from 31 to 37 reported the graphical representation of (A-B) distribution where A= prototype pck and B= EPS pck for each impact category. The confidence interval showed is 99%. Finally Figure 38 summarizes the overall results. In general it is possible to assume that if 90 to 95% of the Monte Carlo runs are favourable for a product, the difference may be considered significant [61]

For water consumption impact category the Monte Carlo simulation was not performed due to lack of data about distribution of inventory data.

Table 55 Statistics of Monte Carlo simulation performed for prototype pck and EPS pck

Number of runs performed	3001
Total calculation time	16:42:48
Part of values that contain uncertainty	43.9%
Distribution	Count
Total	99740
Undefined	49940 (50.1%)
Lognormal	49764 (49.9%)
Normal	6(0.00602%
Triangle	0 (0%)
Uniform	0 (0%)

Global Warming Potential (GWP)

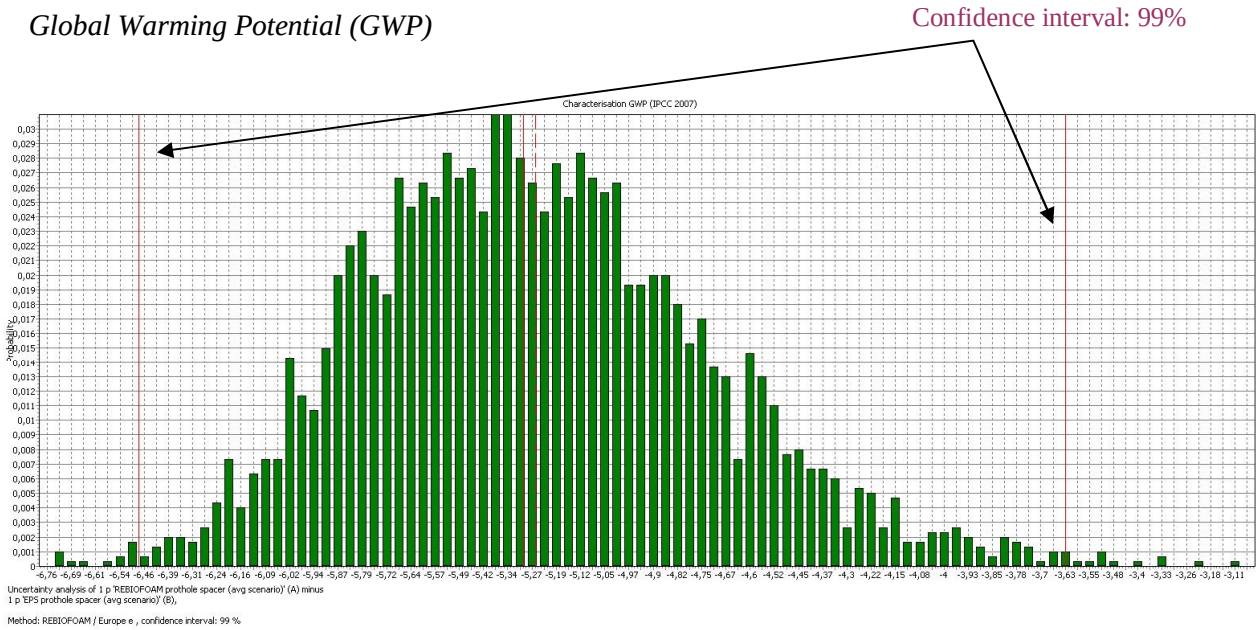


Figure 31 (A-B) distribution for GWP. A = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
GWP (IPCC 2007)	0%	-5.26	-5.3	0.531	-6.48	-3.63	-0.00184

The vertical axis displays the probability that a certain value is reached for (A-B) difference.

Non Renewable Energy Resources consumption (NRER)

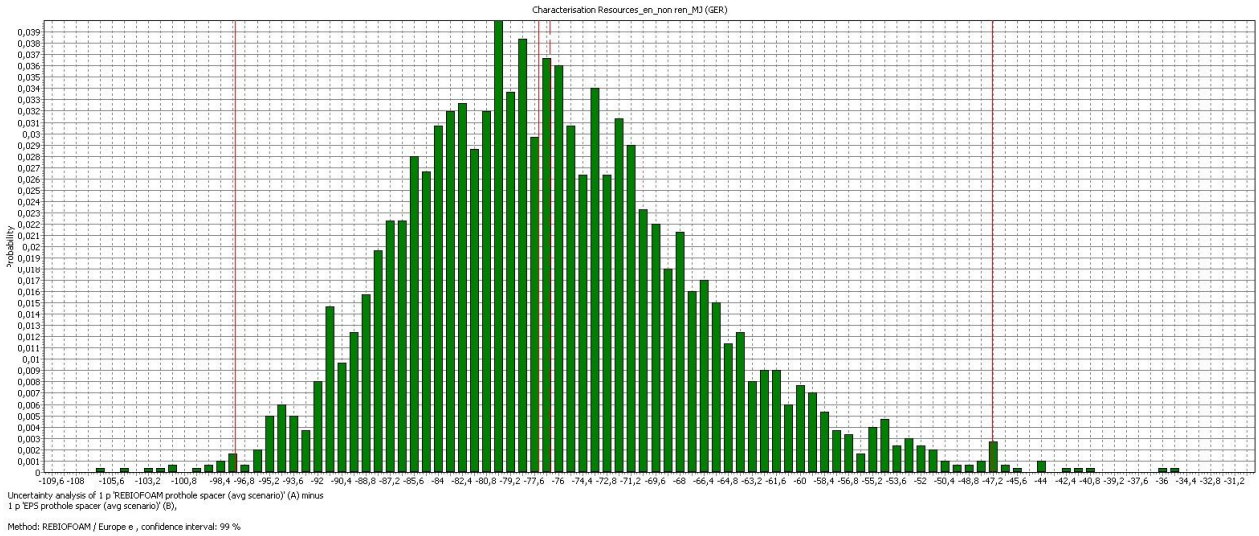


Figure 32 (A-B) distribution for NRER. A (green) = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
Non Renewable Energy Resources	0%	-76.6	-77.3	9.47	-97.4	-47.3	-0.00226

Eutrophication Potential (EU)

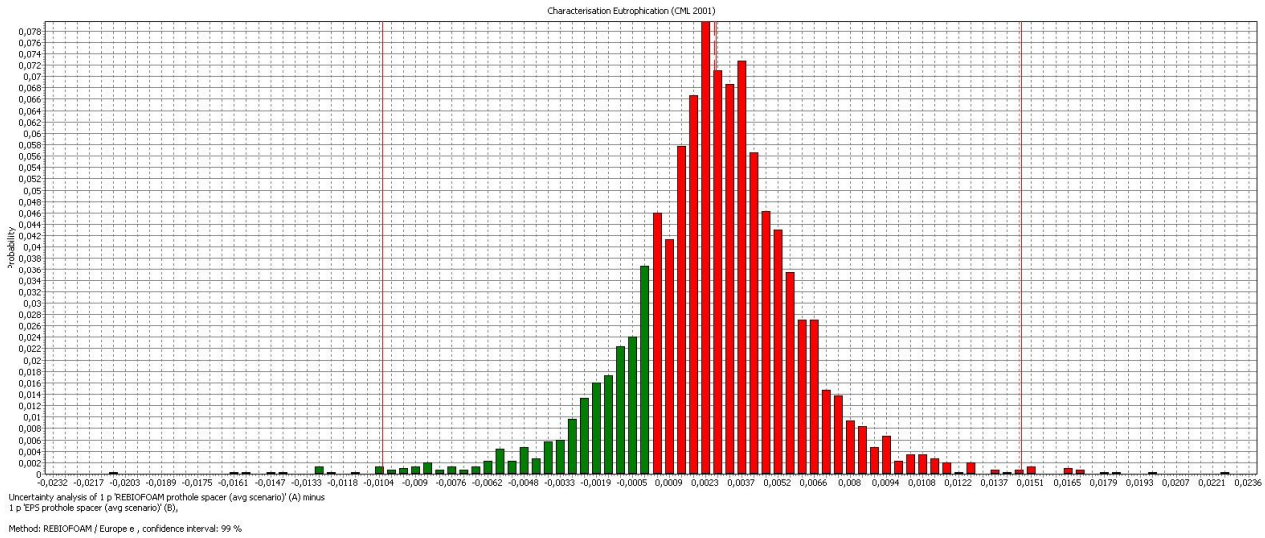


Figure 33 (A-B) distribution for EU. A = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
Eutrophication (CML 2001)	83.8%	0.00267	0.00274	0.00354	-0.0103	0.0147	0.0242

To notice that the mean and median values for (A-B) are now >0 which means A>B. In fact the probability that A<B was 16% (green bars) whereas A>B 84% (red bars). It also meant that within 3000 runs, 2520 times A scored worse than B.

Acidification Potential (AC)

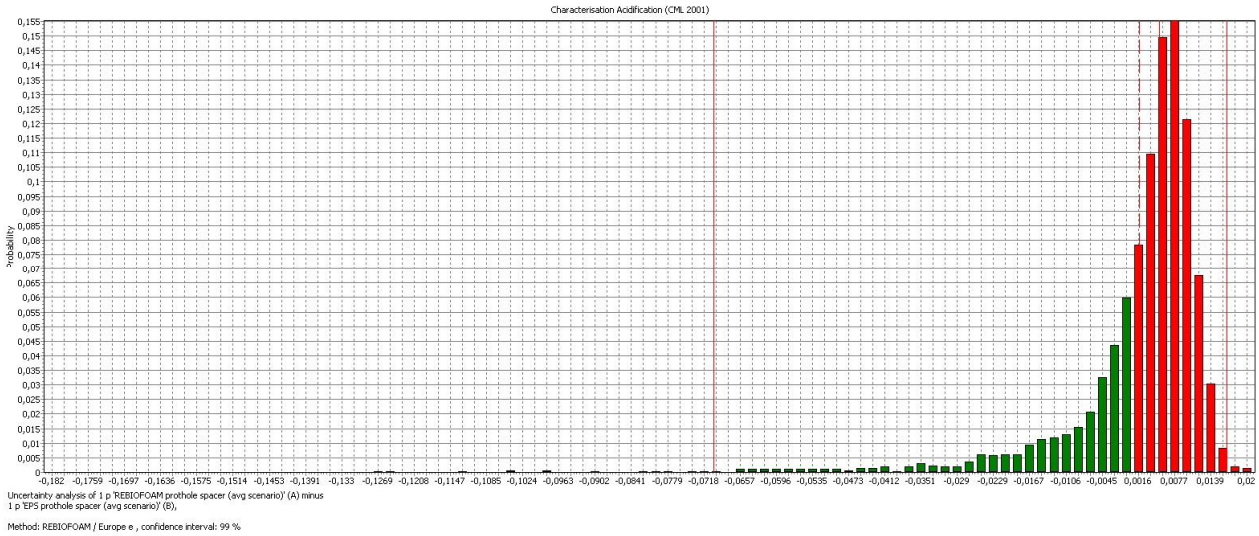


Figure 34 (A-B) distribution for AC. A = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
Acidification (CML 2001)	73.8%	0.00175	0.00518	0.0135	-0.0702	0.0166	0.141

As for EU, the (A-B) mean value for AC is positive, however, the probability that A>B was lower compared to that observed for EU (74% instead of 84%). To notice how the (A-B) distribution for AC showed a very recognizable lognormal distribution.

Photochemical Ozone Formation Potential (POF)

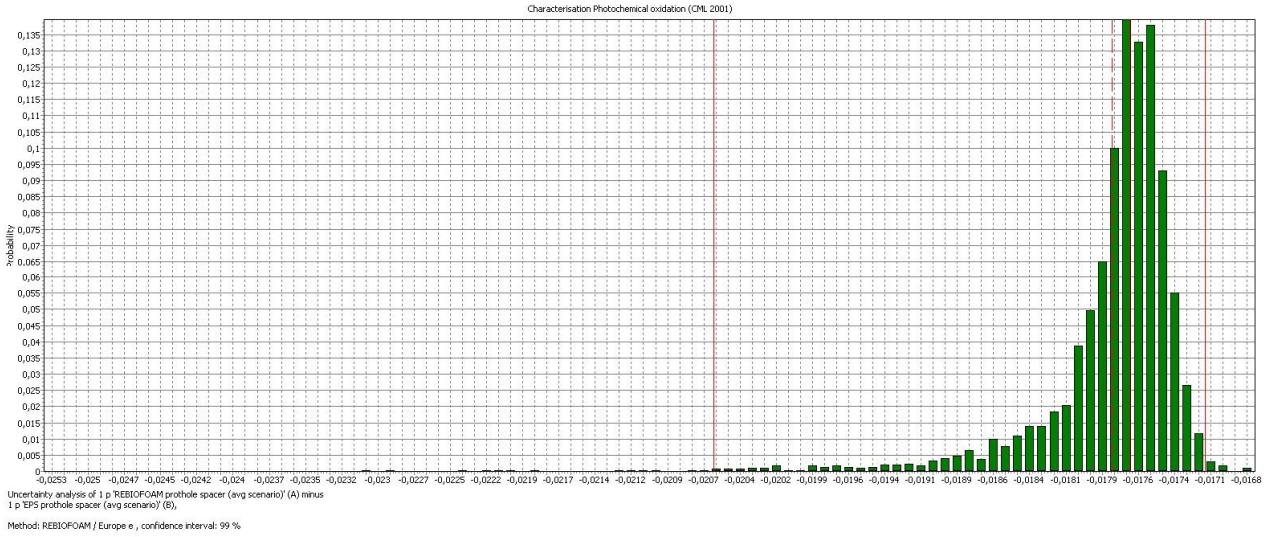


Figure 35 (A-B) distribution for POF. A = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
Photochemical ozone formation	0%	-0.0178	-0.0177	0.000549	-0.0206	-0.0171	-0.00056

Abiotic Depletion Potential (AD)

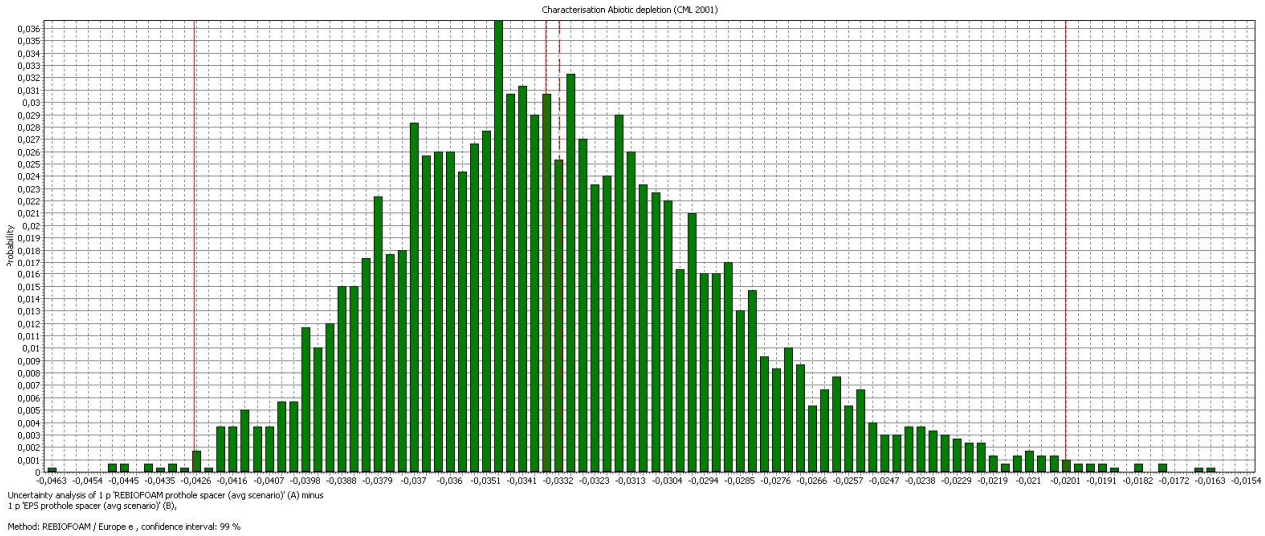


Figure 36 (A-B) distribution for AD. A = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
Abiotic depletion (CML 2001)	0%	-0.0332	-0.0335	0.00431	-0.0426	-0.0201	-0.00237

Ozone Depletion Potential (OD)

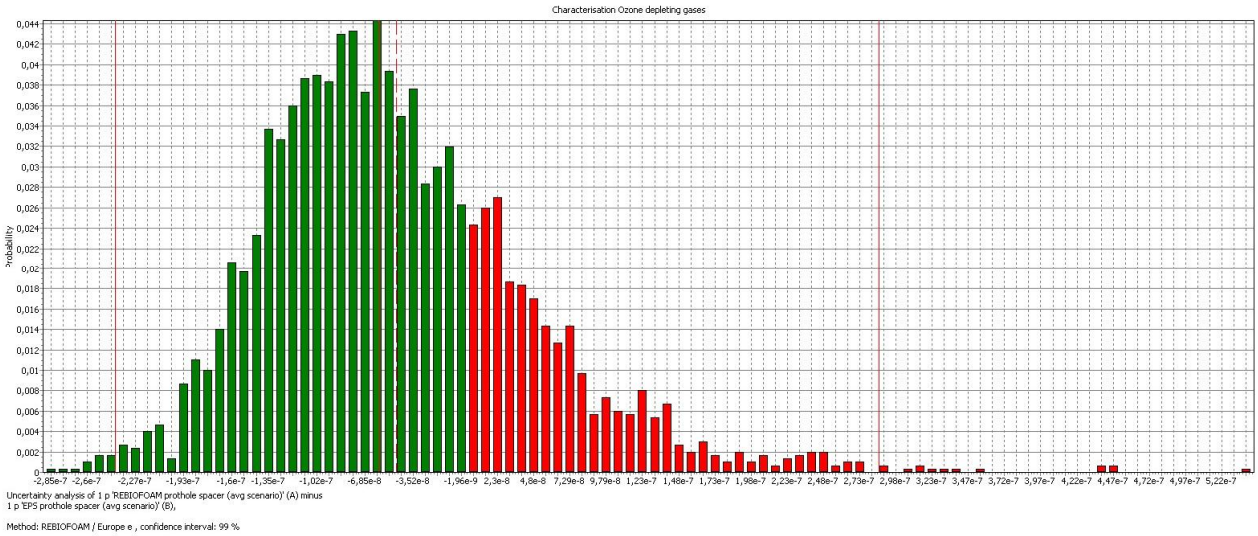


Figure 37 (A-B) distribution for OD. A = prototype pck B = EPS pck

Impact category	Probability A >= B	Mean (A-B)	Median (A-B)	SD (A-B)	0.5%	99.5%	Std.err.of mean
Ozone depletion	26.3%	-4.69E-08	-5.89E-08	9.24E-08	-2.4E-07	2.86E-07	-0.036

Conclusions about Monte Carlo simulation

Figure 38 summarizes the Monte Carlo simulation outcomes.

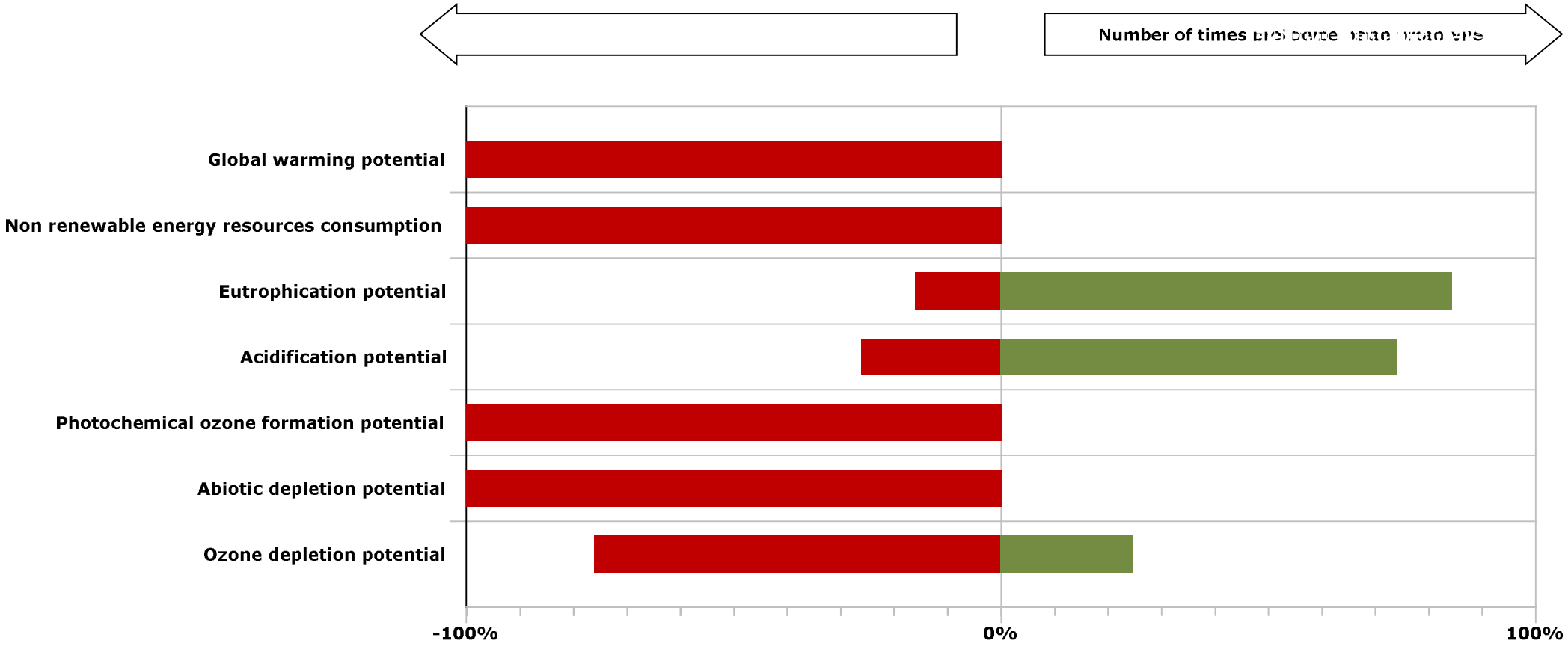


Figure 38 Favourable runs, expressed as percentage, where prototype pck is better than EPS pck and vice versa

Through Monte Carlo simulation was possible to understand how reliable the differences between the prototype pck and EPS pck were. In particular, the simulation showed a significant difference for GWP, NRER, POF and AD and, a less or not significant difference for EU, AC and OD since, for the latter impact categories, neither prototype pck nor EPS pck got favourable runs >= 90% of the total runs[4].

In other words according to Monte Carlo results, it was not possible to state that the prototype pck was worse than EPS one for EU and AC, or better for OD as one might conclude observing Figure 30.

The simulation showed the importance of the statistic elaboration in LCA, nevertheless, it is also important to keep in mind that Monte Carlo outcomes reflect the LCA model that was worked out: if the model is not consistent and/or some inventory data are missing, Monte Carlo simulation can not help it and one may got misleading results even performing a good statistic simulation. Finally, it is worth also to remember that for the present simulation, only ~50% of used data had a statistical distribution[5]. A higher amount of data about distribution of inventory data would be needed for improving the reliability of Monte Carlo analysis, which remains a simple and efficient way to manage uncertainty in LCA.

The following paragraph addressed the sensitivity analysis which represented the third and the last "tool" here adopted for assessing uncertainty.

4.2.3 Sensitivity analysis

By the sensitivity analysis, how variation of the key parameters (e.g. type of raw materials, different end of life scenarios, process technologies etc.) influenced the LCA results was assessed enabling a more comprehensive interpretation of the outcomes. Table 56 and Table 57 summarized the key parameters addressed in the sensitivity analysis along with the corresponding variations of the LCA results obtained for the basic scenarios. The traffic light colours indicated that green = no significant variations (i.e <10%), yellow = medium variations (10-30%) and red = significative variations (>30%) whereas "+" meant that the variation was positive (i.e. increase of impact) and"-"that the variation was negative (i.e. reduction of impact). For example looking at Table 56 the parameter "starch" → "Maize starch DE (Ecoinvent 2.2) economic allocation", it can be concluded that the use of maize starch produced in Germany instead of tapioca starch produced in Thailand (i.e. basic scenario), generated a significant (>30%) and positive variation for NRER, RER, AC, EU, AD GWP and OD impact categories since the boxes are red and with a "+" inside.

[4] In general it is possible to assume that if **90** to **95**% of the Monte Carlo runs are fauvorable for a product, the difference may be considered significant

[5] For example for EPS granule production no distribution data were available at all.

Table 56 Matrix summarizing sensitivity analysis outcomes for the prototype pck

LIFE CYCLE STAGE	Parameter	Variability and uncertainty	Modified parameter description	Contribution importance to the total impacts compared to the prototype pck basic scenario							
				NRER	RER	AC	EU	POF	AD	GWP	OD
Raw Materials	Starch	Variable depends by the starch type, cultivation practices and the country where cultivation and starch extraction takes place	Maize starch (DE, Ecoinvent 2.2) economic allocation	+	+	+	+	+	+	+	+
			Potato starch (DE, Ecoinvent 2.2) economic allocation	+	+	+	+	+	+	+	+
			Maize starch (IT, Novamont database) mass allocation	+	+	+	+	+	+	+	+
	Land use change	Variability of results depend from previous land use	Emission CO_2 eq. from LUC (best case)							+	
			Emission CO_2 eq. from LUC (worst case)							+	
Expansion	Doped Mould	Variable depends by major consumption of electricity	Electricity consumption in expansion processes	+	+	+	+	+	+	+	+
End of life	Biodegradation in landfill	Major formation of CH_4 and CO_2	Anaerobic biodegradaton 50%	-	-	-	-	+	-	+	-
	Waste treatment for prototype pck	Variable depends on waste management system, law etc.	Biological recycling rate (i.e. 50%)	+	+	+	-	+	+	+	+

Table 57 Matrix summarizing sensitivity analysis for EPS pck

LIFE CYCLE STAGE	Parameter	Variability and uncertainty	Modified parameter description	Contribution importance to total impacts compared to EPS pck basic scenario							
				NRER	RER	AC	EU	POF	AD	GWP	OD
End of life	Waste treatment for EPS pck	Variable depends on waste management systems	Material recycling rate (i.e. 30%)	-	+	-	-	-	-	-	-
			Material recycling rate (i.e. 50%)	-	+	-	-	-	-	+	-

Low contribution (<10%)

Medium contribution (10%-30%)

High contribution (>30%)

\+ Higher impact compared to the corresponding basic scenario

\- Lower impact compared to the corresponding basic scenario

A description of the sensitivity analysis is given below.

Starch type

In Table 58 the LCA results for the prototype pck produced with different types of starches are shown. Data on starches derived from Ecoinvent 2.2 ("Maize starch DE" and "Potato starch DE" – economic allocation) and Novamont (maize starch IT – mass allocation) databases.

Table 58 Results of potential impacts for the prototype pck (F.U.). Sensitivity analysis on type of starch

Impact category	Unit	Prototype pck Basic scenario	EPS pck Basic scenario	Maize* starch DE	Potato starch DE	Maize starch IT	Δ Maize starch DE vs. basic scenario	Δ Potato starch DE vs. basic scenario	Δ Maize starch IT vs. basic scenario
NRER	MJ eq.	75.5	152	101	90	93.7	34%	19%	24%
RER	MJ eq.	30.5	0.883	50.3	42	41.1	65%	38%	35%
AP	kg SO_2 eq.	0.0289	0.0273	0.0394	0.0385	0.037	36%	33%	28%
EP	kg PO_4^{3-} eq.	0.00939	0.00674	0.0267	0.0234	0.0156	184%	149%	66%
POF	kg C_2H_4 eq.	0.00135	0.0191	0.00151	0.00149	0.00153	12%	10%	13%
AD	kg Sb eq.	0.035	0.0683	0.0463	0.0411	0.0432	32%	17%	23%
GWP	kg CO_2 eq.	3.43	8.7	5.68	4.71	4.89	66%	37%	43%
OD	kg CFC^{-11} eq.	$5.56x10^{-7}$	$6.03x10^{-7}$	$7.60x10^{-7}$	$6.67x10^{-7}$	$8.32x10^{-7}$	37%	20%	50%

LCA results of Table 58 were normalized to EPS pck (=100%) and graphically reported in Figures 39.

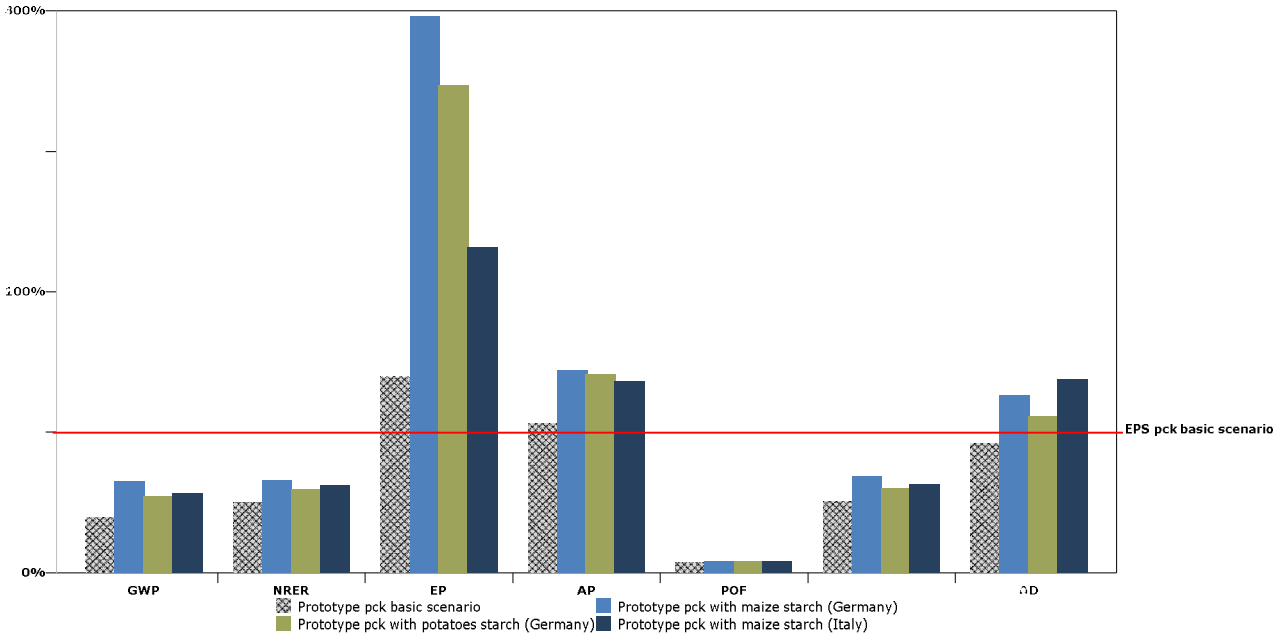


Figure 39 Normalized results (EPS=100%) for prototype pck produced with different starches

The increase observed for almost impact categories, especially eutrophication, was due to the fact that maize and potato, compared to tapioca, were produced in Europe within a fully mechanized agricultural practices using also a higher amount of inputs like fertilizers. In addition, the economic allocation applied in Ecoinvent datasets for maize and potato starches generated a higher impact compared to those observed when a mass based allocation was applied; e.g. for maize starch mass allocation factor was 0.63 whereas the economic one was 0.83 [40], an increase of about 30%.

Land Use Change (LUC)

Soils are characterized by a pool of carbon (carbon stock). The change of land (LUC) and the conversion from a natural situation (e.g. rain forest, grassland) to a anthropic situation (e.g. crops cultivation) causes a change in carbon stocks present in that portion of land. The removal of natural well for carbon dioxide (carbon sink) and its replacement with a rotating or multi-species, means that a proportion of CO_2 is no longer absorbed by the atmosphere. This aspect can have a major indicator for the "greenhouse effect", especially if to be converted for agricultural purposes is an area of rainforest. However it is worth to point out that direct emissions of cultivation (eg emissions of methane, N_2O and CO_2 fossil related to the use of fertilizers and emissions associated with combustion of diesel etc.) do not fall within the LUC, but they are quantified in the inventory of agricultural phase. There are no emissions associated with LUC, at least within the LCA methodology, when:

- switching from one crop to another because the category of agricultural land (arable land) remains unchanged. Eg maize cultivation in an area where he had grown soybeans;
- the change of land use occurred more than twenty years.

Within the sensitivity analysis the LUC emissions were estimated for tapioca produced in Thailand. As no LUC emission factors were available for Thailand those characteristics of Malaysia were used.

Two scenarios were analysed:

1) Best-case: tapioca is produced in an agricultural area previously occupied by pastures (meadows).

2) Worst case: tapioca is produced in an agricultural area previously occupied by rainforest.

The emission factors of CO_2 eq. resulting from the processing of land use (PAS 2050 methodology, emission factors for Malaysia, Annex C Table E.1) are given in Table 59.

Table 59 Emission factors for Malaysia - PAS 2050

Current land use	Previous land use	GHG emissions [t CO_2eq./ha/y]
Annual cropland	Grassland (best case)	10.3
	Forest land (worst case)	37

To produce 2.4 kg of the prototype pck 2.23 kg of tapioca starch (land occupation ≈1.7 m^2 were needed). The related greenhouse gases emissions for 100 port-hole spacers were reported in Table 60. They were obtained applying a simple allocation of LUC emissions.

Table 60 Fossil CO_2 emissions from land use change

	Scenario	Emissions of GHG [kg CO_2/F.U. prototype pck]
Fossil CO_2 from transformation of land use	best case	**1.8** (i.e. 10,300*1.7/10,000)
	worst case	**6.3** (i.e. 37,000*1.7/10,000)

Figure 40 is a revise of GWP results previously showed with the only difference that emissions from LUC were added to the tapioca cultivation phase. (i.e. best case and worst case). Basically three prototype pck scenarios were reported:

1. prototype pck without emissions from LUC – basic scenario

2. prototype pck with emissions from LUC (best case) – basic scenario
3. prototype pck with emissions from LUC (worst case) – basic scenario

The total values of Figure 40 include the atmospheric CO_2 trapped in prototype pck equal to 3.3 kg CO_2.

IMPORTANT NOTE

It is worth to point out that the sensitivity analysis on LUC emissions, does not reflect the real situation for starches used in the project, rather it was performed, on one side, for the sake of completeness of the LCA analysis and, on the other side, for highlighting the importance of using renewable raw materials produced in a rational way. In particular, Novamont (partner and coordinator of the REBIOFOAM project), is committed in the industrial development of local bio-refineries projects which aim to strictly integrate a local "zero-waste" farming activity with the production of renewable raw materials or intermediates suitable to be used in bio-plastic sector but not only. To this ends no deforested or natural virgin soils are or will be exploited, rather marginal areas, or polluted soils not suitable for food production, will be more and more used in the next future [62]. Even possible future pressures on land use, caused by the bio-plastic sector growth are, however, expected to be not valuable [63], thus also LUC or ILUC (Indirect Land Use Change) related emissions would result to be contained, at least, in relative terms.

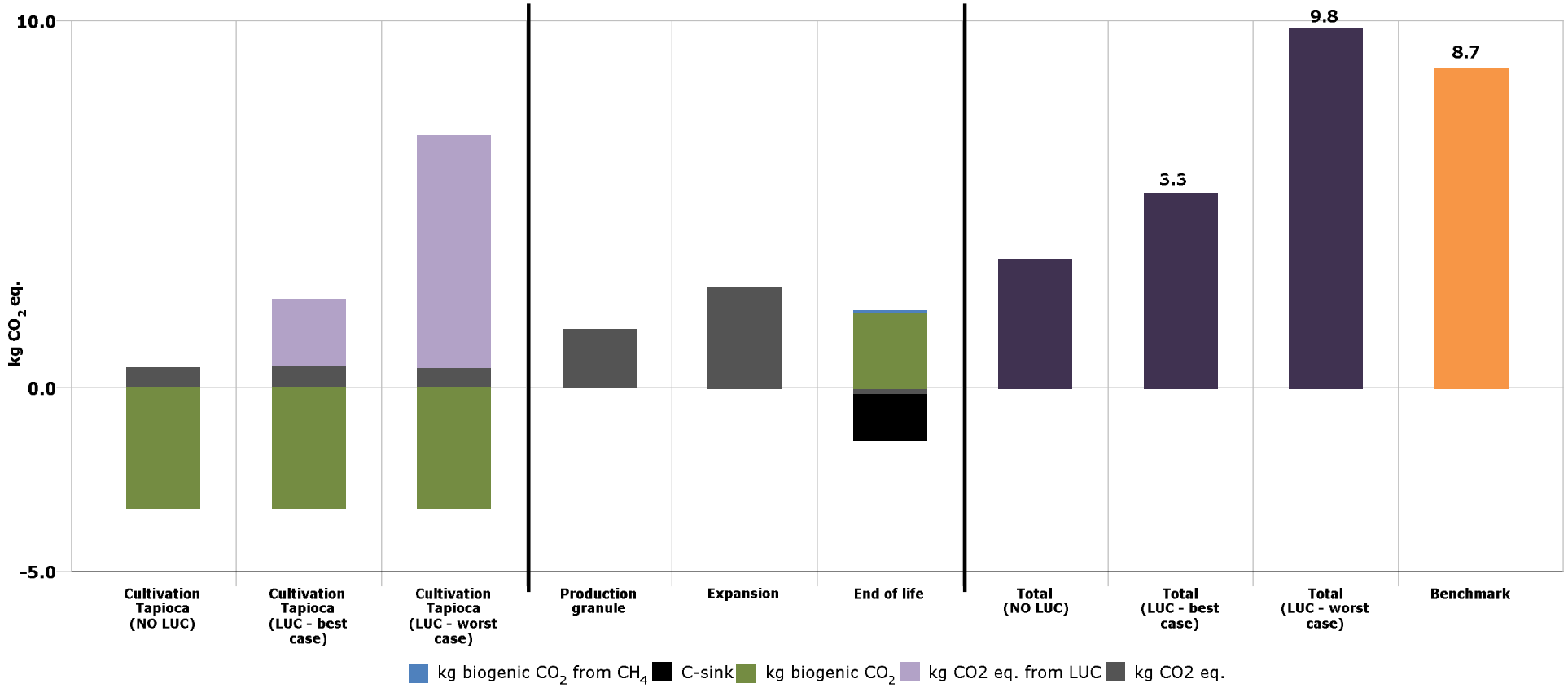


Figure 40 Greenhouse gases "cradle to grave" prototype pck. Sensitivity analysis on LUC

The greenhouse gases emissions related to changes in land use (LUC) may be much more significant compared to those resulting from tapioca cultivation (e.g. diesel combustion in tractor, fertilizers production and use etc.). This sensitivity analysis showed the importance of emissions associated with LUC. Agricultural feedstock has to be produced avoiding the conversion of natural lands into agricultural ones.

Doped mould (prototype pck expansion process)

LCA results related to the use of a doped mound in the prototype expansion are shown in Table 61.

Table 61 Results of potential impact for the prototype pck (F.U.). Sensitivity analysis on doped scenario

Impact category	Unit	Prototype pck Basic scenario	EPS pck Basic scenario	Prototype pck Doped mould	Δ "Doped" scenario vs. basic scenario
NRER	MJ eq.	**75.5**	152	107	42%
RER	MJ eq.	**30.5**	0.883	33.3	9.2%
AP	kg SO_2 eq.	**0.0289**	0.0273	0.0389	35%
EP	kg PO_4^{3-} eq.	**0.00939**	0.00674	0.0115	22%
POF	kg C_2H_4 eq.	**0.00135**	0.0191	0.00176	30%
AD	kg Sb eq.	**0.035**	0.0683	0.0494	41%
GWP100	kg CO_2 eq.	**3.43**	8.7	5.46	59%
OD	kg CFC-11 eq.	**5.56x10^{-7}**	6.03x10-^{7}	7.90x10-^{7}	42%

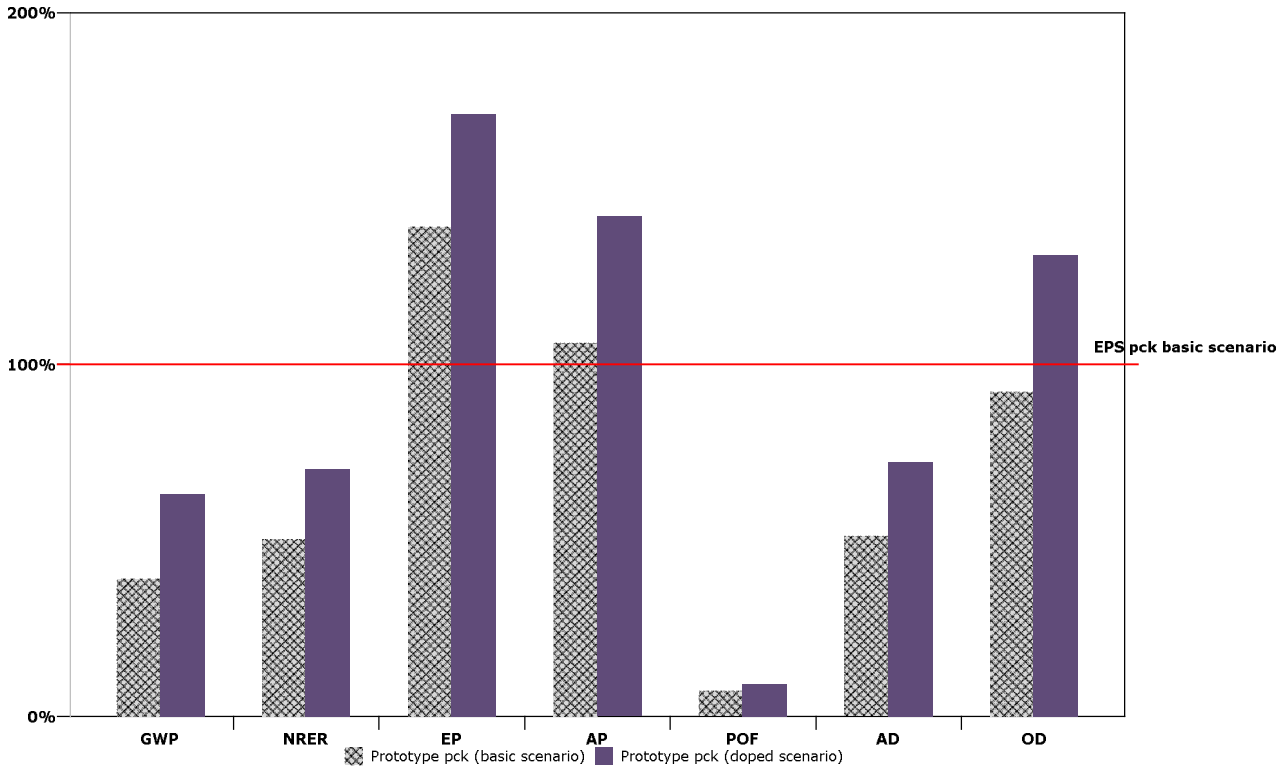


Figure 41 Normalized results (EPS =100%) for prototype pck produced with an undoped mould (basic scenario) and with a doped mould

To notice how an increase of electricity consumption significantly affected all the impact categories especially GWP, NRER and AD due to the fact that electricity mixes are heavily based on non renewable energy resources like oil, natural gas and coal exploitation.

End of life

- *Biodegradation in landfill (prototype pck)*

Table 62 Results of potential impacts for the prototype pck (F.U.). Sensitivity analysis on scenario with 50% biodegradation in landfill

Impact category	Unit	Prototype pck Basic scenario	EPS pck	Biodegradation in landfill 50%	Δ Prototype pck biodegradation in landfill 50% vs. basic scenario
NRER	MJ eq.	**75.5**	152	72.8	-4%
RER	MJ eq.	**30.5**	0.883	30.4	-0.3%
AP	kg SO_2 eq.	**0.0289**	0.0273	0.0282	-2%
EP	kg PO_4^{3-} eq.	**0.00939**	0.00674	0.00784	-17%
POF	kg C_2H_4 eq.	**0.00135**	0.0191	0.00178	32%
AD	kg Sb eq.	**0.035**	0.0683	0.034	-3%
GWP 100	kg CO_2 eq.	**3.43**	8.7	5.86	71%
OD	kg CFC-11 eq..	**$5.56x10^{-7}$**	$6.03x10^{-7}$	$5.49x10^{-7}$	-1%

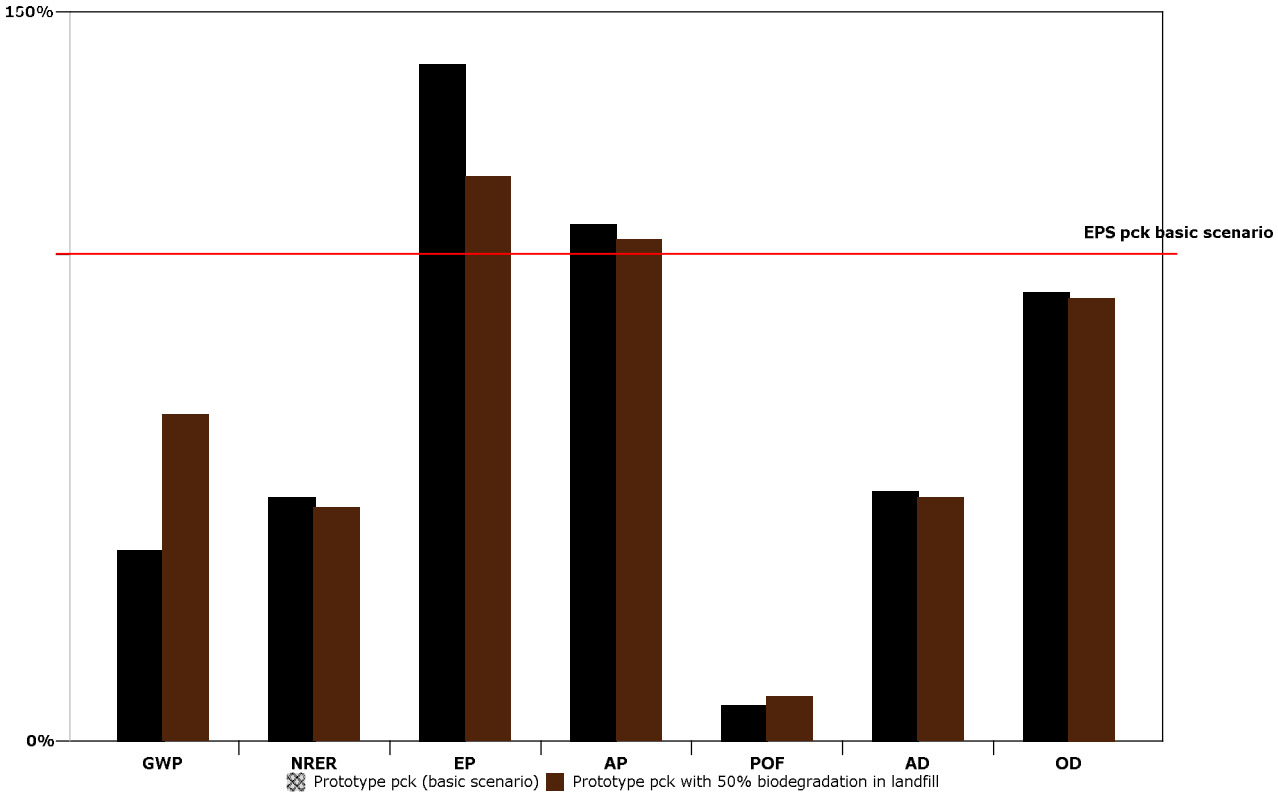


Figure 42 Normalized results (EPS=100%) for prototype pck (basic scenario) and prototype pck with a 50% biodegradation in landfill

As expected the increase of biodegradation rate in landfill generated a valuable increase of GHG emissions mainly.

- *End of life scenarios*

Beyond the basic scenarios three "improved" scenarios (two for EPS pck and one for the prototype pck) were analysed. The obtained LCA results are given in table 63a and 63b.

Table 63 a) Results of environmental impact for improved scenario prototype pck

Impact category	Unit	Prototype pck basic scenario	Improved scenario (50% biological recycling)	Δ Improved scenario vs. prototype pck Basic scenario
NRER	MJ eq.	75.5	76	0.7%
RER	MJ eq.	30.5	30.6	0.3%
AP	kg SO_2 eq.	0.0289	0.0293	1%
EP	kg PO_4^{3-} eq.	0.00939	0.00912	-3%
POF	kg C_2H_4 eq.	0.00135	0.00136	0.7%
AD	kg Sb eq.	0.035	0.0354	1%
GWP 100	kg CO_2 eq.	3.43	3.65	6%
OD	kg CFC-11 eq.	$5.56x10^{-7}$	$5.61\ x10^{-7}$	1%

Table 63 b) Results of environmental impact for scenario 100% end of life EPS pck

Impact category	Unit	EPS pck basic scenario	Improved scenario (30% mechanical recycling)	Improved scenario (50% mechanical recycling)	Δ Improved scenario 1 (30%) vs. EPS pck basic scenario	Δ Improved scenario 2 (50%) vs. EPS pck basic scenario
NRER	MJ eq.	152	130	114	-14%	-25%
RER	MJ eq.	0.883	0.985	1.05	12%	19%
AP	kg SO_2 eq.	0.0273	0.0249	0.0233	-9%	-15%
EP	kg PO_4^{3-} eq.	0.00674	0.00586	0.00526	-13%	-22%
POF	kg C_2H_4 eq.	0.0191	0.019	0.0189	-0.5%	-1%
AD	kg Sb eq.	0.0683	0.0579	0.0509	-15%	-25%
GWP 100	kg CO_2 eq.	8.7	7.49	6.68	-1%	-23%
OD	kg CFC-11 eq.	$6.03\ x10^{-7}$	$5.85\ x10^{-7}$	$5.72\ x10^{-7}$	-14%	-5%

Figure 43 shows the LCA results (Table 63a and 63b) normalized to the prototype pck basic scenario (=100%).

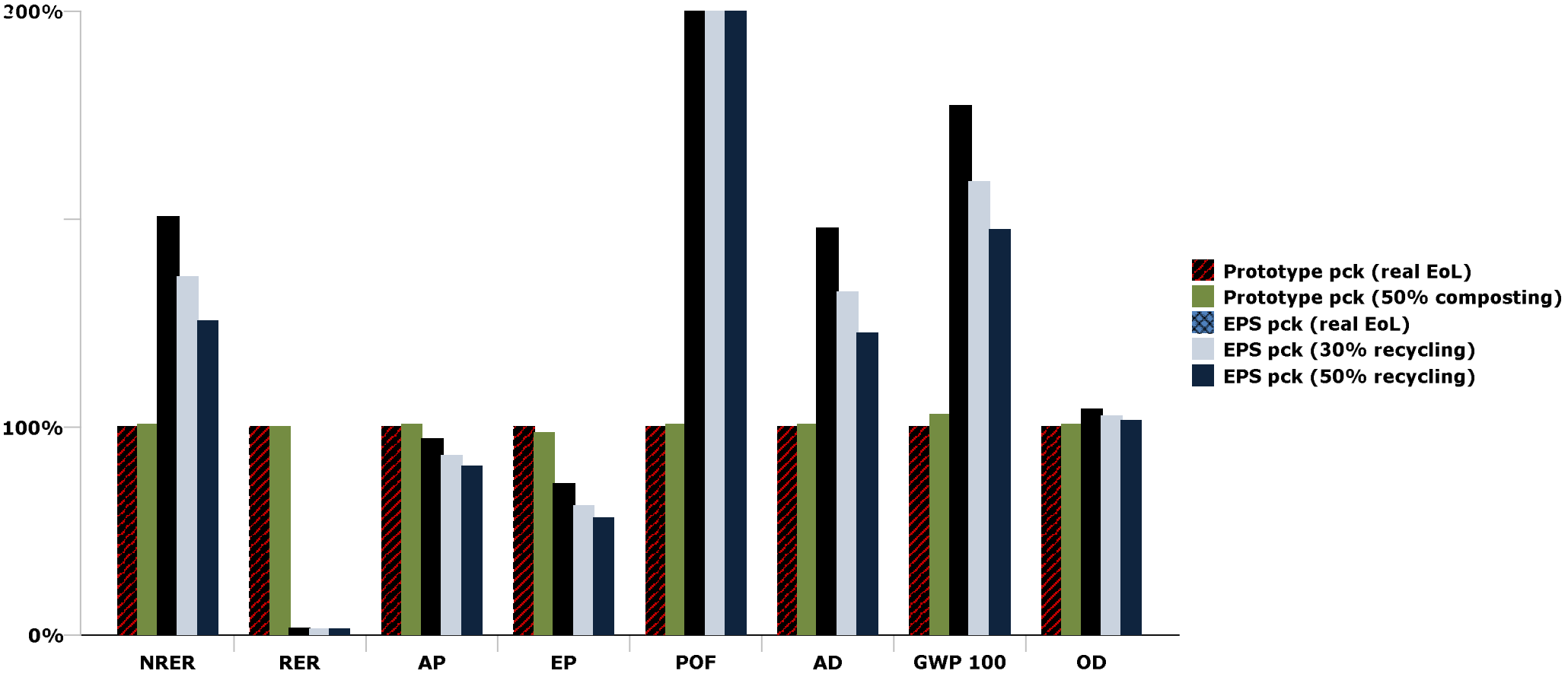


Figure 43 LCA results of the analyzed EoL scenarios normalized to the prototype pck basic scenario (100%)

As can be observed the increase of recycling rate for EPS pck allowed to reduce the potential impacts from 0.5% up to 25% depending on the improved scenario and impact categories considered, nevertheless, the prototype pck basic scenario scored still better. On the contrary the improved scenario for prototype pck did not generate significative changes in LCA results (0.3%-6%) compared to the basic one.

4.3 CONCLUSIONS

Expanded pck systems like those made of EPS are generally characterized by a short life becoming a waste to be handle very quickly. Due to cost-effectiveness issues like low quantities, low bulk density, difficulties in separating and identification of plastics by the end user, EPS pck wastes generated at house hold level are generally characterized by a low recycling rate [3]. A **biodegradable and compostable packaging system like the prototype developed within REBIOFOAM project** (i.e. port-hole spacer) **is potentially suitable, as demonstrated, for inclusion in the industrial composting process or home composting**[6]**, or the waste water system opening new routes for waste treatment.** As the collection of bio-waste fraction of Municipal Solid Waste (MSW) across the countries where washing machines are sold, was estimated to be about 40%, a potential **(biological) recycling rate for prototype pck of 40%, without modifying waste collection schemes currently running** would be expected. On the contrary for a traditional (not compostable) expanded pck system, the estimated recycling rate ranged from 0% up to 2.5%, on average 0.5%[7]. According to such figures it could be argued that a compostable **pck system may increase diversion from landfill.** A preliminary estimation suggested, de facto, that on average landfill would pass from about 52% (current scenario with EPS pck system) to 37% (alternative scenario with a compostable pck system), a reduction of **15%.**

Beyond potential beneficial effects on waste management, the prototype pck was assessed also from a life cycle perspective using LCA methodology performed largely following ISO 14044 standard. The analysis covered the most significative life cycle stages of the prototype like raw material acquisition, prototype pck production and its disposal. Primary data reflecting the best trial outcomes for the prototype pck were used and obtained LCA results were compared with those characterizing EPS pck system, whose LCA was largely based using average industrial data representative of European production. Overall the comparative analysis was performed with a good approximation. A special attention was dedicated to uncertainty aspects that always characterize LCA analysis, thus a Monte Carlo simulation and sensitivity analysis for the key parameters were performed as well.

From a LCA perspective, **the prototype pck showed a lower non renewable energy and abiotic resources consumption (-50% for both categories) along with a significant reduction in greenhouse gas emissions (-60%) compared to EPS pck.** This was mainly due to the use of a renewable feedstock represented by starch. Also photochemical ozone production potential resulted significantly lower **(-90%)** but, in that case, it was due to the absence of the expanding agent (i.e. pentane) used instead in EPS expansion process. The robustness of these preliminary results was verified by performing a Monte Carlo simulation whose outcomes confirmed the reliability of LCA results.

In reference to the other impact categories like eutrophication, acidification and ozone depleting the prototype scored respectively **+40%, +6%** and **-8%** compared to EPS pck, nevertheless, the Monte Carlo simulation suggested for all three impact categories that such differences were little significant (for eutrophication) or not significant at all (for acidification and ozone depleting), however, it is worth to point only 50% of inventory data used in the model had a statistic distribution, especially for polystyrene material where no distribution data were available.

[6] Such scenarios were not analyzed in this analysis.

[7] To point out that the recycling rate was related to the EPS packaging generated at household level.

Normalization suggested that among all impact categories considered, ozone depletion showed the lowest relative importance (i.e. magnitude).

Contrary to what one may expected, the water consumption for the prototype pck was lower (-30%) compared to EPS pck, but uncertainty for this category may be very high. In addition, due to lack of data, the Monte Carlo simulation was not performed so no statically considerations could be done. More complete and representative data will be needed in the future.

Coming to contribution analysis, it showed that **granule production** and **expansion** process both for prototype pck and EPS pck **dominated the overall LCA impacts.** In particular crop cultivation (e.g. tapioca) from which the renewable feedstock (i.e. starch) was obtained, showed the most critical phase for Eutrophication value of the prototype, whereas, tapioca starch transport (from Thailand to Italy) contributed for about 20% of the overall impact for acidification always for the prototype.

The sensitivity analysis suggested that if the starch for producing prototype pck came from maize or potato rather than tapioca and an economic allocation is applied, then a valuable increase for almost all potential impacts especially acidification and eutrophication was observed. It could be argued that the reason of such an increase was due to the fact that maize or potato, compared to tapioca, were produced in Europe within a fully mechanized agricultural practices using also a higher amount of inputs like fertilizers. As expected the use of a doped mould (for the prototype expansion process), associated to an higher electricity consumption, caused an increase of impacts ranged from 20% up to 60% compared to the prototype basic scenario (IR system). An increase of the biodegradation rate in landfill (equal to 50%) for the prototype material caused an increase of 70% of greenhouse gas emissions and 30% of photochemical ozone formation compared to the basic scenario where the biodegradation rate was assumed to be 1% [64].

Regarding EoL scenarios, it was observed that an increase of EPS pck recycling rate (30% and 50% respectively) generated reductions of impacts up to 25% depending on the scenario and impact categories considered, whereas, for the prototype pck an increase of the biological recycling rate, from 40% which is the current collection rate to 50%, did not generate significant variations of the LCA results[8].

Finally, if renewable raw materials like tapioca, maize etc. were produced in agricultural lands derived from natural lands (grassland or forestland) then, the greenhouse gas emissions or GWP potential for the bio-based product may increase very significantly (from 50% up to 180%) as shown by the sensitivity analysis on LUC emissions using Malaysia emission factors. This suggested the importance of producing renewable feedstock in a rationale way.

Overall the sensitivity analysis showed a possible increase of potential impacts for the prototype pck, depending on parameters considered, nevertheless, its environmental profile was expected to result still very promising compared to EPS pck, especially if we consider that **many rooms of improvement exist**.

The magnitude of the use of agricultural resources (starches) for producing an amount of prototype pck material able to replace **30%** of pck oil-based transport materials in EU (about 3 million of metric t per year) , would be about **0,6%** of the total World production of tapioca, maize and potato [18].

[8] For this specific application such a result is quite reasonable since the compostability of the pck. system did not have valuable effects on other systems like other applications did (e.g. biodegradable bin liner, biodegradable catering items etc.)

Based on the analysis outcomes the following recommendations (areas of intervention) for the prototype pck were formulated:

- Reduction of the density of the pck material → less use of resources
- Expansion process: industrial scale design has to be performed with a particular attention to electricity consumption → maximize electricity efficiency
- Use of a IR system rather than a doped mould (already achieved)
- To use only renewable feedstock produced in a rationale way → e.g. no LUC
- Investigate the feasibility of using renewable feedstock coming from vegetable scraps

Further valuable improvements regarding the environmental profile of the prototype could be achieved if the renewable electricity for carrying out expansion process was used[9]. The **reduction** of impacts would range from **30%** up **80%** depending on impact categories considered.

Last but not least was **a clear identification by the end users that they have on their hands a pck that can be disposed of along with bio-waste stream**. The correct disposal, collection and treatment, are crucial for the success of widespread applications of biodegradable packaging materials. Only if these conditions are meet it will be possible to maximally exploit the added value of bio-based and biodegradable pck systems. In other words framework and consumer awareness are fundamentals.

In the worst case, which see the pck left in the environment (i.e. littering), prototype material can represent a "safety net" thanks to its biodegradation.

Finally two foods for thoughts about LCA based on what we have learned here and from other experiences in the LCA field, were provided.

a. LCA hotspots e.g. consistency of the model, availability of high quality inventory data, uncertainty, robustness of results, etc. **have to be "handle with care".** If it is not done then analysis outcomes **may be prive of meaning.** On the other side, this may require a lot of efforts and time making the traditional application of the LCA a no quick-response tool for Eco-design. However, future improvements towards a more harmonized rule, the resolution of debates on analytic aspects and the development of shared databases containing a higher amount of data for processes and materials will lead to a more efficient use of the LCA.

b. Due to the high number of variable parameters, LCA can provide **reliable** answers only to precise questions. For example, questions like: "Are bio-based products better than traditional ones?" may have no sense. In general it was observed that the environmental profile of innovative products **is heavily related** to three "key words":

    1. **WHAT:** What is the product that is going to be replaced by the innovative one? What are the characteristics of products like weight, used materials etc? What about frameworks e.g. waste collection schemes, technologies etc.?

    2. **HOW:** How raw materials are produced? e.g. agricultural practices. How efficiently are the resources along product value chain used? Etc.

[9] This would generate an higher production costs.

3. **INDIRECT EFFECTS:** What is the role of "induced effects" that may occur when a new product/new solution are put in practice? For example according to Denkstatt study [65], beneficial effects associated to the **use phase** of a product (e.g. insulation panel in buildings that prevent an higher amount of heat losses compared to a given benchmark) may be **much more relevant** than the impacts associated to its production. This suggests that whenever there are, or are expected to be, valuable indirect effects[10] they should be investigated and taken into consideration. In other words, a "consequential" LCA approach (CLCA) would be by far preferable making the assessment more consistent and reliable.

[10] The term "valuable indirect effects" can describe beneficial, or negative or both effects.

5 FUTURE WORKS

Future works can be grouped in two different areas. The first one is related to the prototype development and the second one to LCA analysis. In reference to the prototype, the investigation of other possible pck applications based on REBIOFOAM material properties would be very desiderable and useful. Parallel to this further investigations about the interaction between electromagnetic field (microwave) and prototype granule would be desiderable so as to increase the collection of data and increase the knowledge of the interactions. Also the study of the geometry of the microwave system along with the shape of the granule are of great interest. All these future works would allow to define other potential pck applications and a higher efficiency of the innovative process.

In prevision of an industrial exploitation of such an innovative “concept” of pck system, an important aspect to be further investigated is the economic cost analysis of the pck system preferably including also the positive externalities associated to a reduced environmental impact of the innovative pck compared to the traditional ones. Also all formulated recommendations from LCA analysis should be put in practice, especially the possibility to use renewable electricity for carrying out the expansion process that would allow getting an extraordinary environmental profile of the innovative pck compared to traditional pck systems.

From a LCA standpoint many rooms of improvements and future works exist as well. For example an interesting aspect would be the analysis of less common EoL treatments for pck system like home composting, anaerobic digestion followed by composting and wastewater treatment. Surely also the analysis of other possible pck applications would be very desiderable also for guiding the choice of the best application/s where a bio-based and biodegradable pck can maximally exploit its characteristics. From a methodology point of view a higher amount of uncertainty distribution data would be desiderable so as to increase the reliability of the analysis. Also sensitivity analysis about capital goods, system boundaries (e.g. consequential approach for upstream phases) etc. would be very useful to get a broader picture. Further the environmental profile could be calculated also considering other important aspects like human toxicity, eco toxicity and land use but there are still some methodological weak points to be solved by the scientific community and a univocal methodology still does not exist. Also the assessment of water consumption, as performed in this analysis, should be improved. A more consistent method would be desiderable but also in this case the methodological approach is still under development (review) by experts. Concluding the developments on these methods will be monitored and the analysis performed as soon as a consensus will be achieved. Last but not least is the critical review expected for this study. For the time being it will validate or not the performed analysis based on the data and knowledges available so far.

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APPENDIX A

BIODEGRADATION AND COMPOSTING TESTS ON THE PROTOTYPE PCK

(extracted from Milestone Assessment Report MS 9 - 31 July 2012 REBIOFOAM Project)

The present document reports about Milestone MS 9 "**Successful biodegradation and composting**" in the framework of the REBIOFOAM project.

The document provides an initial brief recap of the results expected to be achieved by Milestone MS 9 and provides a brief overview of the assessment criteria foreseen, i.e. those defined by the standards. In particular the European standard for biodegradation performances is the EN 13432. The complete description of the activities will be reported within the deliverable 7.5.

The report refers to activities carried out within Workpackage 7 and more specifically of activities carried out within Task 5 "biodegradation and compostability tests according to the standards".

Assessment Criteria

According to EN13432 a packaging is compostable if it is formed by components, which have been, each individually, qualified as compostable. In this way the analysis of compostability of a packaging is simplified and traced back to the analysis of compostability of the single constitutive materials. Therefore, it is sufficient to use compostable materials in order to obtain a final compostable packaging.

The European norm defines the specific properties of the compostable packaging materials and the test methods needed to verify their conformity. The compostable packaging shall be endowed with four main features.

- Biodegradability that is the metabolic conversion of the packaging material into carbon dioxide (absence of chemical pollution).
- Disintegrability that is fragmentation and loss of visibility in the final compost (absence of visual pollution).
- Absence of negative effects on the process of composting.
- Absence of negative effects on the final compost (i.e. reduction of the agronomic value and presence of ecotoxicological effects on the plant growth).

Each of these points is required for the definition of compostability but is not sufficient, alone (Figure 1). A biodegradable material is not necessarily compostable, because it must also disintegrate during the composting cycle and it must cause no problem either to the process or to the final product (the compost).

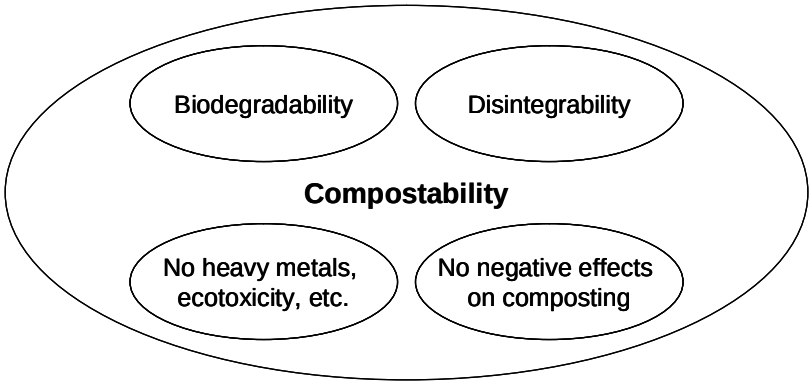

Figure 1 Compostability is a set of properties. Each of them is necessary but not sufficient

Description of relevant Activities

The activities related to the assessment of the biodegradation and composting have been carried out within the task 7.5 and are based on:

- **Biodegradation test (ISO 14851):**

The biodegradation of a test item was studied in aqueous conditions at room temperature (28ºC) using as inoculum an activated sludge collected in an industrial waste water treatment plant. The test material is added to a mineral medium, a salts solution without organic carbon sources, and inoculated with diluted activated sludge. During the aerobic biodegradation of organic materials in an aqueous medium, oxygen is consumed and CO2 is produced, in addition a little part of organic carbon is assimilated from microorganisms (biomass). Measuring the oxygen consumed during the test it is possible to calculate the Biodegradation of the test material as ratio between the Oxygen consumed and the theoretical oxygen demand.

The test is performed according to the international standard ISO14851 "Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium – Method by measuring the oxygen demand in a closed respirometer".

According to the normative the test is considered valid if the BOD/TOD is more than 90% or is 90% of the reference material (cellulose).

- **Disintegration test (ISO 20200:2004):**

The ISO20200 Plastics- Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test specifies a method of determining the degree of disintegration of plastic materials when exposed to a laboratory-scale composting environmental. The method simulate an intensive aerobic composting process. It is necessary to use a synthetic solid waste (sawdust, rabbit food, starch, sugar, urea, oil) inoculated with mature compost taken from a commercial composting plant. Pieces of a plastic material are composted with the synthetic waste. At the end of the test the degree of disintegration is determinate by sieving the final compost in order to recover the non-disintegrated residues of the test material. The weigh loss of the material is considered as disintegrated material and should be more than 90%.

- **Ecotossicity test (EN 13432)**

The sample (porthole spacer) is disintegrated in composting conditions. At the end of the test, the compost (where the sample is completely disintegrated and that will be called “sample”) was used for two ecotoxicity tests for determining the growth of radish plant and cress. In parallel with sample, “reference” compost was tested; it was obtained at the end of a disintegration test without the presence of the test material. The plants grow should be more than 90%.

In parallel on that the amount of heavy metal should be lower than the limits.

Milestone assessment

The results of the tests of characterization are reported bellow.

- **Biodegradation test (ISO 14851):**

The REBIOFOAM sample at the end of the test, after 69 days, reached a final biodegradation of 68.76%; the cellulose (reference material) showed a biodegradation of 64.61% and the starch 68.13%.

The REBIOFOAM sample can be considered as completely biodegradable in aquatic mesophilic conditions, and it satisfies the biodegradation requirements defined in EN13432.

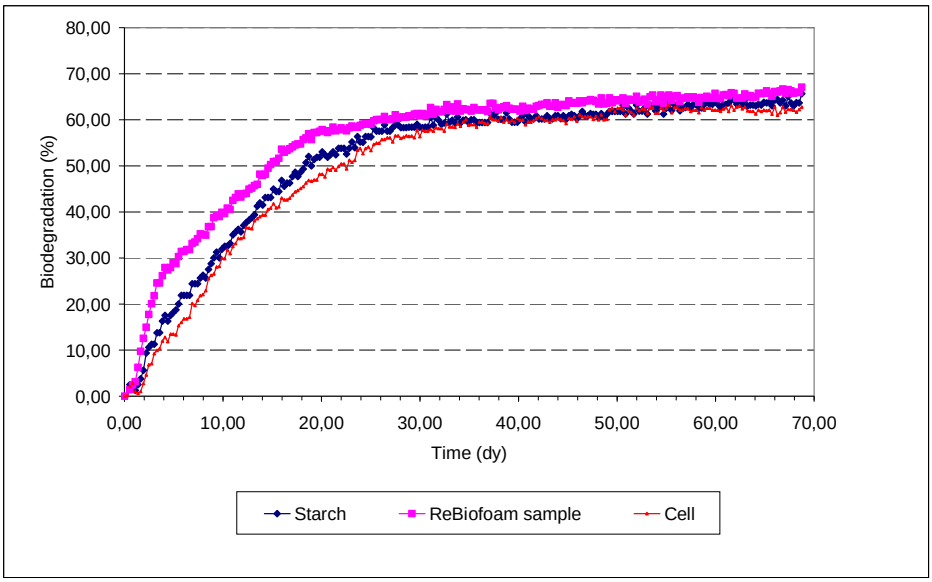

Figure 2 Evolution of the average biodegradation percentages for cellulose (reference material) starch and REBIOFOAM sample.

- **Disintegration test**

After 90 days of test , 45 days at 58°C and 45 days at 45°C, the disintegration of the porthole spacer (having density of 40 kg/m3) was 99.4% (minimal pieces of material were present as reported in figure 3).

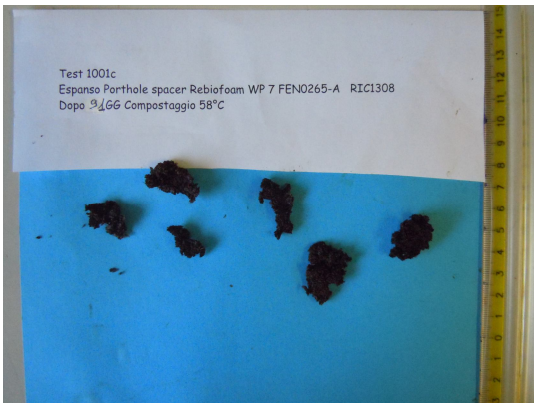

*Figure **3** Samples after 90 days of composting, after cleaning and drying*

Ecotoxicity test Radish plant growth test on compost residuals of the sample

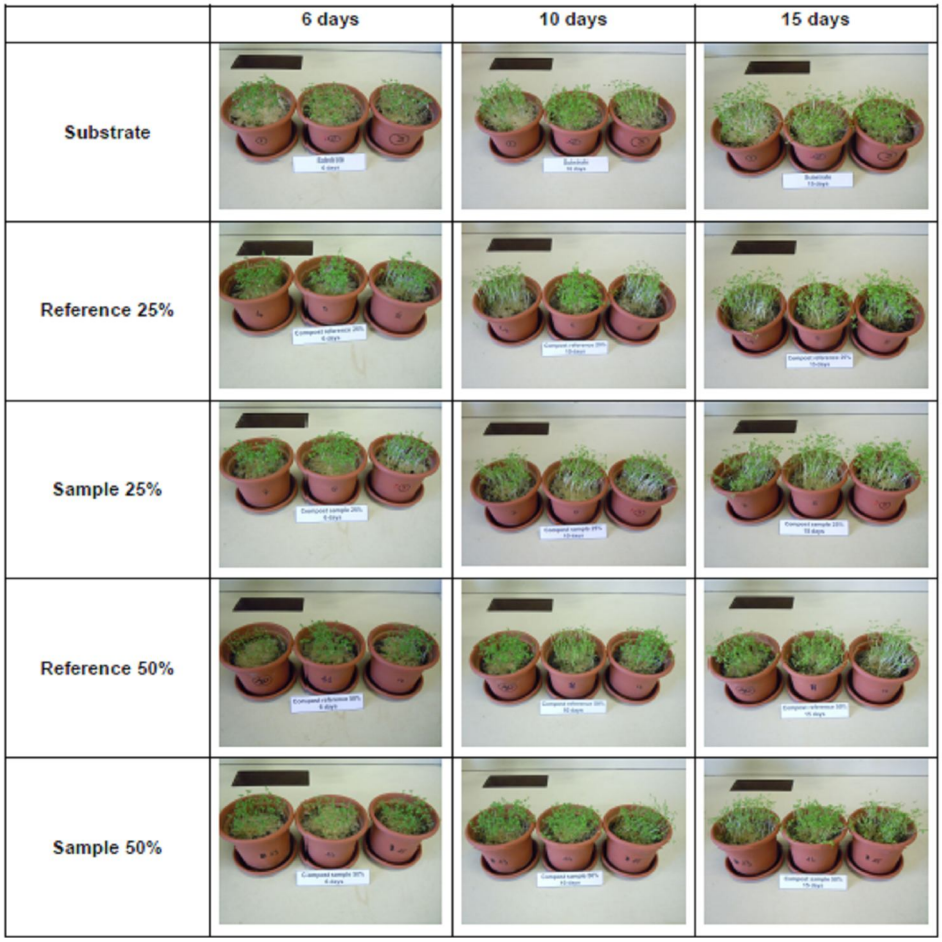

Figure 4 Growth of the cress in the different pots during the test.

The ecotoxic effects to higher plants were determinate on compost after the disintegration of the sample "porthole spacer". The tests were performed according to EN 13432, using radish and cress. The seeds germination and the biomass production were evaluated. In all cases the number of seeds germination and the amount of biomass are over 90% as required by the EN 13432. So, the tested sample has no toxic effects on the tested plants. In parallel on that the presence of heavy metal was evaluated as well. All the elements required by the standard were within the limits.

According to the tests, the porthole spacer can be defined biodegradable and compostable according to the European Standard EN 13432.

APPENDIX B

ABBREVATIONS

Abbreviations	
AP	Acidification
AD	Abiotic depletion
EPD	Environmental Product Declaration
EU	Eutrophication
GWP	Global Warming Potential
NRER	Non Renewable Energy Resources
LO	Land Occupation
OD	Ozone Depletion
POF	Photo-Chemical Ozone Formation
LHV	Lower Heating Value
HHV	Higher Heating Value
CH	Swiss representative
GLO	World representative
RER (Impact category)	Renewable Energy Resources
RERC	Renewable Energy Resources Consumption
RER	European reference
PAS 2050	UK carbon foot print standard
UCTE	Union for the Co-ordination of Transmission of Electricity
WC	Water consumption
LUC	Land Use Change
EoL	End of Life
MSW	Municipal Solid Waste
DE	Representative of Germany
Pck	Packaging
F.U.	Functional Unit
WP	Work Package (i.e. task defined within the REBIOFOAM project)

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