

Life Cycle Assessment (LCA) applied to the sustainability assessment of an environmental biotechnology for air treatment, a case study.

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Abstract: - Life Cycle Assessment methodology has been applied to the sustainability evaluation of an environmental biotechnology in an eco-design perspective. This to avoid possible shifting of burdens among different environmental matrices possibly occurring when a remediation activity is performed. GHG Protocol and IMPACT 2002+ calculation methods have been applied. Results show that about 80% of the impact generated is to be attributed to energy consumption during the use phase, thus promoting an integration of the technology under study with renewable energy sources. In order to try and consider environmental benefit deriving from air treatment activity, an evaluation of the technology as carbon sink has been performed, comparing results obtained from impact assessment with specific reference. Results obtained suggest that a single bioreactor unit could act as carbon sink equivalent to a number of trees ranging from 43 (high growth rate species), to 268 (low growth rate species).

Key-Words: - Sustainability, LCA, carbon sink, air treatment, biotechnology, bioreactor.

1 Introduction

The eco-efficiency concept was defined by World Business Council for Development (WBCSD, 2000) and it “is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impact and resource intensity throughout the life cycle, to a level at least in line with the earth’s estimated carrying capacity”.

In this sense, environmental impact indicators, such as Carbon Footprint (CF) and Life Cycle Assessment (LCA) represent powerful decision supporting tools.

LCA, in particular, results a comprehensive assessment of environmental performances. Society of Environmental Toxicology and Chemistry provided with a definition of LCA in 1993: “Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product or process by identifying and quantifying energy and materials used and wastes released to the environment”. Developed in compliance with UNI EN ISO 14040:2006 [1] and UNI EN ISO 14044:2006 [2], it is generally applied for the assessment of eco-efficiency and environmental impact of product and processes, allowing the

quantification of environmental impacts generated throughout the whole life cycle, already during the design phase.

In the eco-design perspective, the implementation of LCA tool enables to tackle the 80% of the overall environmental impact of a product/process. LCA has been only recently used to evaluate innovative remediation solutions for contaminated groundwater and contaminated sites [3, 4], due to difficulties, on one hand, in adaptation of software tools developed to evaluate product, rather than process (such as SimaPro and Gabi), and, on the other hand, in quantification of environmental benefit granted by the clean-up intervention. Timing to meet the remediation goals and lifespan of the technique applied are also critical elements, strongly affecting the tuning of the model.

Within this framework, a screening LCA has been developed to evaluate the biotechnology under study. SimaPro software, version 7.3.3., by Pré Sustainability (2006), has been applied, as compliant with ISO 14040 [1]-14044 [2] standard and assessment procedure proposed by JRC (2007) in International Reference Life Cycle Data System (ILCD) Handbook e General Guide for Life Cycle Assessment and Detailed Guidance [5].

The goal of the present study is to outline an assessment of environmental performance of a biotechnology, in the form of free-standing bioreactors for air treatment as presented by Bonoli and Zanni [6]. The technology is based on immobilized cell bioreactors, working in open air through a combination of convection and biological digestion of materials captured, as leading mechanism.

For the scope of the study, a single bioreactor for households or healthcare sector application, i.e. small size, was defined as functional unit, over supposed 5 years of activity. Due to the lack of specific information and pilot stage of applications followed, end-of-life phase was not taken into account and it will be subject of further iterations and refinements of the assessment. Considering the longer expected life-span of the technology, the choice of recyclable materials from the supply chain (plastic and metals) and the modular design, this assumption appeared reasonable, at a screening phase. Moreover, no benefit, i.e. positive impact, has been accounted for environmental remediation, except for final evaluation as carbon sink (par. 3.3.).

Where no primary data were available from the manufacturer, literature data has been implemented. In order to improve consistency of data, only one database has been used, among different provided by SimaPro software, i.e. Ecoinvent.

Two different calculation methods have been applied, in order to obtain, on one hand, an overall impact assessment, considering different impact categories and, therefore, effects on the environment, provided by IMPACT 2002+, and on the other hand, a single-issue evaluation, focusing on carbon dioxide, both directly and indirectly, and global warming, with Green House Gases Protocol method.

As screening LCA, significant issues have been identified, in terms of impact categories affected by the technology production and use and key processes, triggering the most relevant contributions to environmental impact. In the eco-design perspective, results have been shared with the manufacturing company, in order to implement conclusions from the present study into production activity.

2 Problem Formulation

The technology evaluated for the present study has been developed in the industrial biotechnology field and it is based on immobilized cell bioreactors. The bioreactors tested and currently applied on air treatment are classified as "Immobilized cell

bioreactors" and work with a combination of convection and biological digestion of materials captured, as leading mechanism.

The bioreactors, in analogy to bioscrubber technology [7], consist of three phases in close contact (Fig. 2.1.):

1. a solid phase, which is the bioreactor itself,
2. a liquid phase, i.e. water,
3. a gas phase, that is air (in case of air treatment application, it corresponds with the polluted medium to be treated).

As in common biofilters, the physical support for biomass growing is offered by a solid medium, but, in this case, a plastic patented bioreactor is provided with optimized configuration [8].

In this case, the air treatment system is based on stand-alone bio-oxidizers providing internal air-mixing within the facility where it is placed and capture particulates and gases by attracting them.

A Life Cycle Assessment is needed, in order to evaluate and quantify the actual environmental impact generated by the production and application of this technology, avoiding possible shifting of burdens among different environmental matrices (e.g. performing remediation over indoor air only to create remarkable impact on water bodies) or locations (e.g. improving air quality at local scale while generating high emissions at global scale).

Compiling Life Cycle Inventory (LCI) represents a major effort, in terms of data collection, processes evaluation, material and energy flows identification and quantification, details definition and simplification decision. Inventory compilation and analysis, in fact, require an extensive data collection and accurate calculations to quantify relevant inputs and outputs of a product system, related to specific functional unit and system boundaries.

As reported by former studies [3], properly accounting the environmental benefits deriving from clean-up activity may be regarded as one of the most challenging aspects of a LCA. In this case, in particular, the technology is applied for a general improvement of indoor air quality and the positive impact should be tuned accordingly to the purpose and standard performance recorded.

3 Problem Solution

Life Cycle Assessment methodology has been applied on the biotechnology under study, following ISO 14040:2006 [1] and 14044:2006 [2].

Within the framework of this study, both primary data (i.e. collected in the production site or provided by the manufacturing company) and secondary data (i.e. collected from manuals, databases and technical

specs of similar product currently on the market) have been used.

In order to work on data from literature as coherent and significant as possible, Ecoinvent has been used as only source of database information. As declared by Swiss Centre for Life Cycle Inventory [9, 10], Ecoinvent is aimed to provide a set of generic and unified data, all relevant, reliable and transparent. This to allow easier Life Cycle Assessment, providing public with credible and widely acceptable results.

Life Cycle Inventory was compiled, for the present study and within the framework of a screening LCA, as reported in the following. Several assumption and cut-off decision were necessary in this phase and they will be subject to revision in future iterations of the analysis.

In particular, the process representing the functional unit, i.e. one bioreactor for healthcare application, has been built up on 10 sub-processes:

1. Tank: plastic vessel hosting the system, made of granular HDPE, thermoformed in a cylindrical shape, open at the top. The tank is, then, varnished with a PVC layer as decalomania. Since no specific primary data was available, a rough estimation was performed.

2. Head: metal topping, hosting the fan and electronics. It has been modeled as a top cover, of cylindrical shape, of steel, manufactured by deep-drawing and finished with powder coating. Materials and processes are taken from Ecoinvent database and data are calculated on the basis of manufacturer primary data.

3. Biostack: inner plastic structure, with two primary functions, with different parts and materials involved: support for biomass growth, by two cylinders of HDPE with different diameter and holes; water circulation, by top plate of polyurethane, with different holes to allow water trickling down on vertical surfaces, and pump outlet.

4. Fan: ventilation system, providing oxygen to the system, which has been modeled by assimilation with processes already implemented into Ecoinvent, referring to average products available on the market. Focusing on the time-span of the study, i.e.5 years, maintenance occurrences are expectable and, therefore, n.2 fans have been included into the inventory.

5. Pump: recirculation pump, responsible for water flow inside the system, which has been modeled by assimilation with processes already implemented into Ecoinvent, referring to average products available on the market. Focusing on the

time-span of the study, i.e.5 years, maintenance occurrences are expectable and, therefore, n.5 pumps have been included into the inventory.

6. Electronics: electronic control system, responsible for water supply electrovalve, overflow valve and system's control. several assumptions were necessary:

- 6.1. Touchscreen was simulated as a LCD screen of equivalent size, since no specific process is present on Ecoinvent version 2.2;

- 6.2. Wiring board was modeled on the basis of size and average weight data;

- 6.3. The power adapter implemented is a laptop power adapter, since it is a multifunctional device;

- 6.4. Supplementary electronics are simulated as electric cable and clamp connector;

- 6.5. The stick water level sensor has no direct equivalent into Ecoinvent database, therefore a model was built up over a potentiometer and electric steel sticks.

7. Packaging: corrugated cardboard box, shockproof material and plastic film. Due to the lack of primary data, several estimations were necessary; moreover, since quantities derived were negligible and it is currently a hand-made operation, a cut-off was applied on packaging process.

8. Transport: the transport Since no specific data on each single part supply chain was available, and being the manufacturing company still in a start-up phase, with consequent work-in-progress approach to production, a generic transport process has been outlined, considering the overall weight of the bioreactor, as declared on shipping documents, as transported for average distance normally considered for European Union (i.e. 200 km).

9. Energy consumption: expected electricity consumption during the use phase, as if the technology were applied in Italy. The energy consumption of the bioreactor has been taken into account for the entire use phase expected, i.e. 5 years (as defined, conservatively, as time-span of the project). The energy production mix implemented is considered as Italian (since first application of the technology were mainly set in Italy). This proved to be a conservative assumption, compared with the average European mix. Further iteration could focus to specific application and geographical framework.

10. Biomass monodose: bacteria consortium of proprietary recipe, added to the system every 30 days. Only partial information was available to be included into the present study:

- a) the biomass is strictly of natural origins;

- b) no GMO (i.e. Genetically-Modified Organism) is included within the bacterial consortium;
- c) no chemical is added;
- d) water is the main constituent of the suspension;
- e) production site is located in New Mexico, US. This allowing to estimate air transport in about 9,000 km.

In addition to this, it must be considered that the amount of U-ox added to the system is typically 1.2 l per year, except for the first year, when two additional mono-dose are necessary for the start-up. Considering the time-span proposed for the study, it corresponds to 6.2 l. In this perspective, and, in comparison with air transport, a cut-off of the elaboration process is considered acceptable.

As required by ISO 14040:2006 [1] and ISO 14044:2006 [2], comprehensive Life Cycle Impact Assessment shall include several mandatory elements, such as the selection of impact categories and characterization models, the assignment of results obtained with LCI to the specific impact categories (i.e. Classification phase) and consequent quantification of category indicators (i.e. Characterization). For the present study, additional elaborations have been performed, by the application of Normalization and Weighting, in order to obtain results easier to communicate and share with manufacturer, to promote design effort to improve environmental efficiency of the bioreactor system.

Two calculation methods have been used: a single-issue calculation method (Greenhouse Gases Protocol v.1.01) and a typical impact assessment method (IMPACT 2002+).

3.1 GHG Protocol, results

The Greenhouse Gas Protocol (GHG Protocol) method was developed by the World Resources Institute (WRI) in cooperation with the World Business Council for Sustainable Development (WBCSD). This method is based on the draft report on Product Life Cycle Accounting and Reporting Standard [9-11]. It may be assimilated to the Carbon Footprint, defined as the sum of GHG emissions and removals, expressed as net impact on global warming in terms of CO₂ equivalent [5, 12].

The time horizon of the calculation method is 100 years.

Characterization results of the impact assessment are reported in the following Figures 1 Characterization. It is immediately evident how energy consumption in the use phase is responsible

for the major impact. In fact, about 82% of the total kg CO₂ equivalent are attributable to energy consumption, affecting in particular the emission from fossil fuel.

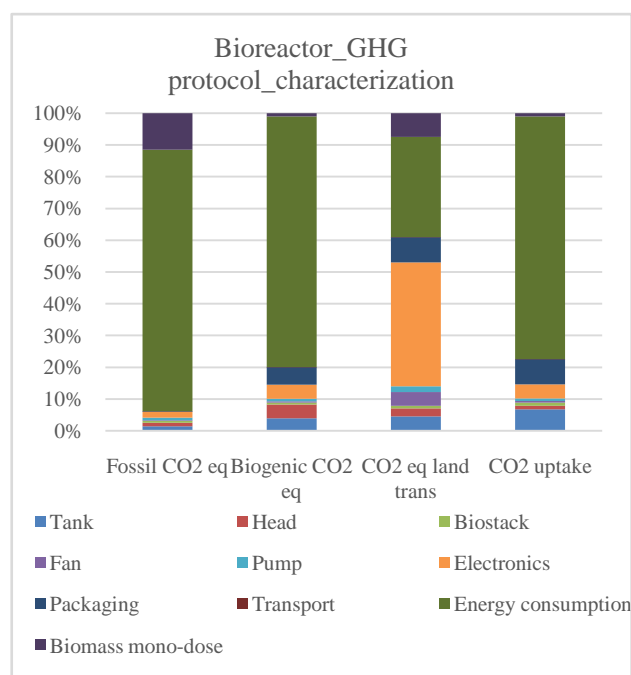


Fig. 1.: Impact assessment results, GHG Protocol, Characterization.

3.2 Impact 2002+, results

The IMPACT 2002+ (IMPact Assessment of Chemical Toxics) calculation method has been developed by Swiss Federal Institute of Technology - Lausanne (EPFL, now Ecoinvent life cycle systems). Its most distinctive feature is the implementation of a combined midpoint/damage approach, relating LCI results (i.e. elementary flows) to 4 main damage categories through 14 midpoints indicators.

Typically, during Characterization phase, LCI results are converted, by the application of specific factors, to a common unit and aggregated for impact categories.

Applying SimaPro software, a modified methodology is used: characterization factors for human toxicity and aquatic and terrestrial ecotoxicity, in fact, are taken from directly IMPACT 2002+, while factors for other categories are adapted from other methods (i.e. Eco-indicator 99, CML 2001, IPCC and Cumulative Energy Demand) and human toxicity is split up in 'Carcinogens' and 'Non-carcinogens'.

Normalization phase is focused on defining the relative magnitude for each indicator result of the product system: each categories' results is, therefore, referred to a reference information, making them dimensionless and, consequently, allowing comparisons.

The Weighting phase involves numerical factors to be attributed to each category on the basis of choice-value.

Figure 2 (Appendix) reports impact assessment results for Characterization.

As evidently displayed by graphics, Global Warming and Non-renewable energy utilization, together with respiratory inorganics category account for more than 90% of the overall impact and the process describing the energy consumption during the use phase is directly responsible for the most part of them (about 80%). These results are confirmed by Weighting phase and consequent attribution to each single process (i.e. Single Score, Fig. 3, Appendix).

Focusing on the CO₂ equivalent impact, results of the two methodologies applied (Impact 2002+ and GHG Protocol) identified bioreactor contribution in about 1 ton of CO₂ equivalent over the 5-year time-span accounted to the technology.

3.3 Carbon sink evaluation

In order to try and assess the environmental burden actually posed by the biotechnology implementation, at present (i.e. with energy consumption affecting the overall performance by 80%), the benefit deriving from air treatment performed should be considered.

Based on information provided by the manufacturer, each bioreactor can capture up to 3.5 kg of airborne contaminants per day. Considering a theoretical scenario, with air pollution represented only by VOC, it could be assessed that a single bioreactor unit should be able to treat up to 3.5 kg of VOCs per day. With a rough estimation, i.e. attributing to the VOCs an average Global Warming Potential related to CO₂ equal to 1 (which is a rather conservative assumption, as reported by IPCC [13]), the bioreactor should be able to sequester up to 1277.5 kg CO₂ equivalent per year.

This result, compared with the impact calculated, i.e. 193.6 kg CO₂ equivalent per year, returns a net CO₂ equivalent uptake of about 1083.9 kg per year, which can be regarded as quite a remarkable result, even considering limitations of the present study.

An additional comparative evaluation may support the definition of the overall environmental performance, i.e. comparison of the estimated CO₂ equivalent uptake of a bioreactor unit with trees, as

typical carbon sinks. In fact, as clearly defined by several studies, they are able to absorb carbon dioxide from the atmosphere, releasing it only partially through night respiration and storing the rest in various organic compounds. Based on most recent results presented by Proietti et al. [12], trees may store from 4.048 (e.g. oak) to 25.391 (e.g. walnut, poplar) kg CO₂ per year per plant, over the a 14-year time-span, considering both standing and accumulated biomass.

These data, compared with results obtained for the bioreactor allow to compare the biotechnological system performance with a number of trees ranging from 43 (42.68), in case of high growth rate species (e.g. walnut, poplar), to 268 (267.76) in case of low growth rate trees (e.g. oaks).

Considering an average tree density spanning from 230 to 455, as proposed by Khan and Chaudhry [14] (Table 1), it could be assessed that the CO₂ net uptake of 1 hectare of properly spaced (i.e. about 300 trees/ha) trees is equivalent to:

- n. 1 bioreactors, in case of low growth rate species,
- n. 7 bioreactors, if high growth rate species are involved.

Table 1: Bioreactor unit/trees equivalence.

Trees density/ha	High growth rate species (walnut, poplar)	Low growth rate species (oak)
230 (3.7X12.2 M)	5.4 bioreactor unit	0.9 bioreactor unit
455 (3.7X6.1 M)	10.7 bioreactor unit	1.8 bioreactor unit

4 Conclusion

A screening LCA was accomplished considering production and use phase of a single bioreactor unit. The assessment, even with several assumptions, simplifications and cut-off, returned interesting results, both in terms of impact categories affected and processes triggering the major environmental impacts.

In particular, energy consumption of the device during the use phase proved to develop the major environmental burden (around 80% of the total), confirmed by GHG Protocol and IMPACT 2002+ method. Therefore, the energy production mix used in the specific context of application, is crucial to

define the overall impact and measures could be taken accordingly, as to obtain a remarkable reduction.

At the same time, biomass transport from the production site, located in New Mexico, US, heavily affects the global warming effect, as well as respiratory contaminants release, suggesting that a modified logistic would ensure a better environmental performance at the production stage.

In an attempt to properly interpret results obtained in the perspective of a remediation technology, i.e. considering the environmental benefit provided by its application, a rough comparison has been performed between net impact, i.e. combining negative and positive impacts, in terms of CO₂ equivalent, provided by bioreactor unit and typical carbon sinks, i.e. trees with different growth rate. Results obtained suggest that a single bioreactor unit could act as carbon sink equivalent to a number of trees ranging from 43, in case of high growth rate species (e.g. walnut, poplar), to 268, in case of low growth rate trees (e.g. oaks).

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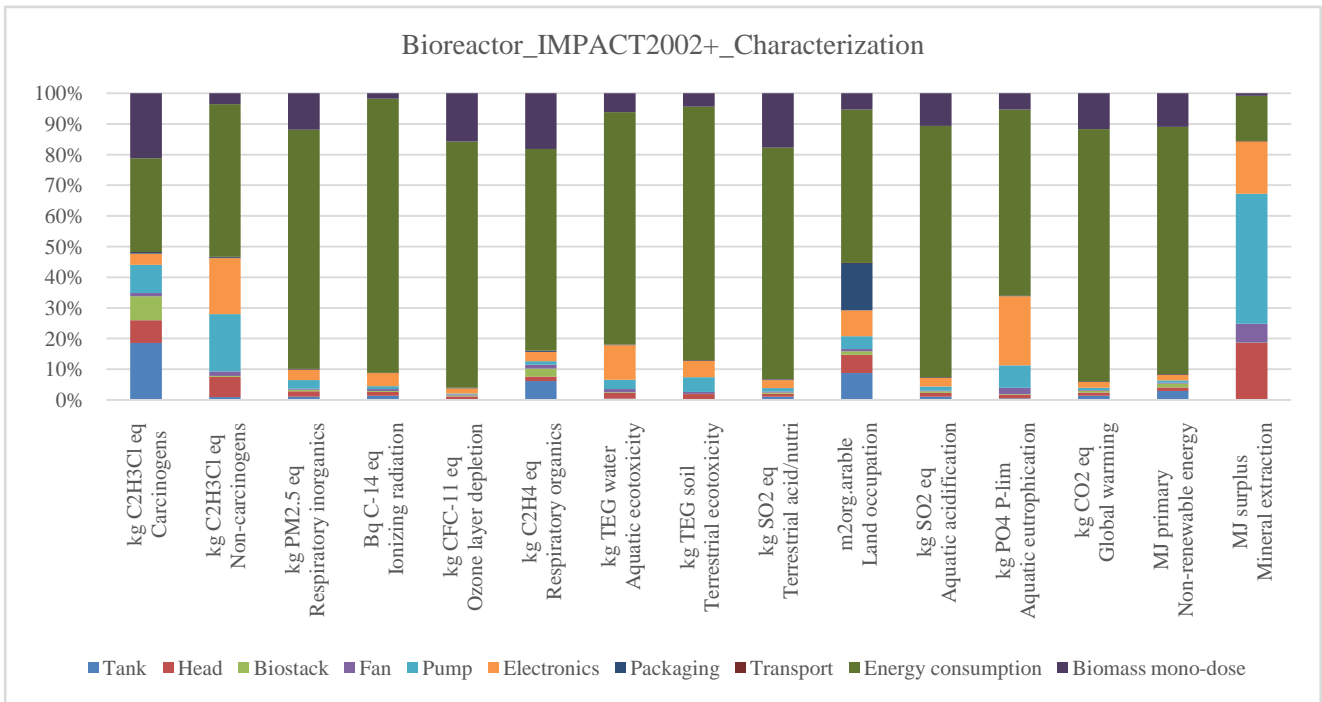


Fig. 2: Impact assessment results, IMPACT2002+, Characterization.

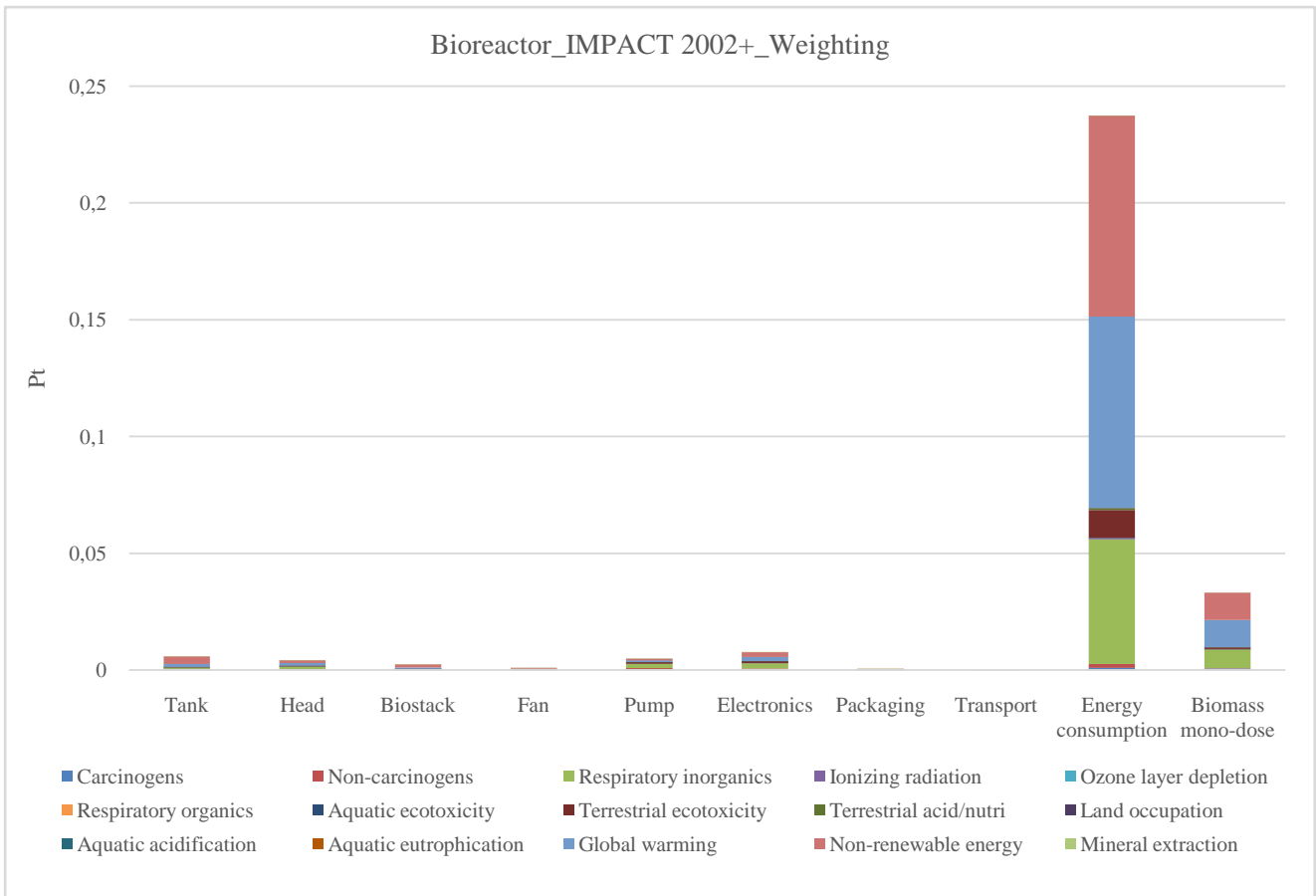


Fig. 3.: Impact assessment results, IMPACT2002+, Weighting, Single Score.