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PLASTICS INNOVATION POLE

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Document title : LIFE CYCLE ANALYSIS ON PET 500 ml BOTTLES, PRODUCED BY MEAN OF A NEW PROCESSING, SINGLE STAGE METHODOLOGY CONSIDERING UP TO 50%rPET AMOUNT

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Executive Summary LCA final

In this preliminary investigation models related to the production of a bottle intended to contain 500 ml of drinking water, have been carried out, as well as the LCA, according to a “From Cradle to grave” approach. In particular the models and the LCA regard the production of the mentioned component according to different methodology: the traditional one, based on extrusion, perform injection moulding and bottle blow moulding, and a new one, in which component is developed in a single stage and in a very flexible apparatus. The apparatus, other than energy saving, allows to save also the plastic materials (7,8 g per bottles versus 8,7 g of the traditional system).

This framework, according to the obtained results, turns out in a significantly lower environmental impact for the bottle produced by mean of the new processing methodology, in comparison to that one produced by mean of the traditional stages.

The employment of the new methods allows to reduce resources exploitation, harmful emission for the ecosystem quality and the human health, other than to save energy.

According to the partners, the flexibility of the new process could allow to employ a significant amount of rPET (up to 50% in weight), which is reasonably higher than the amount which can be employed in the traditional processes flow (30% in weight). This contributes to increase the new process competitiveness.

In comparison to the bottle produced by mean of the traditional group of processes, the new one allows significantly reducing the impact also in terms of environmental effects. At this purpose, according to the mentioned outcomes, a considerable reduction in the exploitation of resources (- 54,09%), as well as a significant reduction in emission occurs (those ones responsible for human health issues (- 48,83%) and those ones responsible for the worsening of the ecosystem quality (- 51,38%)) if the traditional kind of bottle is replaced by another one manufactured by mean of the new process.

1-Introduction

As written in the previous report, the main aim of the project is the development of a single stage manufacturing process for the production of PET bottles used in the drinking water field. The main feature of the new methodology is the capability to guarantee a little reduction of the bottle weight (whichever the contained volume of water) in comparison to the counterpart produced by mean of the traditional processes group. This should also lead to an improvement of the bottle environmental performance thanks to the (supposed environmental friendly or less energy intensive) new production process, as well as the foreseen opportunity to increase the amount of recycled polymer up to the 50% in weight, in comparison to the traditionally produced one.

At this purpose, while in the traditional bottle manufacturing about 30% in weight of recycled PET is employed, in the new kind of methodology a 50% in weight of the recycled PET is foreseen, as a peculiar feature of the process itself.

As introduced in the previous report, the traditional methodology employed in the bottles manufacturing is based on a particular series (sequence) of processes, as extrusion, performs injection moulding and final blow moulding. In general, the average energy expense amounts to 1,10 kWh/kg of produced bottles. The main target for the new process (single-stage based one) is to obtain a maximum energy expense of 0,76 kWh/kg of produced bottles.

As introduced, the new kind of process developed in this project allows to obtain a finished product (the perform and subsequently the bottle) in a single stage (and in a single apparatus): performs extrusion directly inside a mould is followed by compression (inside the mentioned mould) and blowing with no intermediate cooling stages (the plastic material temperature is constantly over 100 °C).

This final version of LCA will be developed according a from cradle to grave approach, hence issues related to the end of life for the bottle produced both by mean of the traditional process and the new one. Anyway, at this point of the investigation, independently form the process employed for the bottle production no issues regarding the product durability and performance have been dealt with.

2-Life Cycle Analysis: Brief theoretical approach

2.1-Introduction to LCA

The LCA can be defined as a methodology for the evaluation of the environmental load of a process or activity by means of all inputs and outputs involved during the entire life cycle of the process or activity itself.

A LCA study is ruled by ISO standards:

- ISO 14040: Principles and framework
- ISO 14041: Goal and scope definition and inventory analysis
- ISO 14042: Life cycle impact assessment
- ISO 14043: Interpretation

A LCA applied to a specific industrial system addresses the study towards the improvement of the environmental efficiency of the system itself by means of a better utilization of natural and human resources.

To perform a LCA study, it is necessary to create a specific model of the system analysed by considering the boundaries of the system, the different processes and sub-processes contained, the inputs, the outputs, etc.

The typical structure of the LCA study is represented in Figure 1. It is composed by four steps:

1. **Goal and Scope definition:** It is the preliminary step where the aims of the study, the system boundaries and the functional units are defined. Concerning the general objective of the present work, the goal is the development of a flexible model for the single stage processes involved in the production of PET based bottles (volume 500 ml), as well as a PET bottle production and the related comparison with a counterpart produced by mean of the traditional group of processes (extrusion, followed by the performs injection moulding and the final blow moulding).

2. **Life Cycle Inventory (LCI):** It is the step dedicated to the collection of information concerning:
    i. the processes in terms of energy consumption, raw materials, emissions, etc;
    ii. the path of the materials by the starting point to the end of the process in order to define all flow involved in each process steps;

3. **Life Cycle Impact Assessment (LCIA):** It is the quantitative analysis and evaluation of the environmental impact of the process studied, by means of specific methodologies and indicators;

4. **Interpretation:** It is the last step of an LCA, aiming to the understanding of the main impact factors and to evaluate the possible solutions to improve the LCA of the process.

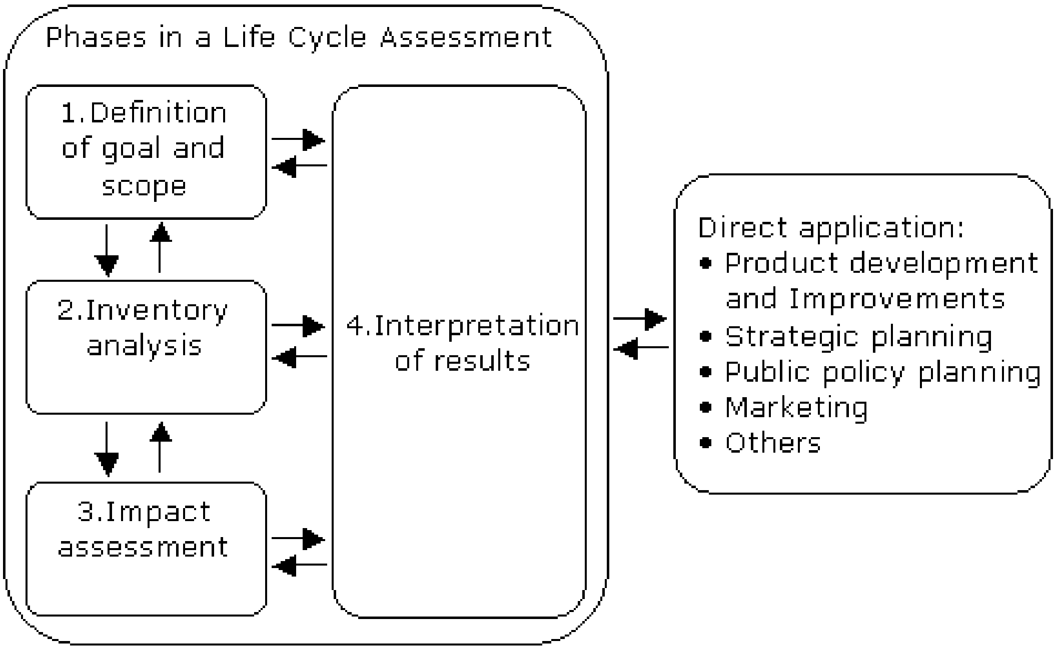

***Figure 1:** Schematic representation of a LCA study.*

Each step is regulated by the respective ISO standard. The system definition is very important, as a LCA of specific processes requires a clear definition of the limits of the system analyzed. This definition is strictly related to the objective of the study, therefore – considering the objective of this study – the physical limits of the production (manufacturing and transformation) processes are considered as system boundaries. Moreover, it is mandatory to define a functional unit, which each materials/energy flow involved in the study is referred to. In general, the functional unit could also be a particular feature characterizing the system performance, as well as the relate weight or surface.

In this project, on the base of the provided data, the single bottle, able to contain 500 ml of water has been chosen as a mere functional unit. The related LCA, as reported in the following section with more details, according a “from cradle to grave approach” has been developed. Actually, as no data regarding the bottle durability and performance have been currently available, the service life has been neglected.

Every LCA study implies, after the Life Cycle Inventory step, a schematization of the different parts of the process where all inputs and outputs and all connection between different parts are clearly represented in order to perform the impact assessment step.

2.2-Goal and scope definitions

Following the ISO standards, every LCA must be addressed by a previous definition of the goal and scope of the study.

In the LCA for this processes, the goal and scope are already defined in the DoW of the project. Therefore, it is possible to assert that the goal of the LCA is the development of a flexible model to be used as a reference for the new processes to be developed in the project. The scope is the evaluation of the performance concerned with the technologies developed in the project, mainly in terms of environmental impact and carbon footprint (carbon dioxide emissions and global warming issues).

As described in the LCA standards, during the step of goal and scope definition, it is necessary to define both the system boundaries and the functional unit.

2.3-Life Cycle Inventory (LCI)

The Life Cycle Inventory is the second step of the LCA. A specific model of the real exchanges (materials, energy, emissions, etc.) between single operations and the environment must be created in this phase to enable a quantitative evaluation of the environmental impact. Indeed, the aim of the LCI is to supply objective data to the following evaluation (LCIA).

The LCI must contain all information concerning the materials involved in the analysed process, the energies, the emissions, as well as the life cycle of each entity, for example the disposal way of the raw materials used, the possibility to perform recycling operations, the types and amounts of waste produced during each step, the kinds and amounts of emissions (in air, in land, in water), etc.

2.4-Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI. Impact assessment should address ecological and human health effects; it should also address resource depletion. A life cycle impact assessment attempts to establish a linkage between the product or process and its potential environmental impacts.

The key concept in this component is that of stressors. A stressor is a set of conditions that may lead to an impact. An LCIA provides a systematic procedure for classifying and characterizing the several kinds of environmental effects.

The following steps comprise a life cycle impact assessment:

- Characterisation: Characterisation factors are used to quantitatively model the impact from each emission/resource that comes from the life cycle inventory and are expressed as a category indicatory results.
  In other words, characterization factors translate different inventory inputs into directly comparable impact indicators. At this purpose, impact indicators are typically characterized using the following equation:

  Inventory Data × Characterization Factor = Impact Indicators

  For example, all greenhouse gases 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 to provide an overall indicator of global warming potential.
  Characterization can put these different quantities of chemicals on an equal scale to determine the amount of impact each one has on global warming.

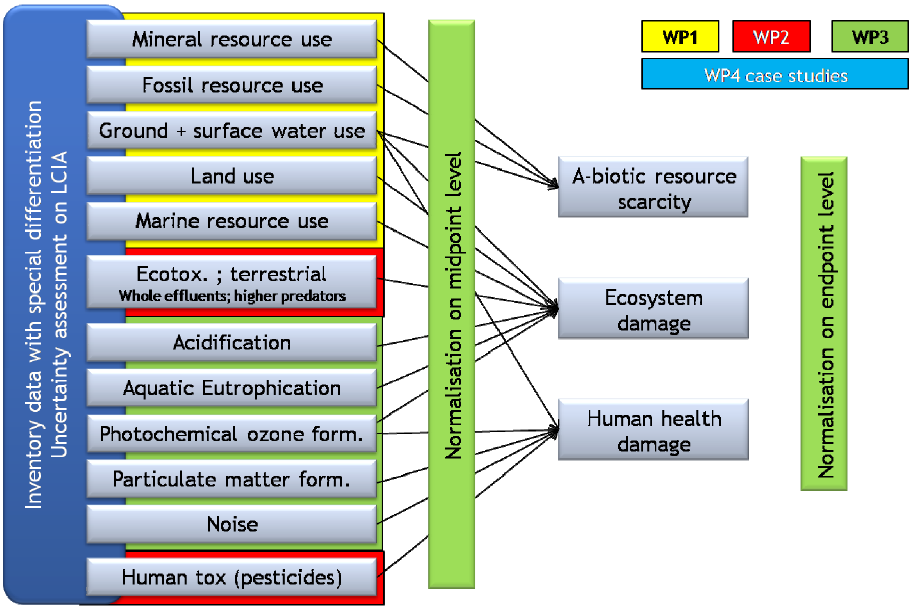

Figure 2: *Schematic representation impact categories (factors) and the related effects the lead to.*

- Normalisation: Normalization is an LCIA (optional) tool used to express impact indicator data in a way that can be compared among impact categories. This procedure normalizes the indicator results by dividing by a selected reference value. Is worthwhile to point out that the goal and scope of the LCA may influence the choice of an appropriate reference value.

- Weighting: The weighting step (also referred to as valuation) of an LCIA assigns weights or relative values to the different impact categories based on their perceived importance or relevance. This is important because the impact categories should also reflect study goals and stakeholder values.

Because weighting is not a scientific process, it is vital that the weighting methodology is clearly explained and documented.

There are also other stages related to the LCIA but these are less significant and fall outside the target of this investigation.

2.5- Interpretation of results

Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively. Life cycle interpretation is the last phase of the LCA process. ISO has defined the following two objectives of life cycle interpretation:

- Analyze results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA, and to report the results of the life cycle interpretation in a transparent manner;
- Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

3-Work performed

In this work the life cycle analysis of a 500 ml bottle has been carried out, according a “from cradle to grave” approach. It means all the issues, from the raw materials extraction, going through to their transformation in specific products (as polymers, metals, process fluids, etc.) or energy, up to their processing to produce the mere bottle, as well as the related end of life have been taken into account and then included in the life cycle. Issues related to the bottle durability (service life time, performance, etc.) have been completely omitted.

About the bottle produced by mean of the traditional processes, the related weight (experimentally tested) is 8,7 g and the process scheme is shown in figure 3, as well as the related inventory. Commercial bottles can contain the 30% of recycled PET (rPET). This has been taken into account into related inventory.

As observed in the mentioned figure, other than the extrusion, injection moulding and blow moulding processes, also an energy contribution for the material drying has been taken into account.

No issues regarding materials (granules transport) from the extrusion plant to the pre-form injection moulding plant and from the latter to the blow moulding stage have been dealt with.

About the bottle manufactured by mean of the new process, the possibility to use the 50% in weight of recycled PET has been take into account (figure 4).

The mentioned features have been exploited also in the production of models simulating the end of life of the investigated bottles. At this purpose, for the product manufactured through the traditional methodology the possibility to reuse the 30% of the PET (after granulation, cleaning and extrusion) has been supposed again. The remaining part it has been considered to be made available for other extrusion processes, whose aim has not been well specified. For the new process based counterpart, the 50% of the PET has been supposed to be reused, while the other 50% is reprocessed by mean of extrusion.

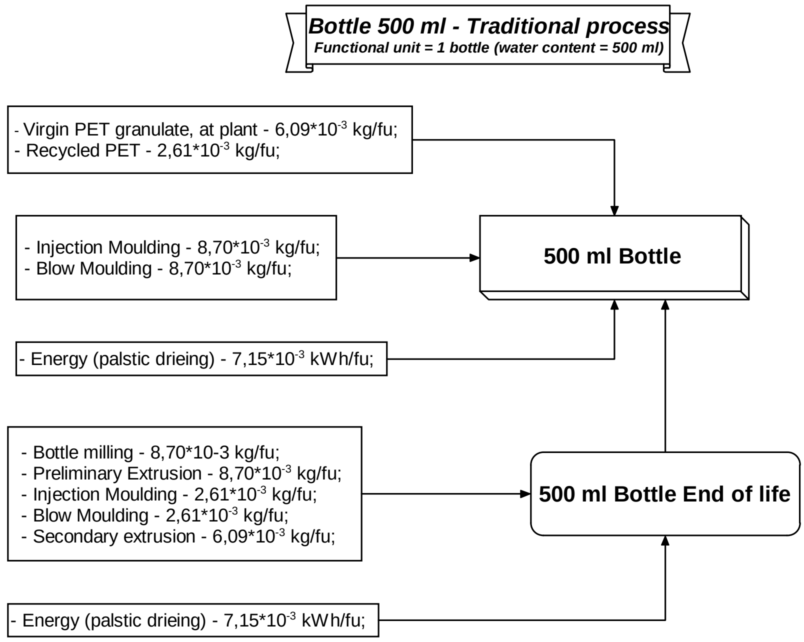

Figure 3: *Flow chart of the processes employed in the traditional bottle production.*

In both kinds of processes recycled PET (rPET) and virgin one are directly processed in the employed devices. Naturally, models have been developed for the mentioned processing methods, taking into account energy expenses, machinery payout, the related land use, and the contribution of each materials and components (including the contribution of each work the component itself has been subjected to, aimed to the related transformation up to the final configuration) the machineries are based on, scaled or normalized to the single bottle production.

Energy expense related to PET drying has been considered equal to those one requested in the traditional process, despite energy saving is foreseen for the new system. This leads to a more conservative approach about the new process.

Furthermore, the preliminary model applied to the new process LCA is based also in the assumption that it allows to produce bottle whose weight is 7,8 g, the average productivity amounts to 45000 bottles per hour, no significant scraps are produced and no lubricants and others ancillary fluids are employed. The compressed air contribution is taken into account according to the related energy exploitation. These assumptions have been experimentally verified.

For both the processes, as a functional unit, the single bottle has been considered. Moreover, as a system boundary, the physical limits of the processing plant, leading to the bottle production, has been considered.

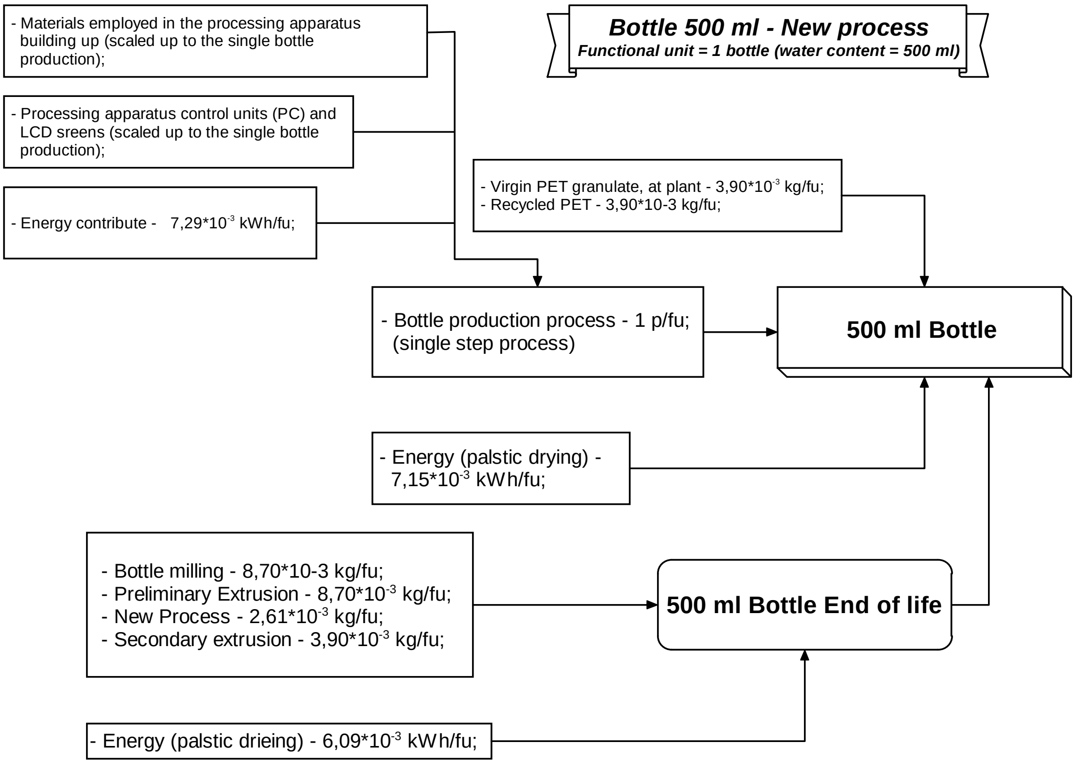

Figure 4: *Flow chart of the new process employed in the bottle production.*

Finally, all the energy inputs have been referred to the Italian grid system for the related production and transport.

4-Results and discussion

In this section result related to LCA of the bottles produced by mean of the two different processes will be dealt with and discussed in details. At this purpose, the models have been implemented in the software Simaprò 7.2 and the impact assessment has been developed by mean the Ecoindicator 99 tool.

4.1-Preliminary Life Cycle Inventory for the produced bottles

4.1.1 LCA not considering Bottle end of life

As previously introduced, a preliminary LCI on the bottles produced by mean of the two kind of processes has been developed. At this purpose, for the impact assessment, dealt with in the next section, the Ecoindicator 99 has been used as a tool. The analysis has been carried out by mean of the SimaPro software.

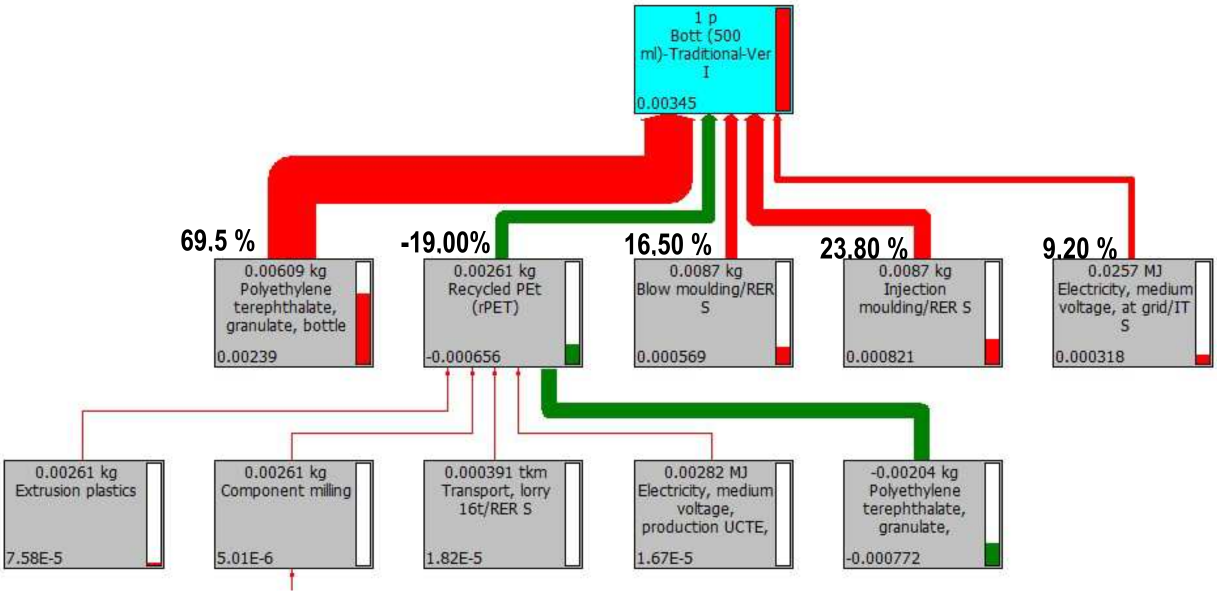

Figure 5: *Process tree concerned with the bottle produced through the traditional system.*

Referring to the scheme of figures 5 and 6, for both kinds of bottles, all the process stages of the whole Life cycle have been modeled and investigated (“from cradle to gate” approach, as no issues on the component durability and end of life have been provided). It is worthwhile to point out all the input (materials, energy, devices pay-out) have been taken into account, while any potential transport has been neglected.

Figure 5 deals with the process tree for the production of the traditional component (a single component); the whole environmental impact is expressed through a life cycle score amounting to 3,45*10^{-3} Pt (eco Points).

About the 69,5% of the whole impact is due to the employment of the virgin polymer matrix, while the manufacturing process series contribute amounts to the 49,50%. The employment of the 30% of the recycled PET allows saving the 19% of the environmental impact.

Figure 6 shows the process tree concerned with the bottle produced by mean of the new kind of single stage process: the environmental impact is expressed through an eco-score amounting to 1,36*10^{-3} Pt. The main role is played again by the virgin matrix employments. The employment of the 50% in weight of the recycled one allow saving more than the half part of the whole environmental impact. The process load is quite low, as its contribute amounts to the 36 %.

Is worthwhile to point out that the new process allows to significantly decrease the environmental impact concerned with the single bottle production (60%). Moreover both the frameworks evidence that, despite the manufacturing stages contributes could be lowered, the main role is played by the virgin PET, as the related synthesis ad production leads to resources depletion and emissions (carbon dioxide and equivalents in terms of environmental effects).

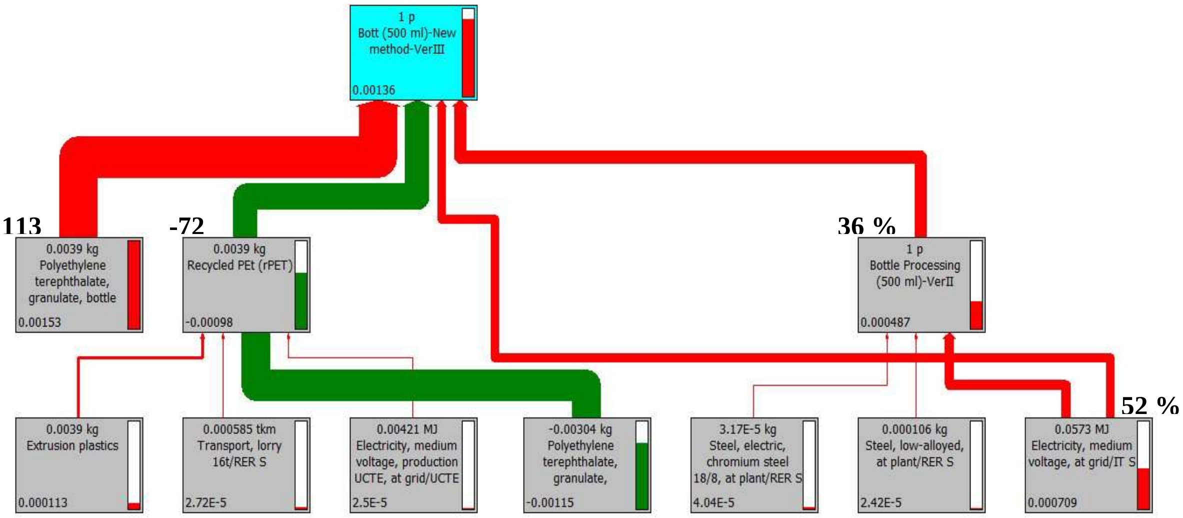

Figure 6: *Process tree concerned with the bottle produced through the new system.*

As discussed in the previous paragraph, the PET recycling allows to significantly save energy, resources and emissions. For this reason, the employment of a given amount of the mentioned product in the processed blend could enhance the environmental performance of the produced bottle.

4.1.1 LCA considering Bottle end of life

As previously introduced, a preliminary LCI on the bottles produced by mean of the two kind of processes has been developed, in which the respective end of life stages have been included.

Referring to the schemes of figures 7 and 8, for both kinds of bottles, all the process stages of the whole Life cycle have been modeled and investigated ("from cradle to grave" approach, despite no issues on the component durability have been provided). It is worthwhile to point out all the inputs (materials, energy, devices pay-out) have been taken into account, while any potential transport has been neglected.

Figure 7 deals with the process tree for the production of the traditional component (a single component); the whole environmental impact is expressed through a life cycle score amounting to 1,01*10^{-3} Pt (eco Points).

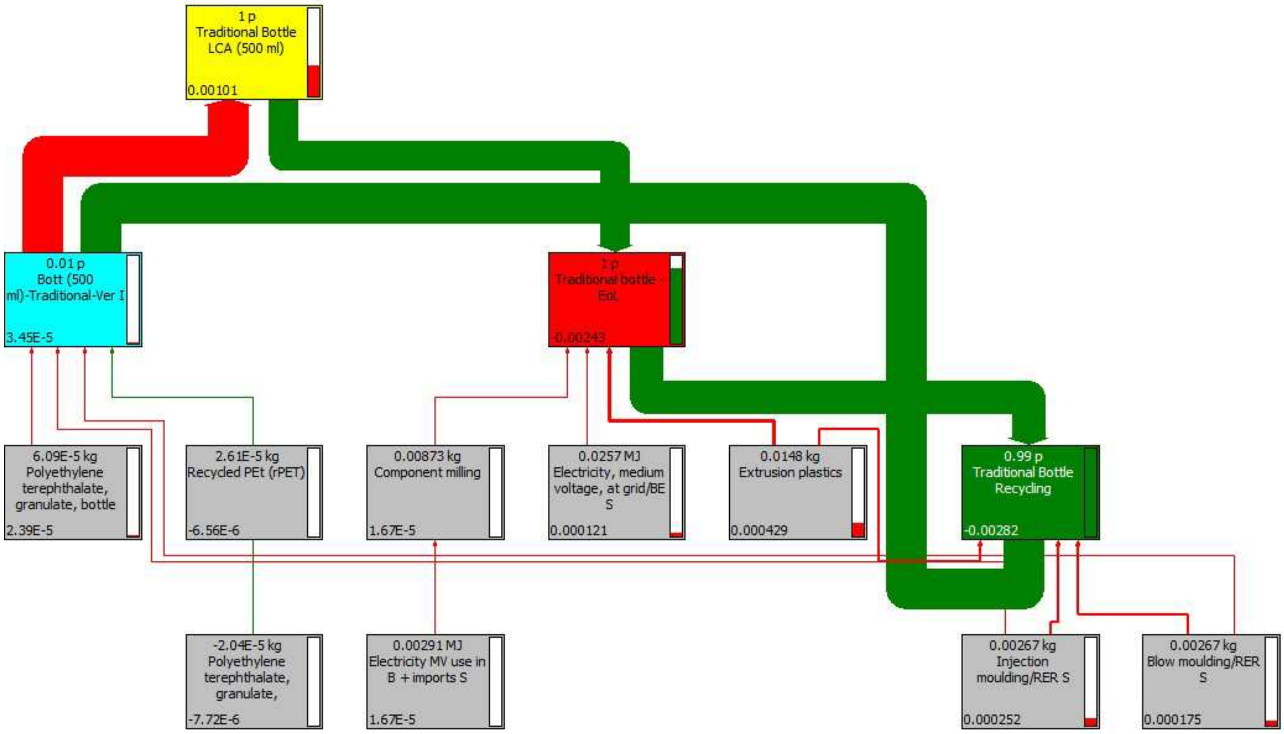

Figure 7: *Process tree concerned with the whole LCA of the bottle produced through the traditional system.*

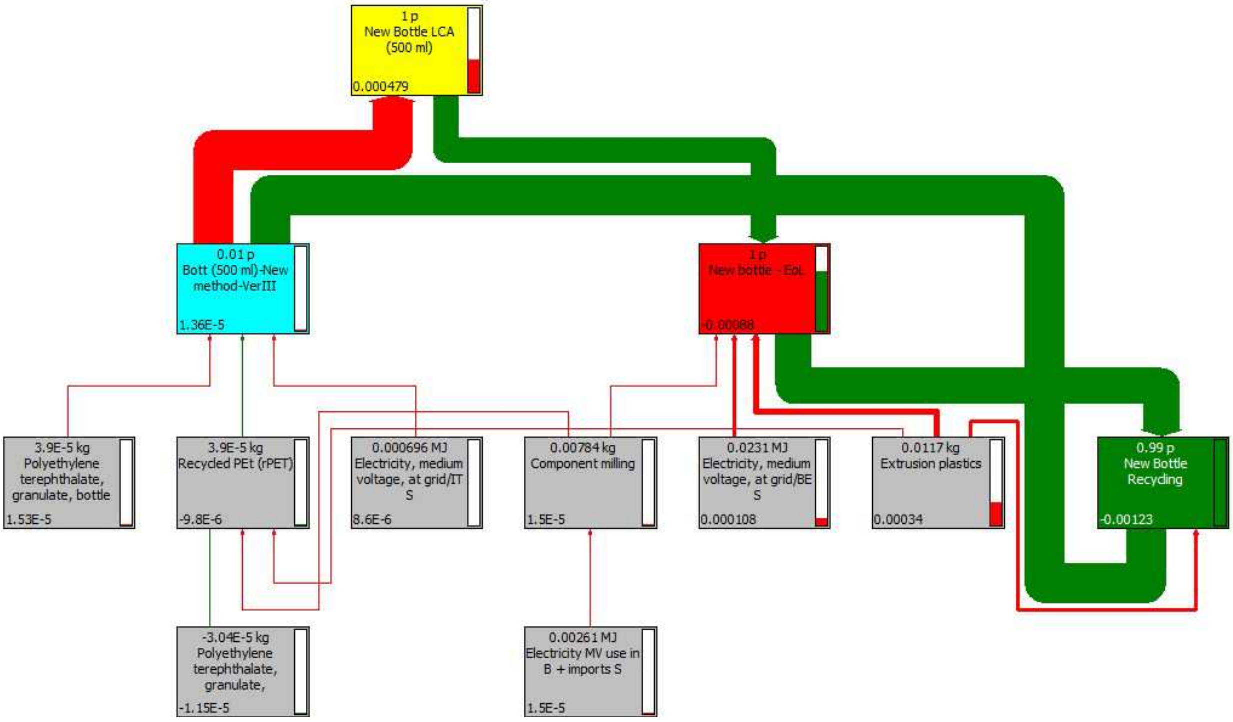

Figure 8 *Process tree concerned with the whole LCA of the bottle produced through the new system.*

Thanks to the End of Life stage the environmental impact has been reduced by the 70%, as the score obtained in the production stage, dealt with in the previous paragraph amounted to 3,45*10^{-3} Pt.

Figure 8 shows the process tree concerned with the bottle obtained by mean of the new kind of single stage process: the environmental impact is expressed through an eco score amounting to 4,79*10^{-4} Pt. Also in this case the bottle End of life leads to a remarkable reduction in the environmental impact (65%), as the eco score regarding the production stages, as shown in the previous reports, amounted to 1,36*10^{-3} Pt

Is worthwhile to point out that the new process allows to significantly decrease the environmental impact concerned with the single bottle production (52,6%).

As discussed in the previous paragraph, also the PET recycling gives the advantage to significantly save energy, resources and emissions.

4.2-Life Cycle Impact Analysis for the produced bottles and related comparison

4.2.1 -Life Cycle Impact Analysis <u>not considering the bottle end of life</u>

As previously reported, the Life Cycle Impact Analysis has been carried out on the two different bottles and the results have been compared.

Single score point evaluation (figure 7) confirms that the new process allows to increase the environmental performance, as the related bottle impact is considerably lower than the counterpart produced through the traditional series of processes.

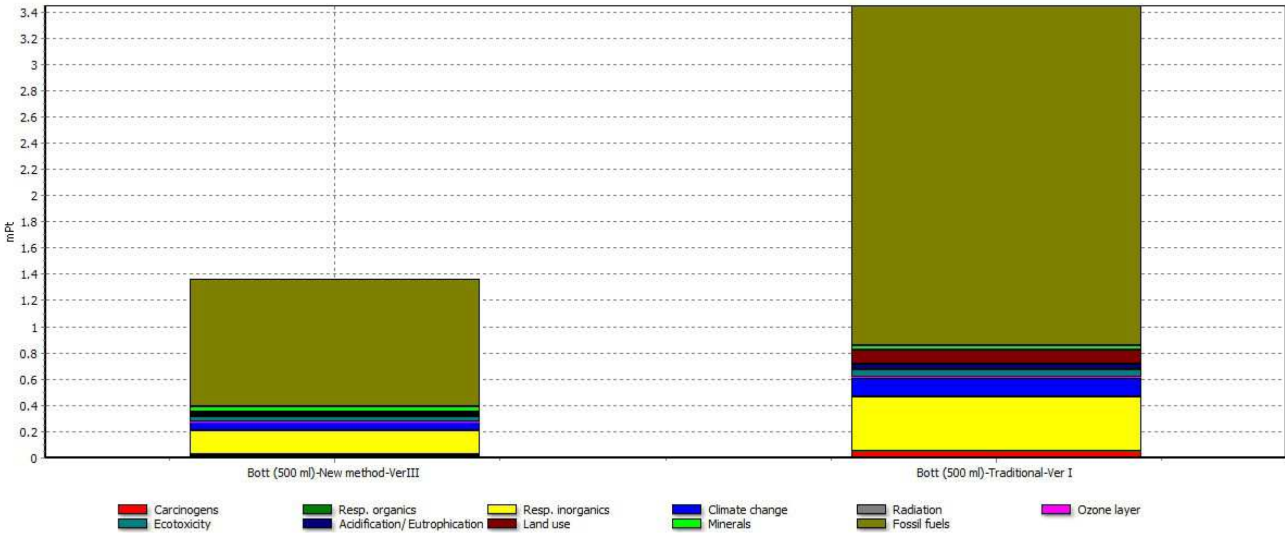

***Figure 7** Single score point evaluation for the LCA related to the bottle produced by mean of the two different methods.*

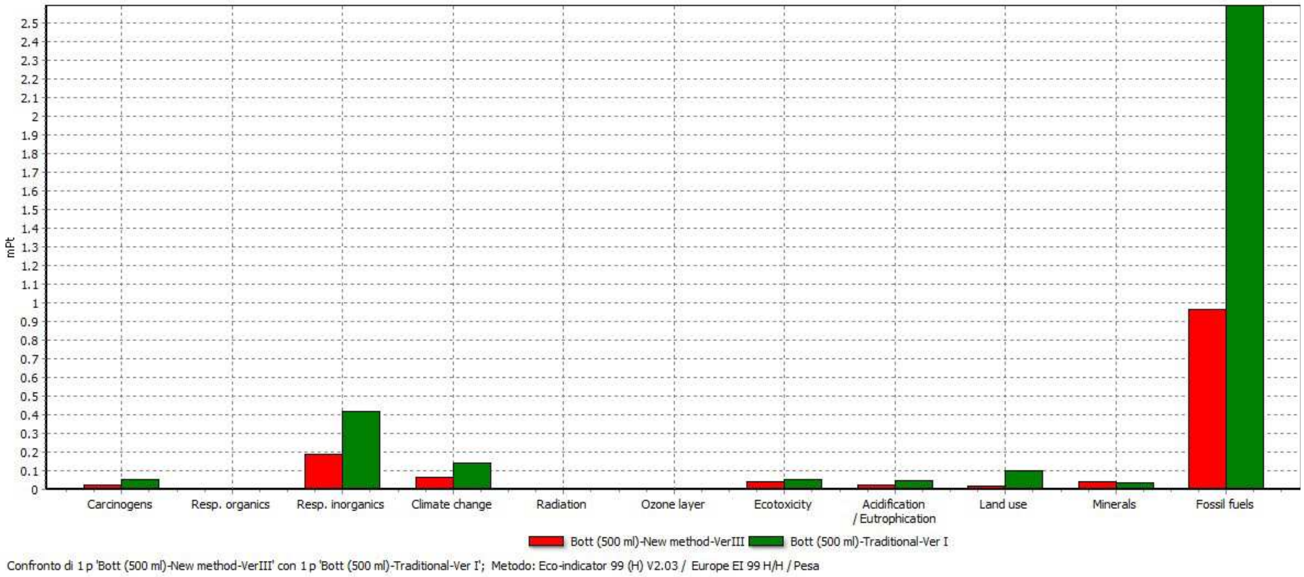

Figure 8: *Environmental impact categories related to the bottle production according to the mentioned methods.*

About the impact categories, for both the kinds of bottles similar results occurs in terms of contribute (percent) to each respective whole environmental impact. Indeed, there are only three significant categories involved in the mentioned impact for each investigated system. At this purpose the Fossil fuels consumption is the most important one, as its contribute amounts to the 71,00% and 75,13% respectively for the new and the traditional process methodology.

About the emissions, Resp. Inorganics contributes to the whole environmental load for the 13,60% and 12,00% respectively for the new manufacturing method and the traditional counterpart. Finally, less relevance for the investigated process could be given to the Climate changes issues, as the related contribute is about 4,74% for the bottle produced through the new process and 4,12% for the other one.

Table 1: *Quantification of the main impact categories in terms of Ecoindicators.*

Ecoindicators (fu = 1 bottle)	**Traditional System**	**New Methodology**
Resp. Inorganics (DALYs)	$2,13*10^{-8}$	$0,95*10^{-8}$
Carcinogens (DALYs)	$2,61*10^{-9}$	$1,06*10^{-9}$
Climate Changes (Kg CO_2-eq)	$4,47*10^{-2}$	$1,71*10^{-2}$
Ecotoxicity ((PAF m_2 Yr)	$6,71*10^{-3}$	$5,10*10^{-3}$
Fossil Fuels (Kg Sb -eq)	$1,06*10^{-4}$	$0,88*10^{-4}$
Minerals (Kg Sb-eq)	$2,28*10^{-7}$	$1,68*10^{-7}$

Notes:

- **DALY:** Disability adjusted life year – number of year lost due to ill-health, disability or early death;
- **PAF m2 Yr:** Potentially disappeared fraction of species per m2 per year;

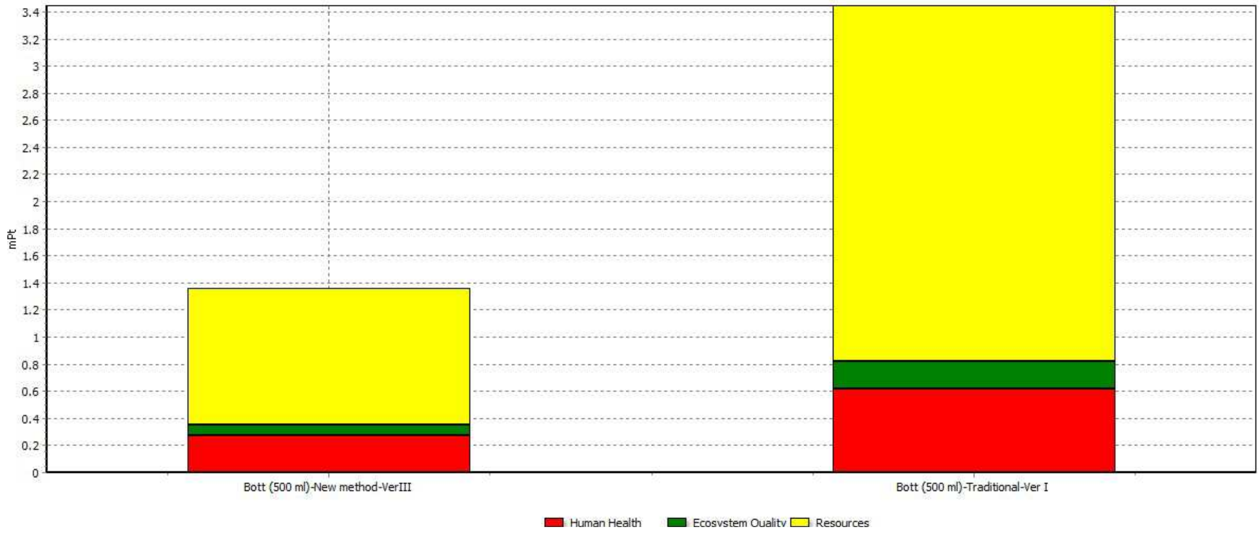

Figure 9: *Bottle production main environmental effects. Comparison between the two different processing methodologies.*

The above mentioned aspects are confirmed in the diagram of figure 8. Moreover, the mentioned graph, other than data reported in table 1, evidences that the new process allows to significantly decrease all the impact categories in comparison to the traditional one. Emissions and the exploitation of the resources could be reduced as indicated in the following bulleted list:

- Resp. Inorganics: - 55,40%;
- Carcinogens: - 59,39%;
- Climate Changes: - 61,75 %;
- Ecotoxicity: - 23,85 %;
- Fossil Fuels depletion: - 17,00 %;
- Minerals depletion: - 26,31%;

According to the mentioned outcomes, a considerable reduction of the exploitation of resources as well as a significant emission reduction occurs if the traditional kind of bottle is replaced by another one manufactured by mean of the new process.

As a consequence of the described framework, also a reduction of the environmental effects occurs. Indeed, there is a decrease of issues as Human health category of the 55,84%, as the worsening of the Ecosystem Quality of the 60,32% and in the Resources depletion of the 61,71%.

4.2.2 -Life Cycle Impact Analysis <u>considering the bottle end of life</u>

As previously reported, the Life Cycle Impact Analysis has been carried out on the two different bottles and the results have been compared.

Single score point evaluation (figure 10) confirms that the new process allows increasing the environmental performance, as the related bottle impact is considerably lower than the counterpart produced through the traditional group of processes.

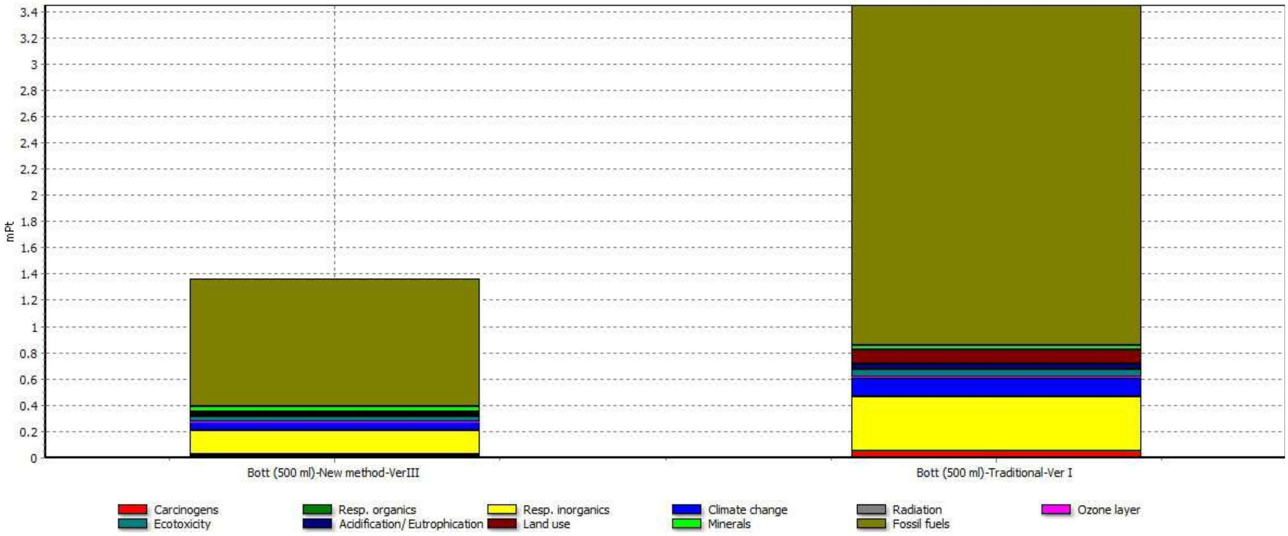

Figure 10 *Single score point evaluation for the LCA related to the bottle produced by mean of the two different methods.*

Talking about the new kind of bottle (produced by mean of the new process), the most relevant part of the impact is due to fossil fuels exploitation (61,97%). About the other impact categories, Respiratory inorganics is responsible for the 16,94% of the whole impact, while Climate Changes role amounts to 6,35%. Land use is responsible for the 5,47% of the whole score.

In few word, the main role in the environmental impact due to the production of the new kind of bottle can be attributed to the resources consumption and in particular to fossil fuels. Emissions can be considered barely relevant.

In terms of Impact Categories, the production of the new bottle lead to relevant advantages in comparison to the traditional one. At this purpose, as shown in figure 10 and 11, as well as in table 2, Emissions and the exploitation of the resources could be reduced as indicated in the following bulleted list:

- Resp. Inorganics: - 50,95%;
- Carcinogens: - 51,75%;
- Climate Changes: - 48,04 %;
- Eco toxicity: - 42,49 %;
- Fossil Fuels depletion: - 49,89 %;

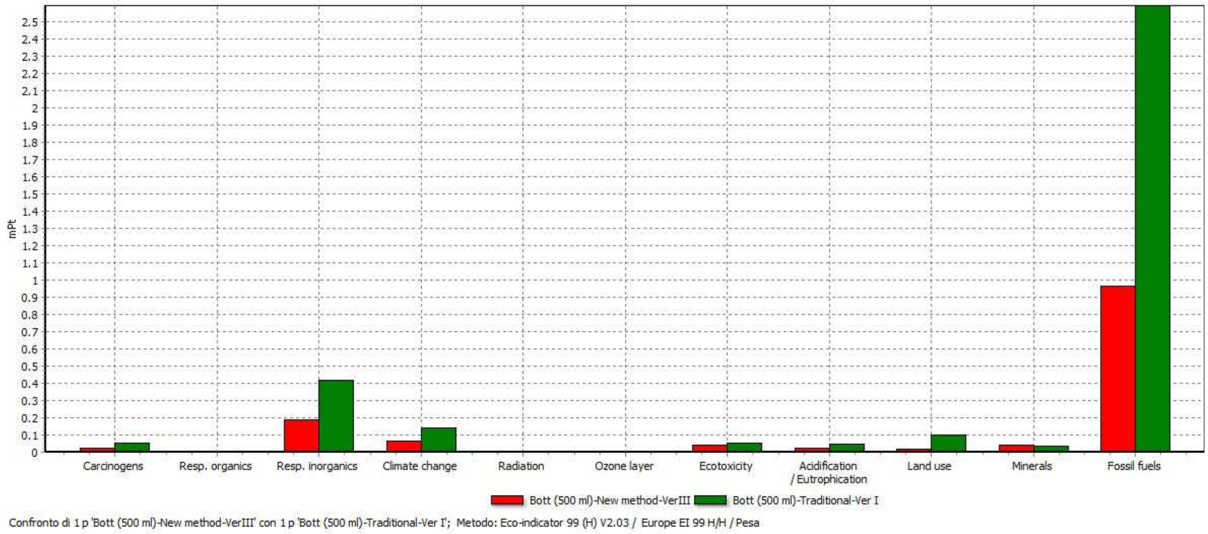

Figure 11: *Environmental impact categories related to the bottle production according to the mentioned methods.*

Table 2: *Quantification of the main impact categories in terms of Ecoindicators.*

Ecoindicators (fu = 1 bottle)	**Traditional System**	**New Methodology**
Resp. Inorganics (DALYs)	$8,46*10^{-9}$	$4,15*10^{-9}$
Carcinogens (DALYs)	$1,14*10^{-9}$	$0,55*10^{-9}$
Climate Changes (Kg CO_2-eq)	$2,04*10^{-2}$	$1,06*10^{-2}$
Ecotoxicity ((PAF m_2 Yr)	$2,73*10^{-3}$	$1,57*10^{-3}$
Fossil Fuels (Kg Sb-eq)	$9,88*10^{-3}$	$4,95*10^{-3}$
Minerals (Kg Sb-eq)	$4,07*10^{-7}$	$0,17*10^{-7}$

Notes:

- **DALY:** Disability adjusted life year – number of year lost due to ill-health, disability or early death;
- **PAF m2 Yr:** Potentially disappeared fraction of species per m2 per year;

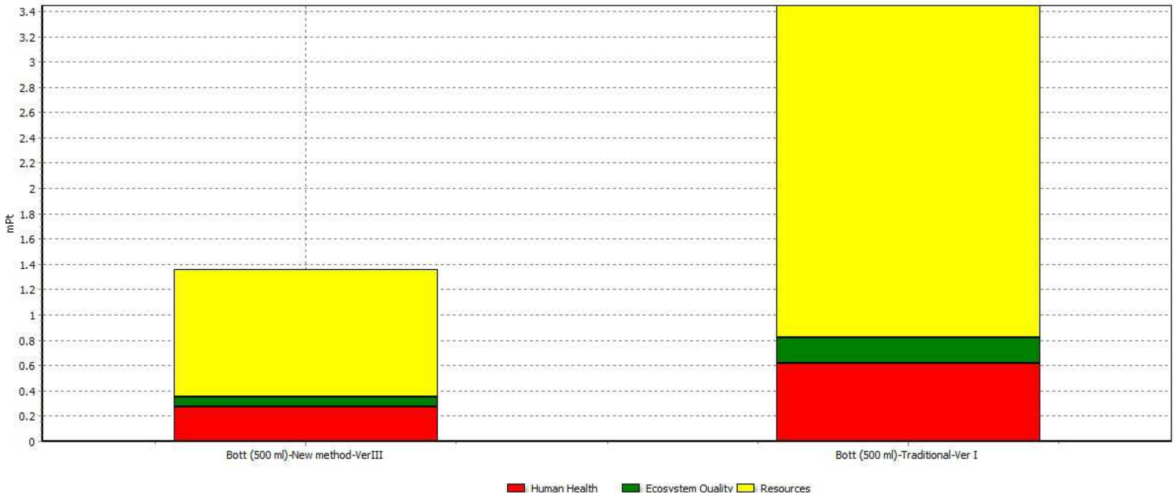

Figure 12: *Bottle production main environmental effects. Comparison between the two different processing methodologies.*

As shown in figure 12, for the new kind of bottle, the main environmental affect deals with the Abiotic Resources consumption, as the related role in the whole impact amounts to 63,55%. A relevant role is played by the effects on Human health, as these are responsible for the 26,57% of the whole LCA score. Finally, the worsening of the ecosystem quality is less significant, as the related category is responsible for less than the 10% of the whole environmental load.

In comparison to the bottle produced by mean of the traditional group of processes, the new one allows significantly reducing the impact also in terms of environmental effects. At this purpose, according to the mentioned outcomes, a considerable reduction in the exploitation of resources (- 54,09%), as well as a significant reduction in emission occurs (those ones responsible for human health issues (- 48,83%) and those ones responsible for the worsening of the ecosystem quality (- 51,38%)) if the traditional kind of bottle is replaced by another one manufactured by mean of the new process.

5-Conclusion

The models and the LCA analysis was implemented on 500 ml bottle according to different methodology: the traditional one, based on extrusion, perform injection moulding and bottle blow moulding, and a new one, in which component is developed in a single stage and in a very flexible apparatus. The apparatus, other than energy saving, allows to save also the plastic materials (7,8 g per bottles versus 8,7 g of the traditional system).

This framework, according to the obtained results, turns out in a significantly lower environmental impact for the bottle produced by mean of the new processing methodology, in comparison to that one produced by mean of the traditional stages.

This second part of analysis could demonstrate that the flexibility of the new process allowing the employment of significant amount of rPET (up to 50% in weight), which is reasonably higher than the amount which can be employed in the traditional processes flow (30% in weight), can contributes to increase the new process competitiveness.