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Executive Summary LCA 1

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 (6 g per bottles versus 8,7 g of the traditional system).

This framework, according to the obtained results, turns out in a 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 significantly reduce resources exploitation, harmful emission for the ecosystem quality and the human health, other than to save energy.

Moreover, it is worthwhile to point out that in this preliminary investigation, as a material, the virgin PET alone has been taken into account, despite a LCA model has been developed also for the recycled PET. At this purpose, the rPET LCI and the related process tree clearly showed the positive effect of the mentioned material recycling and the potentially positive replacement of some amount of virgin material with the recycled one in a polymeric blend.

According to the partners, the flexibility of the new process could allow to employ a significant amount of rPET, which is reasonably higher than the amount which can be employed in the traditional processes flow. This surely can increase the new process competitiveness.

This aspect could be taken into account in a future work, if the exact amount of recycled PET employed both in the traditional system and in the new one could be provided.

1-Introduction

This project main aim 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 bottle weight reduction (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.

Moreover, the mentioned new process could allow to increase the percentage of recycled fraction of PET in a water bottle in comparison to the traditionally produced one.

In general, the production of 1 kg of virgin PET lead to 1 kg of oil consumption equal to 8,5 litres of water. Additionally the average energy consumption amounts to 23 kWh.

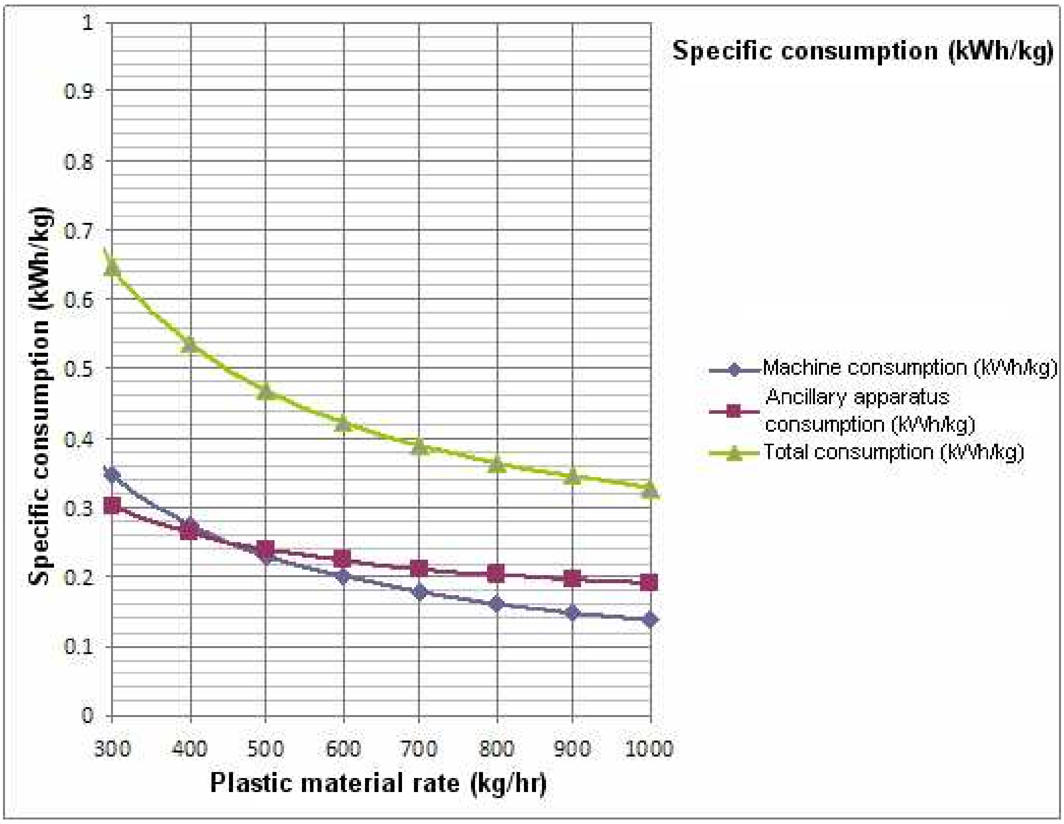

Figure 1: *Energy consumption versus processed material rate.*

The traditional methodology employed in the bottles manufacturing is based on a particular series (sequence) of very important processes, as extrusion, performs injection moulding and final blow moulding. Also assuming that the mentioned processed are carried out in the same process plant (with no issues related to transports), the energy consumption is straightforward. In general, the average energy expense amounts to 1,10 kWh/kg of produced bottles. The main target for the new process (single-stage) is to obtain a maximum energy expense of 0,76 kWh/kg of produced bottles. At this purpose, experimental data evidenced an energy consumption between 0,65 kWh/kg and 0,33 kWh/kg of produced bottles. This according to the diagram shown in figure 1.

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).

In the traditional bottle manufacturing a little (unspecified) amount of recycled PET is employed. Currently some producers employ an average amount of recycled PET equals to 20% in weight. Moreover, a very important Italian producer (Sanpellegrino Group) developed a 1 lt bottle containing the 25% of recycled PET. This as an answer to the Decreto Ministeriale n. 113 enter in force, which legalizes and encourages the development of new kind of ecofriendly packaging. At this purpose, according to the mentioned law, in the bottles production field, the maximum (approved) amount of recycled PET is 50% in weight. This aspect can considerably reduce the resources exploitation as well as the whole environmental impact.

According to the projects partners, the new manufacturing system, thanks to its flexibility, is very promising also from the mentioned point of view. The partners are still optimising the amount of rPET (recycled PET) that can be effectively mixed to the virgin one with no problems for the materials processing capability and for the bottle structural integrity. Moreover, the amount of rPET in the bottle manufactured by mean of the traditional series of processes has to be decided. For this reason this preliminary investigation has been carried out using the virgin polymer as a matrix for the bottle manufacturing, despite LCA models have been developed both for the virgin and for the recycled PET.

2-Life Cycle Analysis

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. In particular, there are 4 standards specifically devoted to LCA applications:

- 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.

The system is defined as the combination of procedures having the function of the generation of products or services. The system is separated from the environment by specific boundaries and it is connected to it by the exchange of inflows and outflows (Figure 2).

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.

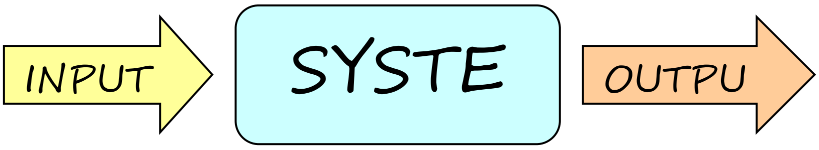

Figure 2: Schematic representation of the system in LCA.

The typical structure of the LCA study is represented in Figure 3. 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). In few word, the scope is the evaluation and the verification of the improvements in the environmental performance related to the technologies developed in the project in comparison to the benchmark technologies used in the same field and for the same purpose;

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.

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, as no data regarding the bottle durability and end of life, have been currently available, in comparison to the traditionally manufactured counterpart.

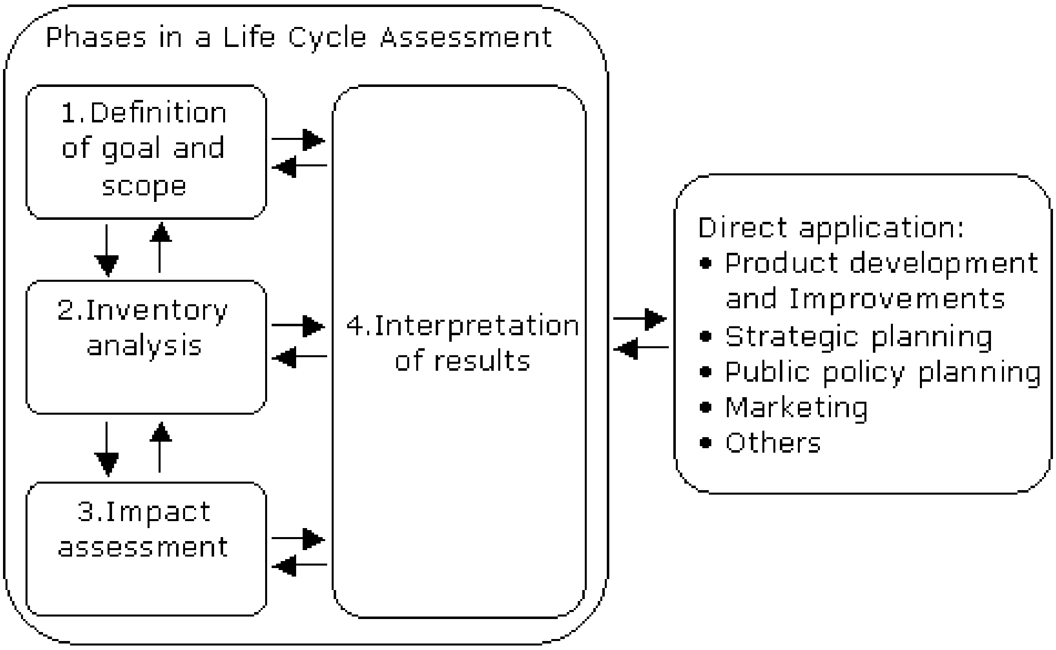

Figure 3: *Schematic representation of a LCA study.*

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. As it was said in the previous paragraph, the system boundaries are coincident with the physical limits of each manufacturing process, and it is useful to consider the generic single bottle production.

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 ISO standards contain a specific methodology for the creation of the LCI, as the only way to make different processes comparable is the creation of their relative LCIs by following the same methodology.

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. For example, what are the impacts of 9,000 tons of carbon dioxide or 5,000 tons of methane emissions released into the atmosphere? Which is worse? What are their potential impacts on smog? On global warming?

The key concept in this component is that of stressors. A stressor is a set of conditions that may lead to an impact. For example, if a product or process is emitting greenhouse gases, the increase of greenhouse gases in the atmosphere may contribute to global warming. Processes that result in the discharge of excess nutrients into bodies of water may lead to eutrophication. An LCIA provides a systematic procedure for classifying and characterizing these types of environmental effects.

Using science-based characterization factors, an LCIA can calculate the impacts each environmental release has on problems such as smog or global warming. What Do the Results of an LCIA Mean? The results of an LCIA show the relative differences in potential environmental impacts for each option. For example, an LCIA could determine which product/process causes more global warming potential.

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. The indicator of an impact category can be chosen anywhere along the impact pathway.
  In other words, characterization factors translate different inventory inputs into directly comparable impact indicators. For example, characterization would provide an estimate of the relative terrestrial toxicity between lead, chromium, and zinc. At this purpose, impact indicators are typically characterized using the following equation:

  $$\text{Inventory Data} \times \text{Characterization Factor} = \text{Impact Indicators}$$

  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.

- 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. There are numerous methods of selecting a reference value, including the total emissions or resource use for a given area that may be global, regional or local, the total emissions or resource use for a given area on a per capita basis, the ratio of one alternative to another (i.e., the baseline), or the highest value among all options.
  Is worthwhile to point out that the goal and scope of the LCA may influence the choice of an appropriate reference value.

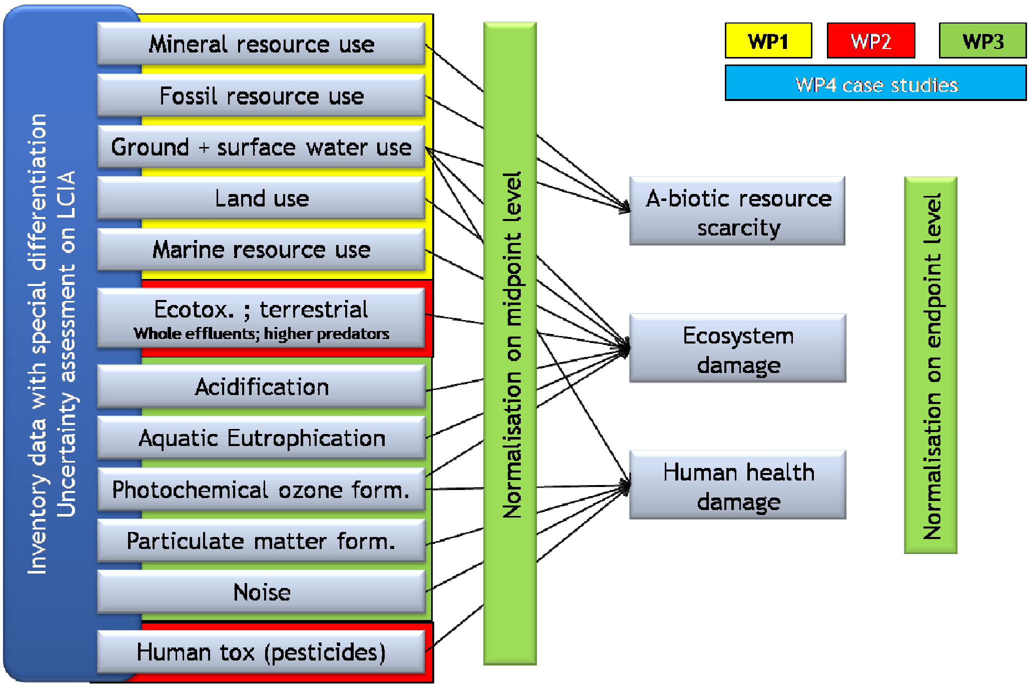

Figure 4: *Schematic representation impact categories (factors) and the related effects the lead to.*

- 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.
  Anyway, in some cases, the presentation of the impact assessment results alone (with no weighting step) often provides sufficient information for decision-making, particularly when the results are straightforward or obvious.

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, have been taken into account and then included in the life cycle. Issues related to the bottle durability (service life time, performance, etc.) and the related dismantling pathway have been omitted at the moment.

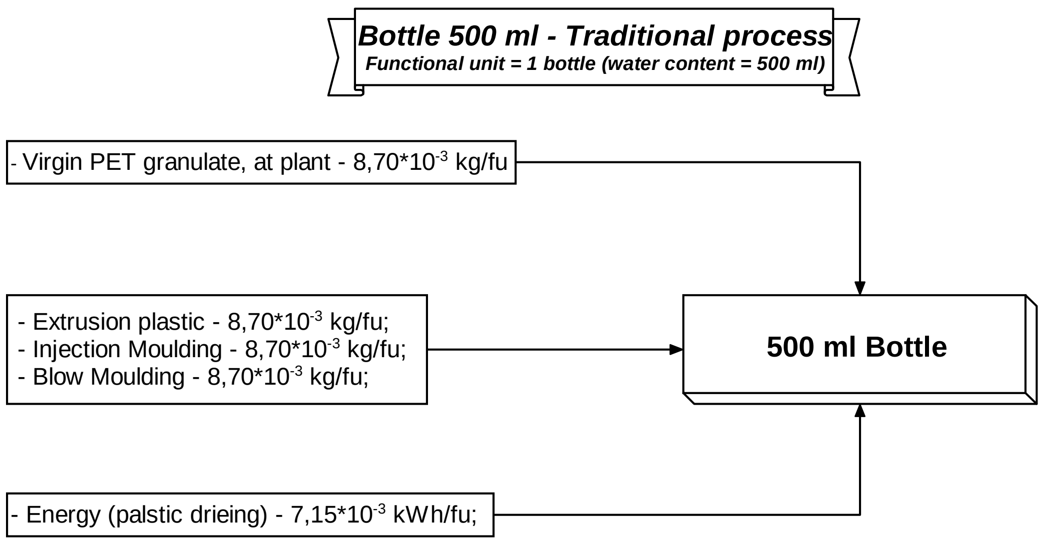

Figure 5: *Flow chart of the processes employed in the traditional bottle production.*

It is reasonable to think that no differences occur in the bottle end of life, both in the case it is produced by mean of the traditional technology and in the new one. Differences could rise in the case the two kinds of bottles contain significantly different amount of PET.

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 5, as well as the related inventory.

As it is possible to observe in the figure, as introduced, only virgin PET, as in the case of the new kind of plastic container, has been considered. Other than the extrusion, injection moulding and blow moulding processes contribution, also an energy contribution for the material (granulate) drying has been taken into account.

No issues have been dealt with regarding materials (granules transport) from the extrusion plant to the pre-form injection moulding plant and from the latter to the blow moulding stage. On the contrary, all the process have been considered occurring in the same production plant, despite this happens only in the case of the very big and international corporation or for the very big enterprises.

About the bottle manufactured by mean of the new process, in figure 6 is shown the production flow chart and the related life cycle inventory. Virgin PET is directly processed by mean the new process and in the related apparatus. Naturally, a model has been developed also for the mentioned processing method, taking into account energy expense, 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.

As in the previous case, non issues regarding transport have been dealt with, as all the processes can be performed in a single apparatus. Moreover, energy expense related to PET drying has been considered as for the traditional process, despite energy saving is previewed for the new system. This leads to a more conservative approach about the new process.

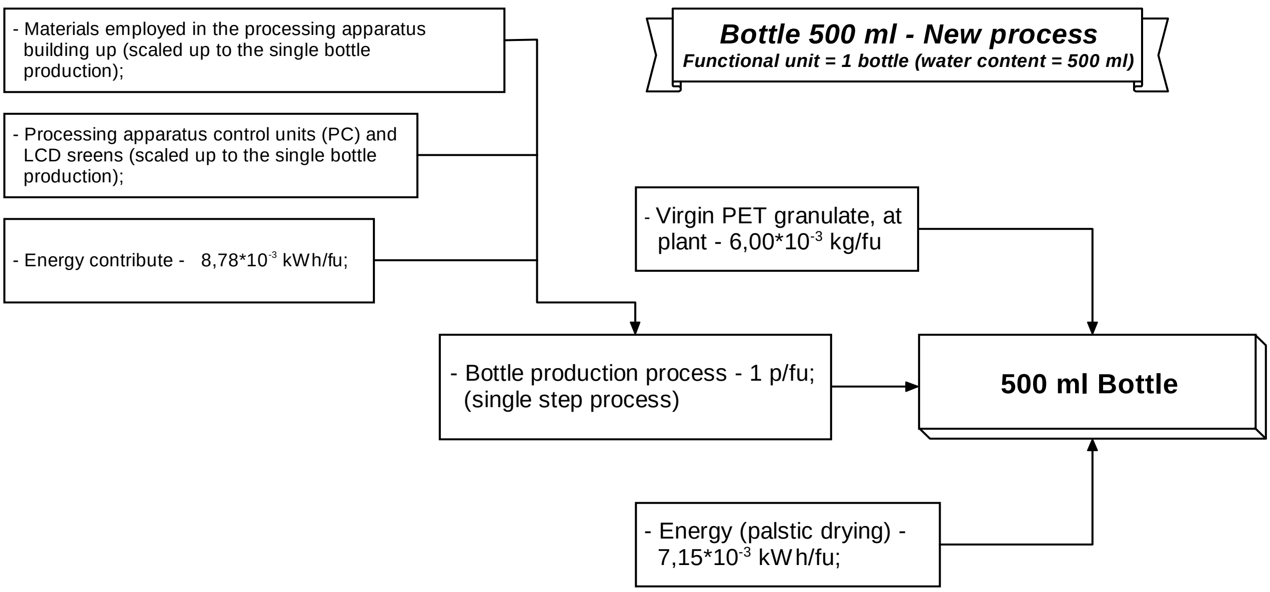

Figure 6: *Flow chart of the new process employed in the bottle production.*

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

It is worthwhile to point out that also a preliminary model has been considered for the PET recycling, despite it has not been exploited in this preliminary stage of the investigation. The models is based on the assumption that 1 kg of recycled PET has been considered as a functional unit and scraps have been neglected. Moreover, the collected PET has been considered to be milled (flakes production) and transported to the processing plant by mean of a 16 tons capacity truck. At this purpose, the average distance between the collecting and the processing plant is about 150 km. According to the literature[1], the recycling of 1 kg of PET allows to save 0,78 kg of virgin PET and to divert the mentioned amount of PET from landfilling. Moreover, also the following inputs can be avoided:

- Natural gas – 0,20 kg;
- Crude oil – 0,50 kg;
- Primary energy feedstock – 11 kWh;
- Process energy – 5,56 kWh;
- Emissions to air – 2,33 kg CO_2-eq;

The energy spent in a collecting plant amounts to 0,28 kWh per kg of recycled PET. This scenario suggests to stress as much as possible the PET recycling.

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, moreover also an example concerned with the environmental outcomes due to the PET recycling will be shown.

4.1-Preliminary Life Cycle Inventory for the produced bottles

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.

Referring to the scheme 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 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 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 $5,38*10^{-3}$ Pt (eco Points).

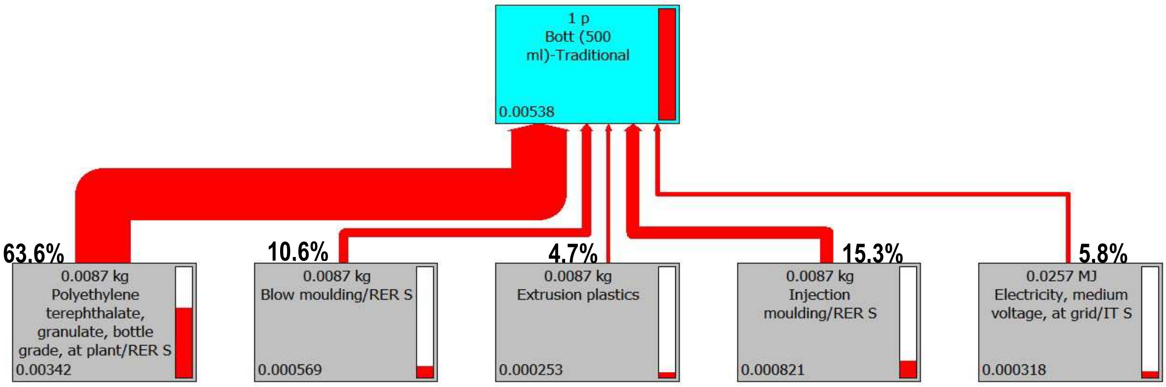

Figure 7: *Process tree concerned with the bottle produced through the traditional system.*

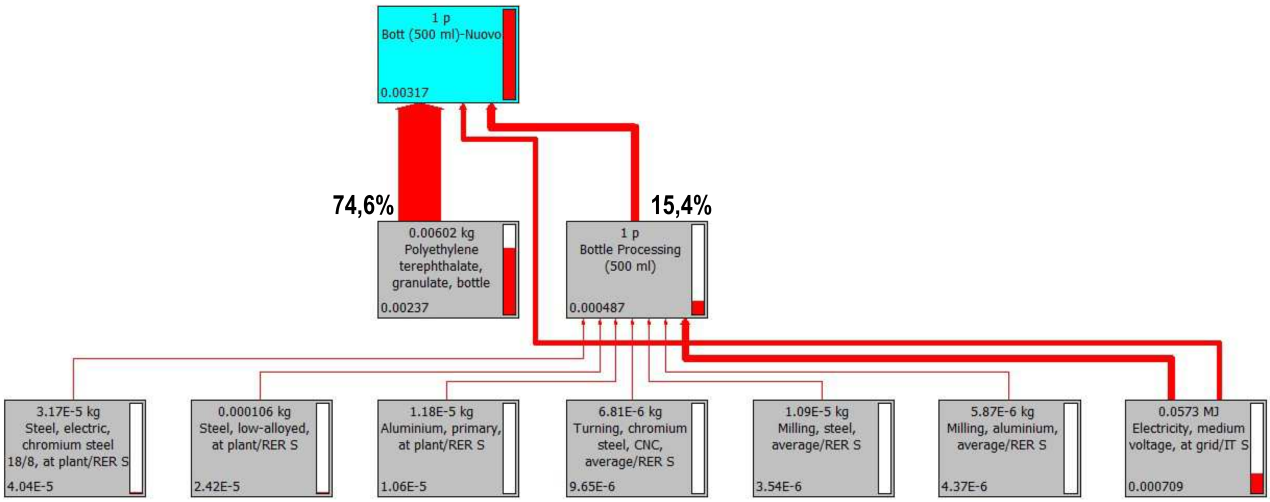

Figure 8: *Process tree concerned with the bottle produced through the new system.*

About the 63% of the whole impact is due to the employment of the polymer matrix, while the manufacturing process series contribute amounts to the 30%. Finally the lowest contribute is due to the energy expense used for the matrix drying before the related inlet into the process chain.

Figure 8 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 $3{,}17 \cdot 10^{-3}$ Pt. The main role is played again by the virgin matrix employments, as the related contribute to the whole impact is equal to the 74,6%. The process load is quite low, as its contribute amounts to the 15,4%. The remaining 10% is due to the energy used in the drying stage for the polymer granulate.

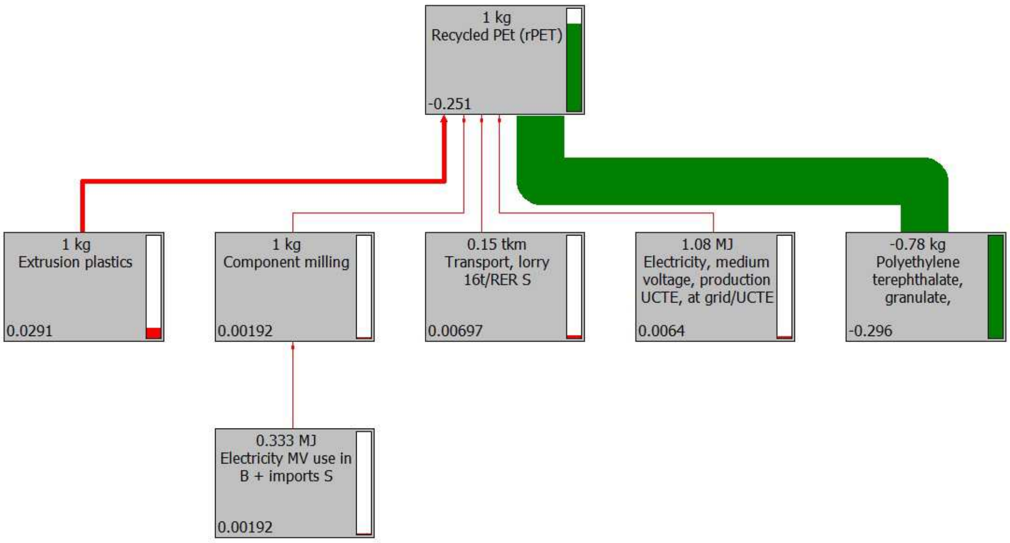

Figure 9: *Process tree concerned with the PET recycling.*

Is worthwhile to point out that the new process allows to significantly decrease the environmental impact concerned with the single bottle production (41%). 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 production leads to resources depletion and emissions (carbon dioxide and equivalents in terms of environmental effects).

As discussed in the previous paragraph, the PET recycling allows to 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. This is entrusted by the diagram of figure 9. It shows as the recycling of 1 kg of PET, despite some energy expense due to material milling, collection and transport, have e negative environmental score (-0,251 Pt). On the contrary the environmental score concerned with the production of 1 kg of the virgin counterpart is quite high (+ 0,393 pt).

The higher is the rPET content into the blend, the lower is the related environmental impact of the single bottle. It could lead to save in the resources depletion and to improve effects related to human health and ecosystem quality issues.

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

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) confirm that the new process allows to increase the environmental performance, as the related bottle environmental impact is considerably lower than the counterpart produced through the traditional series of processes.

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 80,50% and 78,1% respectively for the new and the traditional process methodology.

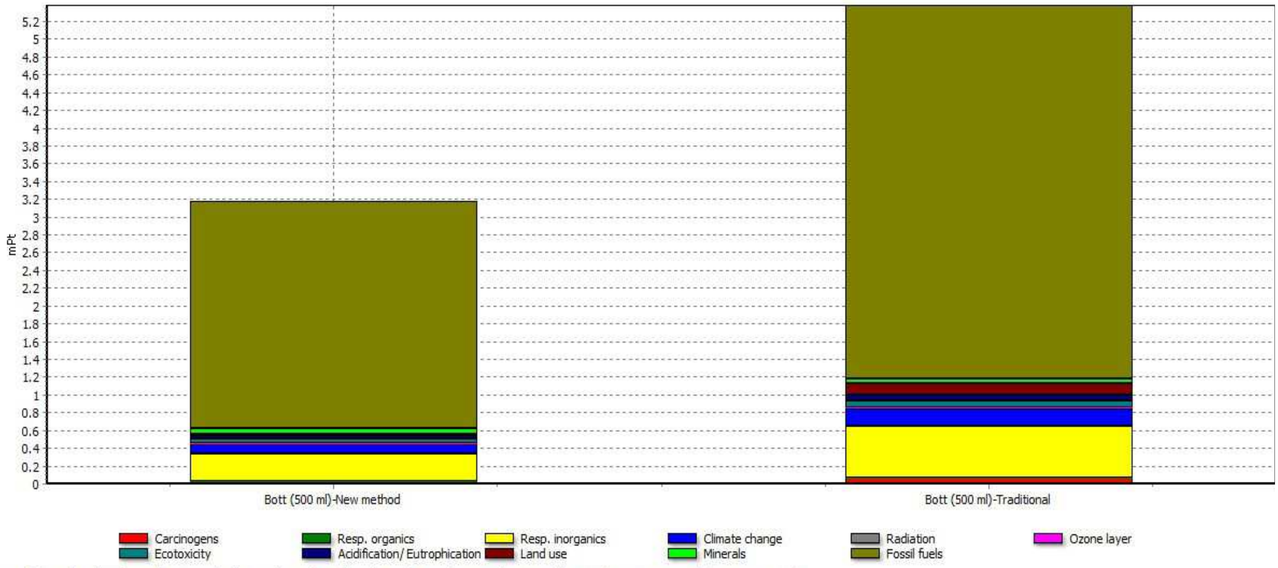

Figure 10: *Single score point evaluation for the LCA related to the bottle produced by mean of the two different methods.*

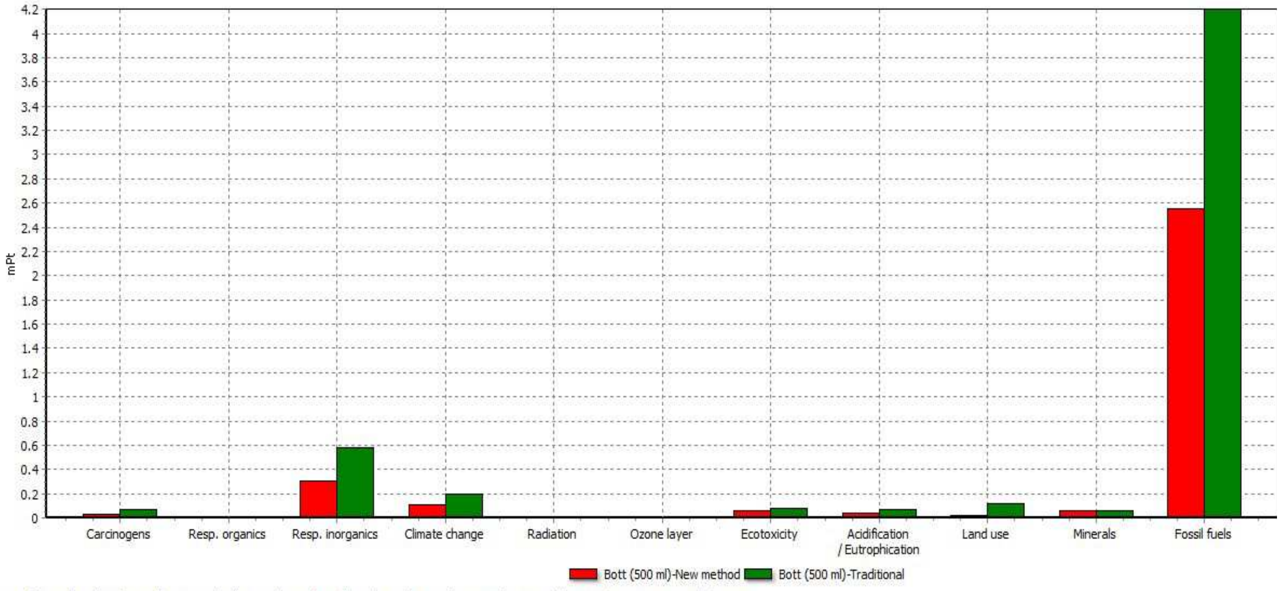

Figure 11: *Environmental impact categories related to the bottle production according to the mentioned methods.*

About the emissions, Resp. Inorganics contributes to the whole environmental load for the 9,7% and 10,8% 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 3,4% for the bottle produced through the new process and 3,7% 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)	$2{,}90 * 10^{-8}$	$1{,}52 * 10^{-8}$
Carcinogens (DALYs)	$3{,}29 * 10^{-9}$	$1{,}40 * 10^{-9}$
Climate Changes (Kg CO_2-eq)	$6{,}02 * 10^{-2}$	$2{,}79 * 10^{-2}$
Ecotoxicity ((PAF m_2 Yr)	$9{,}12 * 10^{-3}$	$6{,}91 * 10^{-3}$
Fossil Fuels (Kg Sb-eq)	$4{,}80 * 10^{-4}$	$2{,}76 * 10^{-4}$
Minerals (Kg Sb-eq)	$2{,}28 * 10^{-7}$	$2{,}32 * 10^{-7}$

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;

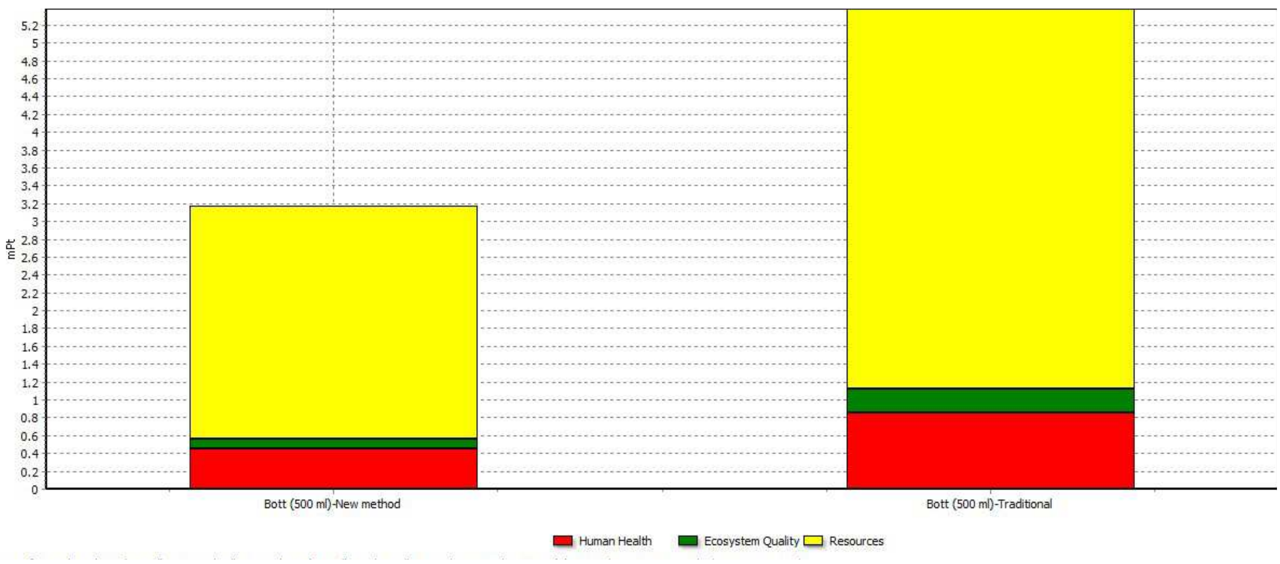

***Figure 12:** Bottle production main environmental effects. Comparison between the two different processing methodologies.*

The above mentioned aspects are confirmed in the diagram of figure 11. 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: - 47,59%;
- Carcinogens: - 57,45%;
- Climate Changes: -53,65 %;
- Eco toxicity: - 24,23 %;
- Fossil Fuels depletion: - 42,50%;
- Minerals depletion: + 1,74%;

According to the mentioned outcomes, only a moderate increase of the minerals depletion occurs, if the traditional processing system is replaced by the new one. On the contrary a considerable reduction of the exploitation of fossil fuels, as well as a significant emission reduction. For example, a reduction of the CO_2 and the other equivalent gasses, from the greenhouse effect point of view, occurs, which amounts to the 53,65%.

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 47,6%, as the worsening of the Ecosystem Quality of the 57% and in the Resources depletion of the 39%.

5-Conclusion

LCA, according to a "From Cradle to Grave" approach, allowed us to assess the real impact of the new process (one step) for the production of a bottle container of volume 500 ml and 6 gr weight compared to the bottle (500 ml and 8,7 gr weight) produced with the current process methodology (two step).

The new process is responsible of a lower environmental impact compared to the old one, this means significantly reduction of resources exploitation, harmful emission for the ecosystem quality and the human health, other than to save energy.

This first results are obtained considering 100% virgin PET therefore are given only by the process itself.

Thanks to the flexibility of the new process, that could allow to employ a significant amount of rPET, which is reasonably higher than the amount which can be employed in the traditional processes flow. This surely can increase the new process competitiveness.

6-references

- [1] B. Kuczenski and R.Geyer, "LCA and recycling policy — a case study in plastic". Life Cycle Assessment - IX - Boston, MA - October 1, 2009;