LCA ANALYSIS OF A SOLAR CONCENTRATION SYSTEM FOR THE MICRO-CHP AND COMPARISON WITH A PV PLANT

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SUMMARY

Life Cycle Assessment (LCA) is one of the main instruments for the implementation of an *Integral Policy of Products*, and it is also an operating instrument of *Life Cycle Thinking*: LCA is an objective methodology of assessment and quantification of the energetic and environmental loads and of the potential impacts associated with a product/process/activity throughout the entire lifecycle, from the acquisition of raw materials up to disposal.

The results of an LCA analysis applied to a solar concentrating type Dish-Stirling for micro-CHP are presented in this work. An estimate of the environmental impacts of the concentration system, in comparison with impacts of a PV system located on a sloped roof with a retrofit system and of the Italian energy mix, is also performed by the Eco-indicator 99, and EPD 2007 methods.

INTRODUCTION

The LCA method (Life Cycle Assessment) is based on the principle that a product needs to be monitored and analyzed at every stage of its life ("cradle to grave"), or rather from when it was produced to when it is disposed of, as each action associated with a phase may have repercussions on earlier or later phases. LCA, therefore, is fundamentally a quantitative technique for determining the input factors (raw materials, use of resources, energy, etc.) and output (waste water, waste, emissions) from the life cycle of each product, and it assesses the resulting environmental impacts. Through the study of LCA therefore the phases and moments in which the most critical environmental factors are concentrated, the individuals who must carry them out (producer, user, etc.) and information needed to implement the improvements can be identified [1, 2, 3].

This methodological approach is thus considered a tool to support environmental management, as it helps the designer to define the actions to be taken to improve the environmental performance of their production process by reducing resource consumption and curbing emissions of pollutants. So it is possible to intervene effectively, through analysis and knowledge of environmental effects caused by the entire production chain, in places where the most critical environmental factors are discovered, and it is possible to perform operations for the improvement and innovation of the design processes.

The structure of an LCA study is based on 4 steps:

1. *Definition of the objectives of the study and of the system boundary* (UNI EN ISO 14041);
2. *Analysis of inventory*, which are quantified flows of matter and energy input and output phases of the cycle (UNI EN ISO 14041);
3. *Impact Assessment*, which estimate the potential environmental impacts associated with the flows determined at inventory (UNI EN ISO 14042);
4. *Interpretation of the results*, which review the outputs of the two previous phases, and can verify the correspondence with the objectives of the study, defined in the first phase (UNI EN ISO 14043).

In the first phase are defined: the purpose of the study, the functional unit, the boundaries of the analyzed system, the necessary data, any assumptions, the verification procedures. The choice of the functional unity should be taken remembering that it is the quantified and measurable performance, objectively verifiable, of a product and it must be used as the reference unit of an LCA study. The purpose of the second phase is to highlight all the input and output flows for the different phases of the product: the physical flows of raw materials, emissions and their components are accounted for, and it brings to the structure a real environmental balance. The Impact Assessment (third phase) is one of the most critical phases of LCA, because in this phase the magnitudes and the potential environmental impacts of a system/product are defined. The Assessment envisages: classification, aggregation and valuation of environmental impacts. The fourth phase shows links between LCA and other instruments of environmental management.

At International level Standards ISO 14000th [4, 5, 6, 7, 8] reflect the general consensus about current good practices aimed at environmental protection, applicable to any organization anywhere in the world.

SYSTEM DESCRIPTION

The paper shows the results obtained by the application of the LCA method to a solar concentration system for micro-CHP [9, 10], which uses the Dish-Stirling System: this system is able to deliver solar energy, collected in a structure reflecting to a Stirling type engine alternator, to produce both electricity and heat (see Fig. 1).

Fig. 1 – Example of Dish-Stirling solar concentration system.

The system studied was designed and tested by Innova Technology Solutions; data and drawings are not supplied in the paper as the system is being patented. The system consists of a structure that supports the strings of the reflective panels (mirrors) and the tower for the attachment of a Stirling engine; the structure has a single engine which can rotate the set of strings and it has a series of smaller engines, whose purpose is to rotate the individual strings: in this way the system is able to pursue the solar radiation in an optimal manner.

The innovative part of the considered system is the Stirling engine, *free-piston* type [11], generating an electric power of 1 kW_e and a thermal power of 2 kW_{th}. The innovative part of Stirling consists of the linear alternator, which is essentially a linear engine used as an electric generator (Fig. 2). The principle used is electromagnetic induction: the force is generated by a set of electromagnets, which generates a flowing magnetic field, and it interacts with fixed conductor elements on the lead.

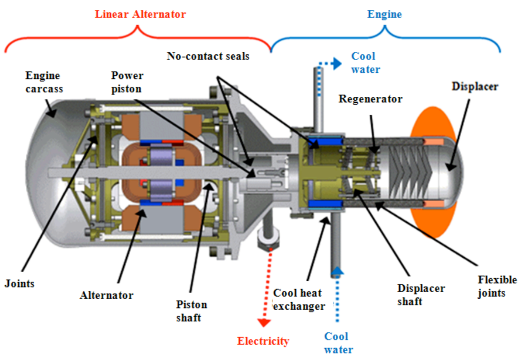

Fig. 2 – Stirling engine.

Moreover, the system has a boiler: its capacity is 150 liters and the water, which is needed for cooling the Stirling engine, can be used as hot sanitary water; there is a removable heating coil in the boiler with a flanged edge, which is caulked with a layer of HDPE.

FUNCTIONAL UNITY AND DISPOSAL SCENARIO

The functional unity is a benchmark for all input and output flows of the system and for potential environmental effects. Specifically, the choice of functional unity fell on the total plant, which consists of the bearing structure, the tower with Stirling engine, the strings with mirrors, the movement system and the boiler. Regarding the system boundaries, the upstream is the extraction of raw materials, which are necessary to the production of several components; the downstream is the disposal of the plant. The time-frame of reference is the lifetime of the plant (25 years).

Concerning the disposal-scenario, it is necessary to collect data concerning the recycling of all materials; specifically, the following options have been identified: reuse of sections/angles in aluminium, steel recycling and reuse of packaging cartons.

ENERGY ANALYSIS

The purpose of energy analysis is to account for the total energy demand of the system or process; then all uses, direct and indirect, of the Energy needed to power the system are evaluated . The main flows of energy are: direct energy, indirect energy and feedstock energy . The direct energy is the sum of the rates resulting from the production of semi-finished products and the processes involved in the life cycle of the system; the indirect Energy is the sum of the components on the production of raw materials needed for the manufacture of semi-finished products and of their transport to the factory; feedstock energy, finally, is the energy that would be obtained burning the materials of the semi-finished products. With reference to direct energy, Fig. 3 shows that, regarding the analyzed plant, the biggest part comes from the realization of the tower which supports the Stirling engine and, in particular, from the aluminium extrusion process which covers almost all of the energy expenditure.

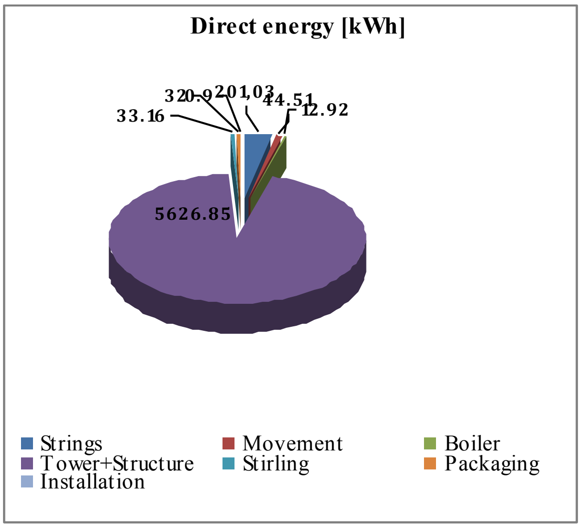

Fig. 3 – Direct energy.

The major contribution of indirect energy also comes from the extraction of aluminium; transport does not play a particularly significant role.

In the disposal phase there are other energy flows which are beneficial to the life cycle of the plant; indeed, thanks to the operation of reuse and recycling, the rates coming from the extrusion process of aluminium profiles, from the rolling of the steel and from the packaging production, are subtracted from the total amount of energy needed for the plant. The assessment of energy recovered in these phases, for different materials, is carried out through the database available in the literature [12, 13, 14].

The Gross Energy Requirement (GER) is the sum of all the energy flows (direct, indirect, feedstock and transports) which enter the system. The assessment may or may not account for the energy-saving related to the processes of reuse and recycling of different materials. Results of simulations, carried out with the software Simapro, are shown in Tab. 1(a) for a Dish-Stirling system (DS) and in Tab. 1(b) for a photovoltaic plant placed in retrofit on a sloping roof (PV).

	LANDFILL		REUSE/RECYCLING	
	Rates of El. En. [kWh]	% Amount	Rates of El. En. [kWh]	% Amount
Direct Energy	5947.37	29.21 %	543	7.53 %
Indirect Energy	14028.44	68.9 %	6224.04	86.32 %
Feedstock Energy	338.18	1.65 %	338.18	4.69 %
Transport Energy	48.58	0.24%	105	1.46 %
TOTAL	**20362.57**	**100 %**	**7210.60**	**100 %**

Tab. 1(a) – GER-Landfill VS GER-Reuse/Recycling for a DS system

The difference between the two values of GER is significant: the energy analysis, assuming the complete disposal of the plant by landfill, is more onerous than the energy analysis based on the complete reuse and recycling of materials. The GER of the first solution appears to be about three times greater than the second solution. This is mainly due to the contribution, direct and indirect, of aluminium, which appears to require a number of high-energy consumption processes both in the extraction/production and in the manufacturing phases.

	LANDFILL		REUSE/RECYCLING	
	Rates of El. En. [kWh]	% Amount	Rates of El. En. [kWh]	% Amount
Direct Energy	21583	95.60 %	19961	96.02 %
Indirect Energy	600	2.66 %	422	2.03 %
Feedstock Energy	235	1.04 %	235	1.13 %
Transport Energy	158	0.70 %	170	0.82 %
TOTALE	**22578**	**100 %**	**20787**	**100 %**

Tab. 1(b) – GER-Landfill VS GER-Reuse/Recycling for a PV plant

The most interesting result that arises as a direct result of the LCA analysis is the calculation of Energy Pay-Back Time (EPBT). It indicates the number of years in order that the plant produce the energy used for its implementation during its operational phase; the EPBT is a very important fact, both energetically and economically, and it is defined [15]:

$$\text{EPBT [years]} = \frac{\text{GER}}{\text{Energy}_{\text{prod./year/net}}} \quad (1)$$

If the analyzed plant, with an electrical power of 1 kW_e and a thermal power of 2 kW_{th}, is installed in a place in southern Italy (Cosenza), it is be able to generate 1792 kWh_e and 6786 kWh_t for one year [16]. The thermal energy can be transformed in "electric equivalent" energy, through the Carnot factor, taking into account the increase of temperature that the cooling water undergoes in the Stirling engine. Assuming an increase of 5°C, the total electric energy production amounts to about 1906 kWh/year. The increase of temperature of water can be even greater , but this has the consequence of a reduction in the electrical efficiency of the engine. According to the data of electricity production, by Eq. (1), we can determine the EPBT, in both cases first examined: landfill disposal of materials and total reuse/recycling of materials.

	LANDFILL		REUSE/RECYCLING	
	DS PLANT	PV PLANT	DS PLANT	PV PLANT
GER	20362.57	22578.22	7210.60	20787.58
Energy prod/year	1905.8	1756.84	1905.8	1756.84
EPBT [years]	**10.68**	**12.85**	**3.78**	**11.83**

Tab. 2 - Energy Pay-Back Time.

The management of the disposal-scenario is fundamental and it has a large influence on the energy payback time; if the processes of reuse/recycling are not included in the disposal-scenario, the EPBT is approximately 11 years, but otherwise the value drops to less than 4 years. Instead, a photovoltaic plant placed in retrofit on a sloping roof, in the case of complete reuse/recycling of materials used, presents a EPBT of approximately 12 years (Table 2).

Moreover, the variation of EPBT depending on the latitude of the site of installation, was evaluated; as can be imagined, further north, the production of electricity decreases and the EPBT increases. It has been suggested to locate the DS plant in three Italian locations (Cosenza, Rome and Milan) and in other different places (see Table 3). Concentration plants, as is known, use only the direct component of solar radiation, so comparisons were made taking into account the direct annual energy values for the different locations. In Rome, direct solar energy is lower by 40.2% compared to Shoubak, while in London it is lower by 72.5%.

LOCALITY	COUNTRY	LATITUDE	PROD/YEAR [kWh]	EPBT [years]
Cosenza	Italy	39° 18’	1905	3.8
Rome		41° 53’	1555	4.6
Milan		45° 27’	1135	6.3
Helsinki	Finland	60° 19’	1106	6.5
London	U.K.	51° 31’	714	10.1
Paris	France	48° 46’	1000	7.2
Shoubak	Jordan	30° 31’	2600	2.8

Tab. 3 - EPBT in different places (with reuse/recycling of materials).

IMPACT ASSESSMENT WITH ECO-INDICATOR 99 METHOD

The method of Eco-indicators is one of the most comprehensive and easier to read, because there are essentially three damage categories : Human Health, Ecosystem Quality and Resources. Each of these macro-categories is assigned eco-points, and several approaches may be followed: individualist, egalitarian, hierarchical, fatalistic and self-employment. The most reliable in the scientific community are: the individual approach, which focuses on the Resources category, and the hierarchical approach, which privileges the Ecosystem Quality category. If the number of eco-points is low, the environmental impact of the product or process is also low [17].

The Eco-indicator 99 Method was applied on the Dish-Stirling plant, according to the Individualist and Hierarchical approach. The results in Eco-points are collected in Table 4 and they are shown in Fig. 4. According to the individualist approach, the greatest impact is in the Resources category, owing to the necessary supply of raw materials, especially aluminium. The influence of the life cycle of the plant on the Human Health and Ecosystem Quality categories is low; this shows that the system, overall , does not cause much damage in terms of environmental emissions and toxicity to human.

Damage category	Unit of measurem.	Individualist Approach	Hierarchical Approach
Human Health	Pt	137.47	96.03
Ecosystem Quality	Pt	12.33	29.65
Resources	Pt	1136.56	116
TOTAL	Pt	**1286.35**	**241.69**

Tab. 4 - Eco-points with Eco-Indicator 99 Method.

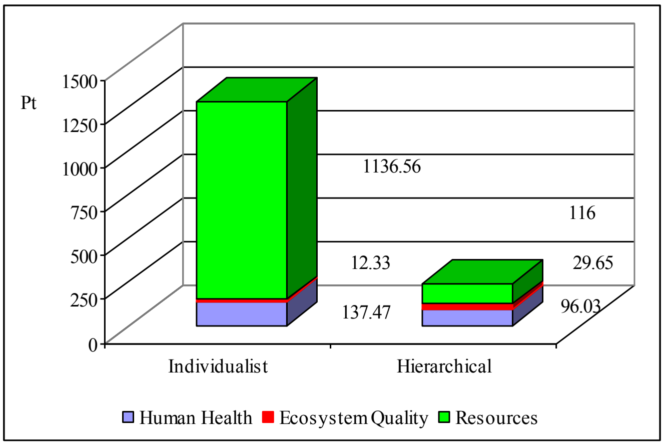

Fig. 4 - Eco-points with Eco-Indicator 99 Method.

The Table 5 and Figure 5 show, however, the variation of the impact in connection with the individual operations of recycling/reuse of materials, emphasizing how the reuse of aluminium is essential to reduce the environmental impacts of the system analyzed.

Damage category	Real disposal scen.	Only alum. reuse.	Only packag. reuse	Only steel recycl.	Landfill
Human Health	137.47	138	3254.9	3254.7	3254.7
Ecosystem Q.	12.32	12.4	327.7	327.79	327.8
Resources	1136.5	1136.6	1642.3	1642.3	1642.3
TOTAL	**1286.3**	1287	**5225**	**5224.8**	**5224.8**

Tab. 5 - Eco-points in operation with level of reuse/recycle.

An interesting result is the comparison between the Dish-Stirling system and a photovoltaic plant for the same peak-power, installed with retrofit system on scope roof. The annual production of PV power plant, estimated by the Siegel method, is about 1750 kWh: slightly lower than electrical production of the concentration plant. The comparison between the two systems was carried out according to the production of electricity annually, and it was evaluated for the lifetime of the two plants, estimated at 25 years.

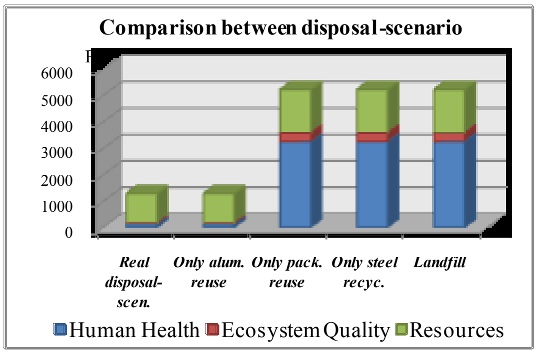

Fig. 5 - Eco-points in operation with level of reuse/recycle.

Thanks to the comparison, shown in Table 6 and Fig. 6, it can be pointed out that the DS plant, despite having a greater impact than the PV plant, concentrates its "harmful" effects on the consumption of resources; the damage caused by the PV plant on human health and ecosystem quality is, in proportion, considerably greater compared with the DS system.

	DS PLANT	PV PLANT	
Damage category	**Amount**	**Amount**	**Un. of meas.**
Human Health	2.95	7.67	MPt
Ecosystem Quality	0.25	0.38	MPt
Resources	24.24	7.043	MPt
TOTAL	**27.46**	**15.10**	**MPt**

Tab. 6 – Comparison between DS and PV plants (Individualist approach).

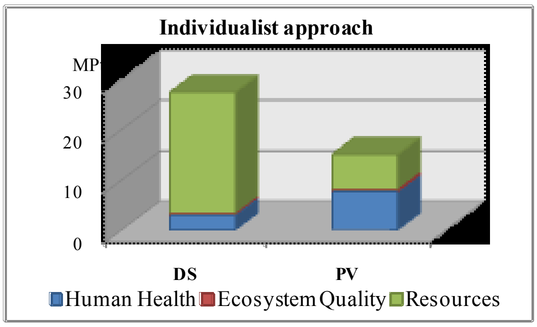

Fig. 6 - Comparison between DS and PV plants.

The comparison with the PV system was also carried out according to the hierarchical approach. In this case (Tab. 7 and Fig. 7), the situation is completely reversed and clearly in favour of the DS plant.

	DS PLANT	PV PLANT	
Damage category	**Amount**	**Amount**	**Un. of meas.**
Human Health	96.03	137	Pt
Ecosystem Quality	29.65	37	Pt
Resources	116.00	680	Pt
TOTALE	**241.68**	**854**	**Pt**

Tab. 7 – Comparison between DS e PV plants (Hierarchical approach).

The marked difference between the two points of view resides in the different interpretation of fossil fuels. Following the individual approach, fossil fuels are considered inexhaustible and, consequently, the category Fossil fuels is excluded from the characterization phase.
This category is instead present in the characterization of the hierarchical point of view, and it surely takes on greater importance in the case of the PV because of the manufacturing process of silicon, which requires high temperatures, with consequent energy expenditure.

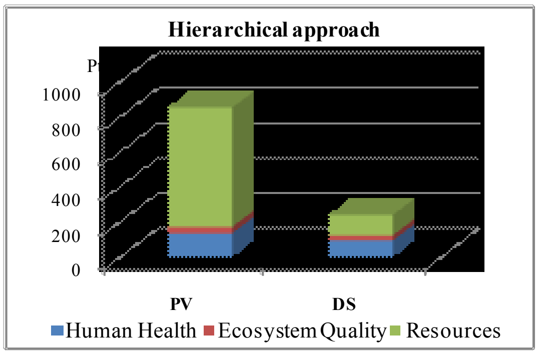

Fig. 7 - Comparison between DS e PV plants.

Human Health and Ecosystem Quality categories also result in favour of the DS plant, but the difference between the values obtained from the PV plant comparison is not so relevant.

The comparison between the DS system and the Italian energy mix is very interesting, accounting for the energy from renewable sources (especially hydroelectric and geothermal energy, which today are an important part of the energy mix). This comparison was carried out on equal energy (annually), using the individualist approach. The results of the comparison, in Tab. 8 and Fig.8, shows that current power plants have a greater impact than the DS power plant.

		DS PLANT	ENERGY MIX
Damage category	**U. M.**	**Amount**	**Amount**
Human Health	Pt	137.47	916.31
Ecosystem Quality	Pt	12.325	45.322
Resources	Pt	1136.56	1186.7
TOTALE	Pt	**1286.35**	**2148.33**

Tab. 8 - Comparison between DS plant and the Italian energy mix

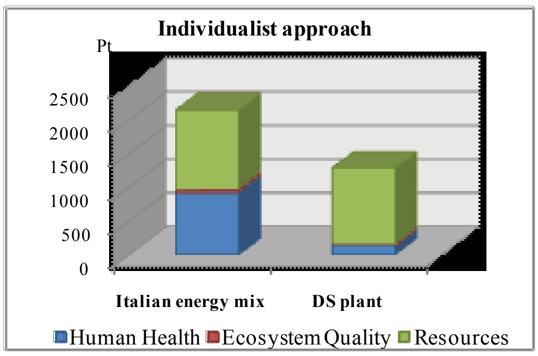

Fig. 8: - Comparison between DS plant and the Italian energy mix.

IMPACT ASSESSMENT WITH EPD 2007 METHOD

The EPD 2007 method is used to create Environmental Product Declarations; the impact categories of the EPD method, which have different titles in comparison with those used in the method Eco-Indicator 99, include: Global warming, Ozone layer depletion, Photochemical oxidation, Acidification, and Eutrophication [18]. Table 9 shows the environmental impacts evaluated by the EPD method for the Dish-Stirling system.

Impact category	Amount	Unit of Meas.
Global warming	3545.05	kg CO_2 eq
Ozone layer depletion	0.00023	kg CFC-11 eq
Photochemical oxidation	2.77	kg C_2H_4
Acidification	33.56	kg SO_2 eq
Eutrophication	1.62	kg PO_4--- eq

Tab. 9 – Environmental impacts of DS plant with EPD 2007 method.

The fundamental contribution is the item Global Warming and it shows the emission of greenhouse gases from the processing and production of raw materials, which has a bigger impact on the result of the total impact, increasing the risk of global warming. A comparison between DS system and PV plant was also carried out with EPD 2007 method; the results are summarized in Tab. 10 and shown in Fig. 9.

	DS PLANT	PV PLANT	
Impact category	**Amount**	**Amount**	**Unit of M.**
Global warming	3545.05	12372.87	kg CO_2 eq
Ozone layer depletion	0.00023	0.0018	kg CFC-$_{11}$ eq
Photochemical oxidation	2.77	4.30	kg C_2H_4
Acidification	33.56	58.51	kg SO_2 eq
Eutrophication	1.62	4.34	kg PO_4-- eq

Tab. 10 – Comparison between DS e PV plant (EPD method).

The advantages, in terms of eco-compatibility, of the DS system in comparison with the PV plant, are much more evident in the results obtained with the EPD 2007 method. The method of Eco-Indicator 99, in fact, gives considerable weight to the effect of consumption of resources, especially in the case of the individualist approach. The assessment of impacts with EPD 2007, however, favours the effects on the environment (global warming, acidity, eutrophication, ozone depletion).

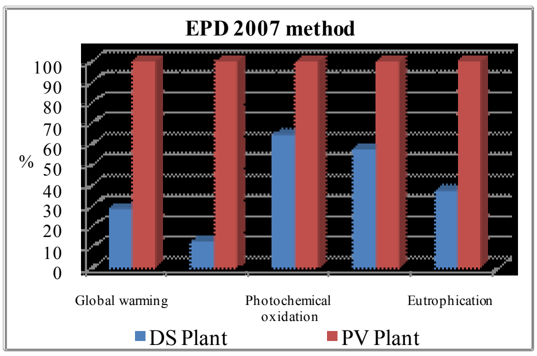

Fig. 9 – Comparison between DS and PV plants.

The comparison with the Italian energy mix, made with the EPD method, reconfirmed the results already obtained by the Eco-Indicator 99 method. The results, summarized in Table 11 and Figure 10, confirm the goodness of concentration system in comparison with the others plants producing electricity in Italy, especially in relation to the categories Ozone layer depletion (ODP) and Global warming (GWP100). The realization of the Dish-Stirling plant determines, therefore, marginal contributions to global warming and the ozone hole.

	DS PLANT	ENERGY MIX	
Impact category	**Amount**	**Amount**	**Unit of M.**
Global warming	3545.04	34022.37	kg CO_2 eq
Ozone layer depletion	0.00023	0.0027	kg CFC-11 eq
Photochemical oxidation	2.77	10.88	kg C2H4
Acidification	33.56	161.36	kg SO2 eq
Eutrophication	1.62	10,42	kg PO4-- eq

Tab. 11 – Comparison between DS plant and Italian energy mix (EPD).

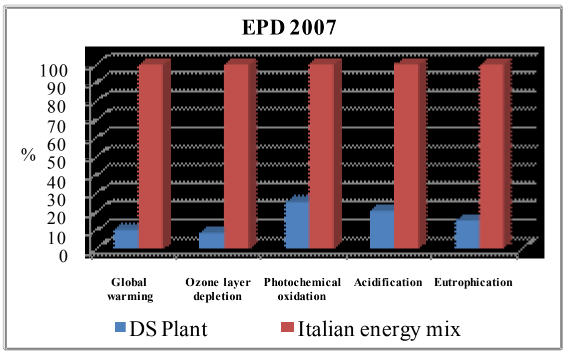

Fig. 10 - Comparison between DS plant and Italian energy mix.

CONCLUSIONS

The LCA method does not need to declare absolute truths, but it can certainly offer some useful guidance to address the alternative choices on materials and energy and to optimize decisions in the field of design, evaluating what are the stages in which to work to minimize environmental damage. Technological improvement can be achieved by changing the processes or the production techniques, the materials purchased from outside, the products used, promoting the recycling of materials within the company, and separating and retaining those that can be reused.

Results of the LCA analysis of a solar power plant concentration Dish-Stirling type are shown in this work. They are obtained through simulation with the Simapro software, and they show a low impact of the DS system, in comparison with a PV power plant and with the Italian energy mix. This result is confirmed both by the Eco-Indicator 99 and the EPD 2007 method.

The Energy Pay-Back Time, if there is a complete reuse and recycling of materials, is absolutely in favour of the Dish-Stirling system.

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