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Life cycle assessment and economic analysis of a low concentrating photovoltaic system

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ABSTRACT
Many new photovoltaic (PV) applications, such as the concentrating PV (CPV) systems, are appearing on the market. The main characteristic of CPV systems is to concentrate sunlight on a receiver by means of optical devices and to decrease the solar cells area required. A low CPV (LCPV) system allows optimizing the PV effect with high increase of generated electric power as well as decrease of active surface area. In this paper, an economic analysis and a life cycle assessment (LCA) study of a particular LCPV scheme is presented and its environmental impacts are compared with those of a PV traditional system. The LCA study was performed with the software tool SimaPro 8.0.2, using the Econinvent 3.1 database. A functional unit of 1 kWh of electricity produced was chosen. Carbon Footprint, Ecological Footprint and ReCiPe 2008 were the methods used to assess the environmental impacts of the LCPV plant compared with a corresponding traditional system. All the methods demonstrated the environmental convenience of the LCPV system. The innovative system allowed saving 16.9% of CO_2 equivalent in comparison with the traditional PV plant. The environmental impacts saving was 17% in terms of Ecological Footprint, and, finally, 15.8% with the ReCiPe method.

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KEYWORDS
Photovoltaic; LCPV; economic analysis; life cycle assessment; LCA

Nomenclature

A	area (m^2)
BIPV	building-integrated photovoltaic
C	concentration factor
c	specific market cost (€/kWh)
CdTe	cadmium telluride
CF	cash flow (€)
CPV	concentrating photovoltaic
E	energy (kWh)
G	irradiance (W/m^2)
HCPV	high concentrating photovoltaic
I	global radiation (kWh/m^2)
LCA	life cycle assessment
LCPV	low concentrating photovoltaic
M	proportionality coefficient
N	number
P	power (kW)
PV	photovoltaic
Si	silicon
STC	standard conditions
t	time (years)
T	temperature (°C)
×	suns

Greek symbols

η	efficiency
σ	temperature coefficient (% / °C)

Subscripts

a	active
BOS	balance of system
c	cell
CPV	concentrating photovoltaic
ee	electric energy
el	electric
g	global
inv	inverter
l	loss
LCPV	low concentrating photovoltaic
m	module
mir	mirror
opt	optic
pb	payback
pv	photovoltaic
std	standard
Sys	system
tot	total
wir	wiring

1. Introduction

In the last years, the use of photovoltaic (PV) systems rapidly increased, allowing a decrease of the unit cost of electricity production. From an industrial point of view, the limits related to the production costs of the materials have been reached.[1] However, new systems

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based on the PV technology are now available. As a matter fact, many PV applications, able to assure a competitive energy production in comparison with traditional systems, are present on the market [2] such as the concentrating photovoltaic (CPV) systems. CPV systems are an evolution of traditional PV systems. The main characteristic of CPV systems is to concentrate sunlight on a receiver by means of optical devices and then to decrease the solar cells area required proportionally with the concentration factor (*C*) [3]; *C* is the ratio between primary concentrator area and solar cell area. In order to focus the solar radiation on the PC receiver, CPV systems can principally employ two types of optics solution: refractive and reflective. The refractive solution adopts optical devices such as Fresnel lens, while the reflective solution uses special mirrors.[4] With a refractive solution, the solar radiation is diverted by means of a glass or plastic equipment and the light can also be decomposed into its spectral components. On the contrary, with a reflective optics the sunlight is diverted from its incidence direction and reflected to the receiver system without being decomposed in its spectral components. Refractive optics are cheaper than reflective ones, but they have lower performance mainly due to chromatic aberration problems. In general, the PV receiver is realized by means of conventional silicon cells, but multi-junction cells are preferred for their electric characteristics when the concentration factor increases. These cells are less influenced by the temperature increase because the open-circuit voltage increases logarithmically with *C*; therefore, efficiencies over 30% are experimentally achieved.[5]

There are various types of concentration systems, which depend on the type of sunlight focus and receiver. They are classified in plants at low, medium and high concentrations according to the *C* value.[6] The use of CPV solutions with an increasing *C* value determines a complete redefinition of the PV plants, introducing new components such as the tracking systems or mechanism for heat dissipation. The increase of concentration level allows a higher electric energy production in comparison with the traditional PV systems as well as an increase of total costs due to a greater complexity that not always allows decreasing the electric energy unit cost. For the above reasons, a low concentrating photovoltaic (LCPV) system is studied in this paper.

An LCPV system allows optimizing the PV effect with a high increase of the generated electric power as well as a decrease of the active surface area necessary to obtain the same electrical output. Moreover, this solution does not determine an excessive increase of the equipment costs.

In an attempt to utilize resources efficiently, several industrial sectors have involved in programmes to coordinate upstream (e.g. raw materials extraction) and downstream (e.g. end of life) activities to reduce environmental impacts. To assist suppliers and industrialists in fulfilling these tasks, systematic analytical tools have been developed, such as the life cycle assessment (LCA) for assessment of environmental performance.[7]

LCA is a general methodological framework introduced to assess all the environmental impacts related to a product, process or activity by identifying, quantifying and evaluating the overall resources consumed as well as all the emissions and wastes released into the environment.[8] Consequently, opportunities for optimizing the environmental impact, while maintaining process functionality, can be realized with the LCA.[9]

Some studies about LCA of PV systems have already been published. In [10] an accurate overview of the LCA on PV systems is presented in order to classify these according to the module type and the impact assessment method. In [11] the environmental impact of a building-integrated PVs (BIPV) with ceramic modules is analysed. In [12] the LCA methodology is applied to a cadmium telluride PV (CdTe PV) power generation system. Some papers also analyse the CPV system field. In [13] a CPV system with Fresnel lens and a *C* value of 550× is investigated from an environmental point of view. In [14] an LCA study of a PV system with a dual-axis tracking is implemented to evaluate the higher energy production rates. Finally, in [15] an integrated concentrated PV scheme with a *C* value of 10× is evaluated.

In this paper, a new CPV system has been introduced. It represents an evolution of a classic PV plant employed for a residential user. Differently from other papers, the new system has been sized starting from the classic PV system and its environmental impact is compared with that of a traditional PV system. Three different environmental impact assessment methods are used: Carbon Footprint, Ecological Footprint and ReCiPe 2008. Carbon Footprint is a single-issue method, while Ecological Footprint and ReCiPe 2008 are multiple-issue methods with 3 and 18 impact categories considered, respectively. The comparison between the LCPV and PV traditional system can be evaluated from three points of view. This a novelty of the performed study, because all the majority of published paper usually only consider one single impact assessment method, mainly Carbon Footprint. It is important to point out that the production of greenhouse gases and the consequent climate change is only one aspect of ‘the environmental question’. Carbon Footprint (typically expressed as the area needed to compensate CO_2 emissions) is part of Ecological Footprint and it is therefore interesting to verify what happen passing from a single-impact method to a three impacts methods containing when the CO_2 issue . Moreover, the global warming impact is also included in the method ReCipe containing 18 impact categories at the mid-point level (where each impact category is expressed in terms of category indicator and not in terms of damage category).

The second section of the paper is devoted to the description of the LCPV system adopted and to its energy evaluation and sizing. The third section describe the LCA methodology, while the fourth section regards the economic analysis and the economic model adopted. The obtained results and related discussion are separately presented in terms of economic and environmental aspects. Finally, the main outcomes based on the results obtained are stated in the Conclusions.

2. LCPV system

A CPV system is generally composed of three parts: receiver, focusing optics and sun tracking system. A LCPV system can avoid the tracker as function of the concentration level required. The receiver is made up by the PV cells on which the sunlight is focused by optical devices. The optics increases the incident radiation as function of the C value chosen. C is expressed in suns (×) and 1 sun is equal to 1000 W/m^2. C changes the incident radiation and is equal to:

$$C = \frac{A_{opt}}{A_c} \cdot \eta_{opt}, \qquad (1)$$

where the optical efficiency (η_{opt}) depends on the transmission and reflectivity coefficients of the optics used. Typical values for a refractive optical efficiency such as Fresnel lens are equal about to 80%. Adopting a reflective optics, the efficiency can reach higher values near to 90%.[16] A reflective optics requires a greater precision in the mirrors processing and consequently higher costs.

In the LCPV field, systems with a value of C up to 3× are called solar multipliers. Usually, when the concentration factor used is greater than 3×, the tracking system is required because the concentrating plants can operate only with direct radiation.[17] For lower C values, the sun tracking is not mandatory; hence, the LCPV can partially exploits the diffuse radiation. The choice of PV cells also depends on the C value. Multi-junction cells are the most efficient when operating at high concentration levels because the sunlight is absorbed selectively by different layers that constitute the cell and they are less influenced by the temperature increase. Although the single-junction cells, such as Si-ones, present a lower electrical efficiency, due to the thermal effects [18] in the energy conversion, they can well operate when C is very low, allowing a costs decrease compared to the multi-junction ones.

2.1. LCPV system description

In this paper, a LCPV system is presented in order to evaluate its electric energy production and related environmental impacts. There are two main configurations of an LCPV system: point-focus and line-focus. In point-focus systems each lens or mirror focuses the sunlight only in one cell.

The optics is mainly refractive consisting of generally acrylic material lenses. In line-focus systems the concentration takes place along a line where cells are usually arranged; these systems use refractive optics or reflective optics based on trough parabolic concentrators. The LCPV system considered presents a V-Trough configuration. These systems usually employ reflective optical components (parabolic mirrors, flat mirrors or composite mirrors) with a concentration ratio of 2–3×.

The reflective surface focuses sunlight on a point or on a line where the PV receiver, typically conventional polycrystalline or monocrystalline silicon cells, is placed. Since a low concentration factor has been chosen, the use of expensive multi-junction cells is not justifiable. The V-Trough reference configuration of the LCPV system, used for the LCA, presents a structure equipped with flat aluminium mirrors with a V-shaped profile that transfer the light beam on polycrystalline cells placed in central position. In Figure 1, the module scheme for the LCPV system is shown, the geometric concentration factor, which takes in account only the ratio between mirrors and cells area, is 2×. The module has 60 cells, each one with an active PV area of 0.156×0.156 m^2.

The manufacturing process of these systems is carried out with simple and inexpensive manufacturing techniques, suitable for small-scale residential users. The use of common silicon cells with a low C values does not require active cooling systems and sun tracker. These features make the V-Trough systems suitable for low-cost domestic applications.

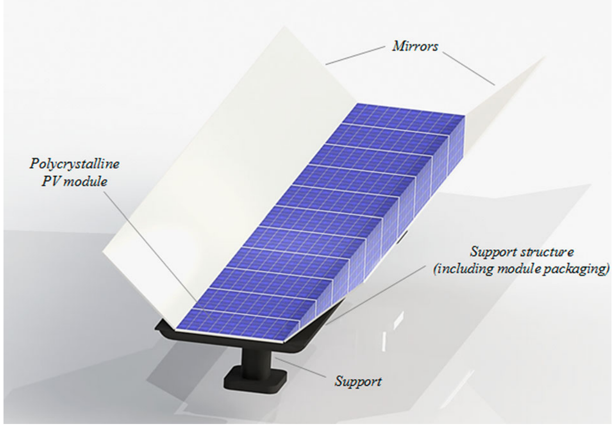

Figure 1. Module scheme for the adopted LCPV system.

2.2. LCPV system energy evaluation and sizing

The LCPV system analysis is strongly influenced by the user energy demands, and the system configuration have to be able to ensure a proper energy production. The module, shown in Figure 1, and the electrical loads of a domestic user represent the starting point for the energy evaluation and the sizing of the LCPV system. The low C value considered allows to employ a static optic system with flat mirrors. Therefore, the system can work with the global radiation.

Considering a total electric power of 3 kW_p for a domestic user, the LCPV system sizing has been carried out regarding a traditional non-concentrating PV system. The electric power of a traditional PV module can be expressed by:

$$P_{PV} = [(G_m \cdot \eta_{PV}) - P_l] \cdot \eta_{inv}, \tag{2}$$

where G_m (W/m^2) is the average irradiance on the module, the inverter efficiency (η_{inv}) is generally considered equal to 0.90. P_l is the electric power losses, typically negligible because equal to 2–3% of the total power.[19] η_{PV} is the PV efficiency that can be evaluated as

$$\eta_{PV} = \eta_{std} \cdot (1 - \sigma \cdot \Delta T), \tag{3}$$

where η_{std} is the PV efficiency in standard test conditions (ambient temperature of 25°C and solar irradiance of 1000 W/m^2), σ is the coefficient temperature (typically for polycrystalline silicon cells is equal to 0.40%/°C) and ΔT is the temperature gradient.

In order to meet the user loads,[20] the traditional PV sizing is based on 14 modules, with electric power of 0.210 kW_p. Considering the same G_m, estimated by means of the European database of solar radiation PVGIS,[21,22] and under the assumption of STC operating conditions, it is possible to compare a traditional PV system with the LCPV system presented. In particular, the components sizing of the V-Through system allows to evaluate the proportional relationship with the traditional one in terms of electrical output. Hence, it is possible to numerically quantify the differences between the two systems analysing performance, design and environmental impacts in order to provide the necessary electric energy for a standard domestic user.

Since the V-Through configuration works under the same operating conditions, the electric power of the LCPV module can be evaluated as

$$P_{LCPV} = [(G_m \cdot \eta_{PV} \cdot \eta_{opt} \cdot C) - P_l] \cdot \eta_{inv}, \tag{4}$$

where it is necessary to consider a loss factor given by the optical efficiency (η_{opt}) generally equal to 0.85 for good quality optics and the concentration factor C. Adopting Equations (2) and (4) for the two different systems, it has been obtained a proportionality coefficient equal to:

$$M = \frac{P_{LCPV}}{P_{PV}} = 1.296 \approx 1.3. \tag{5}$$

This factor shows that, during the system operating, the relationship between the electric power ratio and the geometric concentration ratio is not proportional. The V-Trough system allows a saving of PV active surface area estimated by a factor of about $1/1.3 \approx 0.75$. Therefore, a C value of 2× allows a decrease of the PV cells area of about 25% to obtain the same electrical output. Given the active area of the single Si-cell ($A_{a,c} = 0.156 \times 0.156$ m^2), the module active area can be evaluated considering the number of cells:

$$A_{a,m} = A_{a,c} \cdot 60 = 1.458\, m^2. \tag{6}$$

Hence, the mirror surface (A_{mir}) is equal to 2.916 m^2 ($C \cdot A_{a,m}$). So, considering the active area of the sized traditional PV system, which takes into account the $A_{a,m}$ and the 14 modules, and the proportionality coefficient, the V-Through active area can be evaluated:

$$A_{a,\,LCPV} = \frac{A_{a,\,PV}}{1.3} = 16.0\, m^2. \tag{7}$$

The modules number of the LCPV system required to satisfy the electric load of 3 kW_p is equal to:

$$N_m = \frac{A_{a,\,LCPV}}{A_{a,\,m}} = \frac{16.0}{1.458} \approx 11. \tag{8}$$

Referring to the V-Trough geometric configuration which has two flat mirrors for each module, the total number of mirrors is 22. Hence, the total mirror area of the LCPV system ($A_{mir,\,LCPV}$) is equal to 32 m^2. It is evaluated considering the 2.916 m^2 of mirror area required and the 11 modules sized. The relationship between the LCPV system and the traditional one, expressed by the M coefficient considering the electric power supplied and the active area required, is basic in order to compare the systems in term of LCA analysis.

3. LCA methodology

LCA methodology, as defined by SETAC or by ISO (International Organization for Standardization), consists of four steps [23,24]: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) improvement assessment.

3.1. Scope definition

The LCPV sizing equations, introduced in the previous sections, have been the starting point to extend the modelling of this category of PV systems according to the LCA requirements. Using Ecoinvent 3.1 database, all the LCA steps from the extraction of raw materials for each component until its end-of-life scenario (recycling/disposal) have been evaluated. Adapting appropriately the traditional PV system processes depending on the characteristics of the LCPV system and introducing the possibility of recycling, three specific environmental impact assessment methods have been considered: Ecological footprint, Carbon Footprint and ReCiPe 2008 H/H.

The Ecological Footprint method calculates the amount of biologically productive land and water required by a population to produce the resources it consumes and to dispose of the waste generated by the consumption of fossil and nuclear fuel.[25] Carbon Footprint was calculated by means of the IPCC 2007 GWP 100y indicator that is based on the factors of climate change over a period of 100 year considering the gaseous emissions of high potential greenhouse effect.[25] The ReCiPe 2008 H/H indicator combines a mid-point level approach (problem-oriented) with an endpoint approach (damage-oriented) considering impact categories such as ozone depletion, agricultural land occupation, fresh water depletion, fossil fuel depletion, etc.[26] Environmental impacts measured with the above-mentioned methods have been compared to the corresponding values of a traditional non-concentrating PV system.

3.2. Functional unit definition

The ultimate scope of every PV system is producing electricity. Therefore, a functional unit of 1 kWh of electricity produced has been chosen.

3.3. System definition

An LCPV system with concentration factor of 2× and V-Trough configuration was analysed. The life cycle of a typical low concentration plant consists of the following phases: production of the solar cells, production of optics, production of *balance of system* (BOS), installation, maintenance and end-of-life management. BOS represents a set of devices and electrical components necessary to transfer the energy produced by the system, such as cables, connectors, etc. In life cycle models, these phases are described by means of the individual sub-processes, which may vary depending on the type of technology and specifications. The functional structure adopted for the analysis of the LCPV system is based on the scheme proposed by the software SimaPro® 8.0.2 for concentrating PV systems with polycrystalline modules. Figure 2 shows the flowchart of the macro-structure of the reference plant.

3.4. System boundaries definition

The adopted approach is an attributional 'from cradle to gate' LCA. The system boundaries range from the acquisition of raw materials, their processing for the generation of semi-finished products to the final production of components (supports, inverters, optical concentrators and solar cells), use phase for the production of 1 kWh of electricity and end-of-life.

3.5. Data collection

In this phase, the focus is the collection of data necessary for the LCA calculations. Due to the lack of specific data, the PV database *Ecoinvent* has been used and properly adapted according to the specifications of an LCPV system sized for the production of 1 kWh of electricity.

3.6. System sizing

Implementation of the process in SimaPro® assumes the sizing of the reference system in order to calculate the quantities of necessary materials. In the previous sections, the sizing has been performed according to the electrical load required by a standard domestic user. Therefore, the analysis of both standard PV system and LCPV system has been realized. This has allowed to numerically quantifying the differences in performance, design and environmental impact.

A process that represents the CPV is missing in SimaPro® 8.0.2. Therefore, similarly to the sizing phase, it should be adapted the processes related to the production of PV modules and structure according to a rated output of 3 kW_p and the functional unit of 1 kWh of electric energy. The reference process has been named '3 kW_p LCPV Plant'. The LCA analysis of the

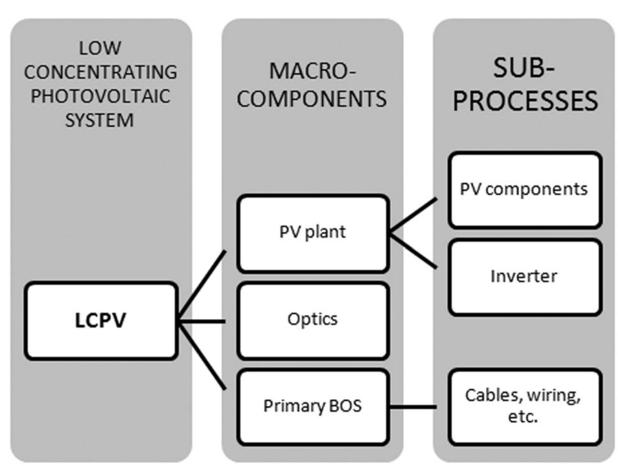

Figure 2. Flowchart of the macro-structure of the adopted LCPV plant.

Table 1. Materials, emissions and wastes related to the process "3 kW$_p$ LCPV Plant" (Ecoinvent 3.1 database).

Materials/fuels	Material for 1 m^2	Material for 18.1 m^2	Unit of measure
Electricity	4.7107	85.2637	kWh
Natural Gas	5.4071	97.8685	MJ
Industry PV panels	0.000004	0.0001	parts
Water	21.286	385.2766	kg
Tempering of flat glass	10.079	182.4299	kg
Copper wire drawing	0.11269	2.0397	kg
Photovoltaic cells (multi-Si)	0.93241	16.8766	m^2
Aluminium Alloy	2.6294	47.5921	kg
Nickel	0.00016277	0.0029	kg
Welding (cadmium)	0.0087647	0.1586	kg
Solar glass	10.079	182.4299	kg
Copper	0.11269	2.0397	kg
Plastic reinforced with glass fibre	0.18781	3.3994	kg
Ethylvinylacetate	1.0017	18.1308	kg
Polyvinylfluoride film	0.1104	1.9982	kg
Polyethylene	0.37297	6.7508	kg
Silicone	0.12195	2.2073	kg
Acetone	0.012959	0.2346	kg
Methanol	0.0021556	0.0390	kg
Vinyl acetate	0.0016434	0.0297	kg
Lubricating oil	0.0016069	0.0291	kg
Carton	1.0956	19.8304	kg
Propanol	0.0081386	0.1473	kg
Ship Transport	1.6093	29.1283	ton/km
Rail transport	9.4484	171.0160	ton/km
Air emissions	Emission for 1 m^2	Emission for 18.1 m^2	Unit of measure
Heat waste	16.958	306.9398	MJ
Waste treatment	Waste for 1 m^2	Waste for 18.1 m^2	Unit of measure
Solid waste disposal (incinerator)	0.03	0.543	kg
Polyvinylfluoride disposal (incinerator)	0.1104	1.99824	kg
Plastic disposal	1.6861	30.51841	kg
Mineral oil waste disposal (incinerator)	0.0016069	0.02908489	kg
Water treatment	0.021286	0.3852766	m^3

LCPV system is based on the evaluation of a series of sub-processes, which consider the energy expenditure for the production of the PV modules, auxiliary components and structural supports as well as for the phases of transport, assembly, maintenance and disposal. For example, Table 1 shows the standard process for the PV part. Using the values emerging from the sizing, the software has calculated, for a PV plant of 3 kW$_p$, an absorbing area of 23.474 m^2. This value is automatically increased compared to that previously calculated (22.9 m^2) as it takes into account additional space for maintenance. Considering the proportionality factor, the area occupied by the LCPV 2× plant, is equal to 18.1 m^2. Similarly, this procedure of adjustment has been applied to the processes related to structural supports, electrical system, PV inverter and flat mirrors. The values thus modified have been used as input in SimaPro® for the execution of the LCA analysis.

4. Economic analysis

The system costs analysis is an important step in the global impact evaluation of the LCPV scheme presented. The total cost of a CPV module is usually higher than a traditional Si-based one. A CPV system represents a set of parts whose costs have to be separately evaluated. Therefore, especially considering high concentration systems, the cost analysis takes into account the presence of optical elements, high efficiency multi-junction cells as well as sun tracking systems.[27] Traditional solutions with a proven technology have been previously employed; on the contrary, only in the last years the CPV systems have been adopted in commercial applications. However, the advantages obtained by adopting a concentrating system depend on operating conditions, user characteristics and market conditions. The unitary total cost of generated energy can indeed become convenient in some zones with high average global radiation and favourable energy incentive policy. All these considerations, given the absence of a common standard, have to be evaluated for a specific system configuration, such as the presented V-Trough system with a geometric concentration ratio of 2×. The solar cells performances have a high impact on the CPV system investment analysis, while the optical components influence, realized by low-cost materials such as glass or plastic, is typically negligible. Hence, for the LCPV configuration shown, the use of standard Si-cells with a reduction of their required area due to the optical elements presence could represent an interesting solution. However, the economic analysis is complex to generalize because of the presence of auxiliary component and commercial factors not fully predictable as national incentive policies and market balance of supply and demand.

4.1. Economic model of the LCPV system

The cost analysis for the LCPV reference configuration is based on some technical data supplied by manufacturers and adopting a theoretical model.[28] The model, originally developed for high concentrating photovoltaic (HCPV) systems with multi-junction cells, has been properly adapted to LCPV systems and generalized for the traditional Si-based PV plants. The main differences are related to the cell types, optics, trackers and other components such as structures, supports or active cooling systems. Generally, multi-junction solar cells cost is two or three times higher than traditional Si ones. The cost per peak kW is the reference parameter for the economic model and for the comparison between the various PV technologies. The economic analysis takes into account a consumer perspective, the payback period is related to a residential user.

The model evaluates the system cost incidence as function of the energy production:

$$\left(\frac{C}{E}\right)_{sys} = \frac{C_{CPV} + C_{BOS} + C_{inv}}{A_{CPV}*I_g*\ \eta_{tot}*t_{pb}}, \tag{9}$$

where $(C/E)_{sys}$ is the unit cost per kWh of electricity supplied, C_{CPV} is the PV components cost, C_{BOS} is the cost of the balance of system (structures, supports and tracker), C_{inv} is the cost of the inverter,[29] A_{CPV} is the total active surface of the modules, I_g is the average annual global radiation. The system total efficiency (η_{tot}) takes into account electric, optical, inverter and assembly losses, t_{pb} represents the simple payback time of the investment. The PV cost (C_{CPV}) considers the total modules costs, such as cells, concentrators and wiring costs [30]:

$$C_{CPV} = C_c + C_{opt} + C_{wir}. \tag{10}$$

The average annual global radiation has been estimated for different Italian zones by means of the European database of solar radiation (PVGIS).[31] Hence, for different configurations the payback time has been evaluated considering the total costs and the energy savings:

$$t_{pb} = \frac{C_{tot}}{CF}, \tag{11}$$

where the yearly cash flow (CF) is calculated as function of the electric energy obtained (E_{el}) and the energy specific market cost (c_{ee}):

$$CF = E_{el} \cdot c_{ee}. \tag{12}$$

5. Results and discussion

5.1. Economic aspects

The total LCPV area required is about 32 m^2, with 11 modules and 22 flat mirrors. Each module has 60 Si-cells and 2 mirrors. The geometric concentration adopted is 2×, the real proportional coefficient (M) related to a traditional PV plant of the same size is about 1.3. According to the reference cost model and taking into account a nominal power of 1 kW$_p$, the economic prospects in dollars, for a HCPV system, an LCPV and a traditional PV are shown in Table 2.

The costs for the traditional PV system and for the V-Trough 2× have been adapted according to the data of commercial polycrystalline silicon cells and for a domestic use inverter.[32] The optics influence has been evaluated considering the technical specifications of a flat solar mirror.[33] HCPV data relative to the cell packaging, the BOS and installation, maintenance and financing (IMF) have not been modified in absence of specific references related to the LCPV systems.[28] The overall system cost has been estimated as function of the system cost per module area unit.

With regarding to 1 kW$_p$, it has been calculated with a traditional PV plant a required PV surface of 7.29 m^2. As for the V-Trough 2×, an area of 5.6 m^2 is necessary to obtain the same power. Hence, referring to the nominal power of 3 kW$_p$, it has been determined an indicative cost value of $10,100$ for the PV system and 8400 for the reference system, that corresponds to about €7500 and €6300, respectively. The analysis shows that, for the same power output, it is possible to achieve a saving of about 17%. The comparison between the t_{PB} period of the V-

Table 2. Economic prospects for a HCPV system, an LCPV and a traditional PV (in dollars).

Parameter	HCPV	LCPV (2×)	PV
C_{cell}/A_{cell}	7.5 \$/cm^2	0.0055 \$/cm^2	0.0055 \$/cm^2
$C_{cell\ packaging}/A_{cell}$	2.5 \$/cm^2	2.5 \$/cm^2	2.5 \$/cm^2
STC cell efficiency	0.40	0.150	0.150
Concentration ratio	625×	2×	1×
Optical efficiency	0.80	0.80	–
AC electric efficiency	0.268	0.135	0.135
C_{cell}/A_{module}	120 \$/m^2	50 \$/m^2	50 \$/m^2
$C_{cell\ packaging}/A_{module}$	40 \$/m^2	40 \$/m^2	40 \$/m^2
$C_{module\ packaging}/A_{module}$	122 \$/m^2	122 \$/m^2	82 \$/m^2
$C_{inverter}/A_{module}$	48 \$/m^2	30 \$/m^2	30 \$/m^2
$(C_{BOS} + C_{IMF})/A_{module}$	260 \$/m^2	260 \$/m^2	260 \$/m^2
$C_{tracking}/A_{module}$	51 \$/m^2	–	–
C_{module}/A_{module}	282 \$/m^2	212 \$/m^2	172 \$/m^2
C_{system}/A_{module}	641 \$/m^2	502 \$/m^2	462 \$/m^2

Table 3. Comparison between the t_{PB}^{a} period of the V-Trough 2× system and the traditional PV solution, for different Italian cities.

Site	Latitude–longitude	Average annual global radiation (kWh/m^2)	LCPV system PB (year)	PV traditional system PB (year)
Bari	41.1°N–16.9°E	1820	6.3	7.5
Bologna	44.5°N–11.3°E	1430	8.1	9.6
Cagliari	39.2°N–9.1°E	1840	6.3	7.4
Firenze	43.8°N–11.2°E	1540	7.5	8.9
Milano	45.5°N–9.2°E	1470	7.8	9.3
Napoli	40.9°N–14.3°E	1690	6.8	8.1
Palermo	38.1°N–13.4°E	1870	6.2	7.3
Roma	41.9°N–12.5°E	1680	6.9	8.1
Salerno	40.7°N–14.8°E	1710	6.7	8.0
Siracusa	37.1°N–15.3°E	1990	5.8	6.9
Torino	45.1°N–7.7°E	1560	7.4	8.8
Trento	46.1°N–11.1°E	1380	8.4	9.9
Venezia	45.4°N–12.3°E	1460	7.9	9.4

[a] t_{PB} = simple payback time of the investment.

Table 4. Carbon Footprint of the production of 1 kWh of electricity with a 3 kW_p LCPV Plant, complementary processes and a Traditional 3 kW_p PV Plant.

Impact category	Unit	Tap water	Sewage from residence to wastewater treatment	3 kW_p LCPV Plant	Traditional 3kW_p PV Plant
IPCC GWP 100 years	kg CO_2 eq	7.03E–07	1.77E–06	0.054	0.06488

Trough 2× system and the traditional PV solution, for different Italian cities, is reported in Table 3. The V-Trough system allows a quicker t_{PB} than the traditional system due to the combination of two factors: a smaller use of the silicon component per kW_p and an increase of the energy efficiency using mirrors. It can also be verified a significant dependence of t_{PB} by the sites latitude; in particular, the t_{PB} is lower in southern cities.

5.2. Environmental aspects

For the production of 1 kWh of electricity (i.e. the functional unit), a value of 0.054 kg CO_2 equivalent has been estimated with the method IPCC GWP 100years for the 3 kW_p LCPV system. As shown in Table 4, the main responsible for the environmental load (that with the highest percentage contribution on the total impact) is the LCPV plant because the contributions due to complementary processes (i.e. tap water and sewage from residence to wastewater treatment) are negligible.

Compared to the traditional 3 kW_p PV system, the LCPV 2× system allows to save 16.9% of Carbon Footprint.

The Ecological Footprint method takes into account three impact categories: land occupation due to climate change (i.e. the soil needed to absorb the CO_2 produced), the land consumption necessary to compensate the use of nuclear energy and the direct land consumption.[25] Even in this case, the ecological footprint of the life cycle of the 3 kW_p LCPV plant has the greatest percentage incidence on the total impact (due to the very low incidence of the complementary processes). On the base of the values reported in Table 5, 79.7% of the ecological footprint is associated to carbondioxide, 17.8% to nuclear energy and 2.5% to direct land occupation.

The LCPV plant allows saving 17% of ecological footprint in comparison with the traditional system: 16.2% is due to the carbon dioxide, 20.1% to nuclear and, finally, 19.6% to land occupation. As shown in Table 6, the Recipe Endpoint H/H method has shown that the most impacting categories are fossil depletion, metal depletion, climate change (as a threat to human health and as damage to ecosystems) and human toxicity. In terms of human health, ozone depletion is the category with the highest impact saving between the traditional and LCPV plant (−20%); terrestrial ecotoxicity is the category with the greatest impact saving in terms of Ecosystems (−22.9%); finally, in terms of resources, fossil depletion is the category with the highest impact saving (−16.8%). Overall, as shown in Table 7, 15.8% is the saving evaluated with the ReCiPe 2008 Endpoint H/H method. Resources is the most impacting damage category with an incidence of 53.6%, while ecosystems is the lowest impacting category with 15.3%.

6. Conclusions

The main aim of this study was to perform a LCA and economic analysis of a LCPV system. The CPV systems in the last years have been greatly developed; they are an evolution of the standard PV modules. Their use for domestic applications, compared to the traditional PV

Table 5. Ecological Footprint of the production of 1 kWh of electricity with a 3 kW_p LCPV plant, complementary processes and a traditional 3 kW_p PV plant.

Impact category	Unit	Tap water	Sewage from residence to wastewater treatment	3 kW_p LCPV plant	Traditional 3 kW_p PV plant
Carbon dioxide	m^2 year	1.74E−06	4.04E−06	0.124289	0.148307
Nuclear	m^2 year	2.75E−06	1.78E−06	0.027846	0.034842
Land occupation	m^2 year	2.55E−07	9.58E−08	0.003882	0.004826
Total	m^2 year	4.74E−06	5.916E−06	0.156017	0.187975

Table 6. Impact values of the production of 1 kWh of electricity with the 3 kW_p LCPV plant, complementary processes and traditional 3 kW_p PV plant calculated with the ReCiPe 2008 Endpoint H/H method.

Impact category	Unit	Tap water	Sewage from residence to wastewater treatment	3 kW_p LCPV plant	Traditional 3 kW_p PV plant
Climate change human health	DALY[a]	1.46E−05	3.67E−05	7.56E−08	9.08E−08
Ozone depletion	DALY	1.98E−09	6.21E−09	3.23E−11	4.04E−11
Human toxicity	DALY	5.98E−06	1.11E−05	5.15E−08	6.08E−08
Photochemical oxidant formation	DALY	1.33E−09	4.76E−09	7.93E−12	9.68E−12
Particulate matter formation	DALY	4.87E−06	1.78E−05	2.26E−08	2.74E−08
Ionizing radiation	DALY	3.45E−07	2.14E−07	2.28E−10	2.76E−10
Climate change ecosystems	species.yr[b]	1.23E−05	3.1E−05	4.28E−10	5.14E−10
Terrestrial acidification	species.yr	3.38E−08	1.74E−07	1.31E−12	1.58E−12
Freshwater eutrophication	species.yr	3.96E−08	4.41E−07	1.92E−12	2.29E−12
Terrestrial ecotoxicity	species.yr	6.38E−08	1.96E−07	1.62E−11	2.1E−11
Freshwater ecotoxicity	species.yr	3.6E−08	8.02E−08	1.19E−12	1.41E−12
Marine ecotoxicity	species.yr	4.71E−09	1.55E−08	2.79E−13	3.34E−13
Agricultural land occupation	species.yr	2.26E−06	5.41E−07	2.49E−11	3.13E−11
Urban land occupation	species.yr	2.81E−06	1.36E−06	8.13E−12	9.78E−12
Natural land transformation	species.yr	1.53E−06	2.76E−08	1.73E−11	2.18E−11
Metal depletion	$[c]	5.69E−06	3.07E−05	0.001398	0.001595
Fossil depletion	$	2.61E−05	5.57E−05	0.002551	0.003067

[a]DALY = Disability adjusted life years (DALYs for a disease or health condition are calculated as the sum of the years of life lost (YLL) due to premature mortality in the population and the years lost due to disability (YLD) for people living with the health condition or its consequences).
[b]species.yr = number of species lost per year.
[c]$ = marginal cost increase due to the extraction or yield of a resource.

plants depends on costs and environmental results. An overview of the concentrating technology was necessary in order to support the analytic phase, reinforcing the calculation hypothesis and orienting subsequent evaluations. Afterward, it was possible to characterize the PV system from an economic point of view, as well. A cost model was purposely constructed of the LCPV plant in order to estimate the required investment as well as the payback time for different siting locations. The model was validated on the base of updated informing furnished by PV industries. The LCA study was performed with the software tool SimaPro 8.0.2, using the Econinvent 3.1 database. A functional unit of 1 kWh of electricity produced was chosen. Carbon Footprint, Ecological Footprint and ReCiPe 2008 were the methods used to assess the environmental impacts of the LCPV plant compared with a corresponding traditional system. All the methods were unanimous in demonstrating the environmental convenience of the LCPV system. In particular, the innovative system allowed saving 16.9% of CO_2 equivalent in comparison with the traditional PV plant. The environmental burden saving was 17% in terms of Ecological Footprint, and, finally, 15.8% with the ReCiPe method. Hence, an LCPV allows a high reduction in terms of pollution. The main problem for a definitive diffusion in the market is linked to the large-scale production. Anyway, as showed in this paper, a simple LCPV plant can be realized starting from a traditional PV plant; the difference is linked to the mirror production, which constitutes the distinctive element between two plants. As observed, the mirror production process has allowed to reduce the materials and fuels for other processes.

Table 7. Damage values of the production of 1 kWh of electricity with the 3 kW_p LCPV plant compared with those of a traditional 3 kW_p PV plant calculated with the ReCiPe 2008 Endpoint H/H method.

	3 kW_p LCPV plant		Traditional 3 kW_p PV plant		Impact saving
Impact category	mPt[a]	%	mPt	%	%
Human Health	2.23	31.1	2.66	31.2	16.2
Ecosystems	1.1	15.3	1.33	15.6	17.3
Resources	3.84	53.6	4.53	53.2	15.2
Total	7.17	100.0	8.52	100.0	15.8

[a]mPt = Recipe millipoint.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] Zhang D, Chai Q, Zhang X, et al. Economical assessment of large-scale photovoltaic power development in China. Energy. 2012;40:370–375.

[2] Mokri A, Emziane M. Concentrator photovoltaic technologies and market: a critical review. Paper presented at World Renewable Energy Congress. 2011 May 8–13; Linkoping, Sweden.

[3] Zahedi A. Review of modeling details in relation to low-concentration solar concentrating photovoltaic. Renew Sust Energ Rev. 2011;15:1609–1614.

[4] Hang Y, Du L, Qu M, et al. Optical performance of solar reflective concentrators: a simple method for optical assessment. Renew Energ. 2013;52:67–78.
[5] Cotal H, Fetzer C, Boisvert J, et al. III–V multijunction solar cells for concentrating photovoltaics. Energy Environ Sci. 2009;2:174–192.
[6] Chemisana D. Building integrated concentrating photovoltaics: a review. Renew Sust Energ Rev. 2011;15:603–611.
[7] Foolmaun RK, Ramjeeawon T. Comparative life cycle assessment and life cycle costing of four disposal scenarios for used polyethylene terephthalate bottles in Mauritius. Environ Technol. 2012;33:2007–2018.
[8] De Feo G, Malvano C. The use of LCA in selecting the best MSW management system. Waste Manag. 2009;6:1901–1915.
[9] Gaterell MR, Griffin P, Lester JN. Evaluation of environmental burdens associated with sewage treatment processes using life cycle assessment techniques. Environ Technol. 2005;26:231–250.
[10] Gerbinet S, Belboom S, Léonard A. Life cycle analysis (LCA) of photovoltaic panels: a review. Renew Sust Energ Rev. 2014;38:747–753.
[11] Belussi L, Mariotto M, Meroni I, et al. LCA study and testing of a photovoltaic ceramic tile prototype. Renew Energ. 2015;74:263–270.
[12] Hyoungseok K, Kyounghoon C, Fthenakis VM, et al. Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems. Solar Energ. 2014;103:78–88.
[13] Nishimura A, Hayashi T, Tanaka K, et al. Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. Appl Energ. 2010;87:2797–2807.
[14] Bayod-Rùjula AA, Lorente-Lafuente AM, Cirez-Oto F. Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems. Energy. 2011;36:3148–3158.
[15] Menoufi K, Chemisana D, Rosell JI. Life cycle assessment of a building integrated concentrated photovoltaic scheme. Appl Energ. 2013;111:505–514.
[16] Chemisana D, Barrau J, Rosell JI, et al. Optical performance of solar reflective concentrators: a simple method for optical assessment. Renew Energ. 2013;57:120–129.
[17] Renno C, Petito F. Design and modeling of a concentrating photovoltaic thermal (CPV/T) system for a domestic application. Energ Buildings. 2013;62:392–402.
[18] Aprea C, Renno C. A numerical approach to a very fast thermal transient in an air cooling evaporator. Appl Therm Eng. 2002; 22: 219–228.
[19] Renno C, Petito F, Gatto A. Artificial neural network models for predicting the solar radiation as input of a concentrating photovoltaic system. Energ Convers Manage. 2015;106:999–1012.
[20] Aprea C, Renno C. Experimental model of a variable capacity compressor. Int J Energ Res. 2009;33:29–37.
[21] PVGIS: Photovoltaic Geographical Information System [Internet]. Available from: http://re.jrc.ec.europa.eu/pvgis.
[22] Cesarano A, Bellia L, Minichiello F, Sibilio S. Sky luminance models: sensitivity to sky-dome subdivision. Lighting Res Technol. 1996;28(3):131–140.
[23] Curran MA. Environmental life cycle assessment. New York: McGraw-Hill; 1996.
[24] Society of Environmental Toxicology and Chemistry (SETAC). Life cycle assessment and conceptually related programmes. SETAC-Europe Working Group, CRP report; 1996; Brussels, Belgium.
[25] PR (2015), SimaPro Database Manual Methods library, Report version: 2.8 [cited 2015 Aug 14]. Available from: http://www.pre-sustainability.com/download/DatabaseManualMethods.pdf.
[26] Goedkoop M, Heijungs R, Huijbregts M, et al. ReCiPe 2008 – a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level First edition (version 1.08), Report I: Characterisation; 2013 [cited 2015 Aug 14]. Available from: http://www.lcarecipe.net/filecabinet/ReCiPe_main_report_MAY_2013.pdf?attredirect s = 0.
[27] Renno C. Optimization of a concentrating photovoltaic thermal (CPV/T) system used for a domestic application. Appl Therm Eng. 2014;67:396–408.
[28] King RR, Bhusari D, Larrabee D, et al. Solar cell generations over 40% efficiency, EU PVSEC; 2011; Germany.
[29] Aprea C, Renno C. An experimental analysis of a thermodynamic model of a vapour compression refrigeration plant on varying the compressor speed. Int J Energ Res. 2004;28:537–549.
[30] Renno C, Petito F. Choice model for a modular configuration of a point-focus CPV/T system. Energ Buildings. 2015;92:55–66.
[31] Renno C, De Giacomo M. Dynamic simulation of a CPV/T system using the finite element method. Energies. 2014;7:7395–7414.
[32] ENF Business Consulting (Wuhu) Co., Ltd. [cited 2014 Nov 5]. Available from: http://it.enfsolar.com/.
[33] Cited 2014 Nov 5, Available from: http://www.greenrhinoenergy.com/.