Renewable and Sustainable Energy Reviews 78 (2017) 916–932

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Concentrating solar systems: Life Cycle Assessment (LCA) and environmental issues

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ARTICLE INFO

Keywords:
Life Cycle Assessment (LCA)
Environmental issues
$CO_{2.eq}$ emissions
EPBT (energy payback time)
Concentrating solar systems
Concentrating photovoltaic (CPV)
Concentrating Solar Power (CSP)

ABSTRACT

The present article is a critical literature review about studies which are based on LCA (life cycle assessment) and about studies which include environmental issues about concentrating solar systems (concentrating photovoltaic (CPV), concentrating solar power (CSP), etc.). The results reveal that CPV environmental profile depends on several factors such as the materials of the concentrator and the direct solar radiation. On the other hand, there are different factors which influence CSP profile (from environmental point of view), including water use and materials e.g. for storage. By considering the literature review presented it can be noted that: 1) Regarding CPV, there is a need for more studies which investigate different concentration ratios, CPVT (concentrating photovoltaic/thermal) systems, low-concentration CPV, strategies to reduce the impact of certain components such as the tracking (especially for large-scale applications) and the concentrators, 2) Concerning CSP, there is a need for more investigations about dish-Stirling, storage materials, strategies for water savings, soiling effect, 3) In general, regarding concentrating solar systems, there is a need for more studies with Fresnel lenses and reflectors, for small-scale systems for buildings and for multiple final applications (desalination, drying, etc.), 4) With respect to the adopted methods/environmental indicators, certainly $CO_{2.eq}$ emissions, embodied energy and EPBT (energy payback time) can provide useful information for concentrating solar systems; nevertheless, there is a need for utilization of additional methods (e.g. based on midpoint, endpoint approaches) which can also offer useful information.

1. Introduction

Concentrating solar energy systems can be used for small-scale applications (e.g. Building-Added (BA) or Building-Integrated (BI) configurations[1]) as well as for large-scale schemes (e.g. Concentrating Solar Power (CSP) plants). There are different types of concentrators (parabolic-trough, parabolic-dish, Fresnel lenses, Fresnel reflectors, etc.) while solar energy can be concentrated for example in a single focal point or in a line. Among the concentrating solar technologies, there are systems which produce heat (known as concentrating solar thermal); electricity (e.g. Concentrating Photovoltaic (CPV)); heat and electricity (Concentrating Photovoltaic/Thermal (CPVT) and CSP) [1].

There are different possible classifications of the concentrating solar systems, for example, based on: the size of the systems (small-scale (e.g. BA or BI) vs. large-scale applications); the type of concentration (e.g. point-focusing vs. line-focusing); the concentration ratio (CR); the type of concentrator (reflector, lens, luminescent, etc.); the use or not of sun tracking system.

Concentrating solar systems offer multiple advantages (in comparison to the solar systems without concentration) such as improved efficiency, increased energy-delivery temperatures, reduction of the cost (for the case when there is replacement of an expensive large receiver by a less expensive component e.g. reflecting area) and multiple configurations for BI applications (e.g. façade-integrated

Abbreviations: BA, Building-added; BI, Building-integrated; BICPV, Building-integrated concentrating photovoltaic; BOS, Balance of system; CED, Cumulative energy demand method; CML, CML method; $CO_{2.eq}$, $CO_{2.equivalent}$; CPV, Concentrating photovoltaic; CPVT, Concentrating photovoltaic/thermal; CR, Concentration ratio; c-Si, Crystalline-silicon; CSP, Concentrating solar power; DALY, Disability adjusted life years; Ecological footprint, Ecological footprint method; EI99 PBT, Eco-indicator 99 payback time; EI99, Eco-indicator 99 method; EPBT, Energy payback time; EPD, Environmental product declaration method; EPS 2000, EPS 2000 method; EVA, Ethylene vinyl acetate; GHG, Greenhouse-gas; GPBT, Greenhouse-gas payback time; GWP, Global warming potential; IMPACT 2002+, IMPACT 2002+ method; IPCC, Intergovernmental panel on climate change; LCA, Life cycle assessment; LCA-NETS, LCA-NETS method; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; LSC, Luminescent solar concentrator; NIR, Near-infrared; PBT, Payback time; PCM, Phase change material; PMMA, Polymethylmetacrylate; PV, Photovoltaic; PVB, Polyvinyl butyral; PVT, Photovoltaic/thermal; PVT/air, PVT system with air as working fluid; QD, Quantum dots; ReCiPe PBT, ReCiPe payback time; ReCiPe, ReCiPe method; SOG, Silicone-on-glass; USEtox, USEtox method; UV, Ultraviolet

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[1] BI systems are integrated (and not added) into the building, replacing a building component e.g. façade [1].

http://dx.doi.org/10.1016/j.rser.2017.04.065
Received 21 October 2016; Received in revised form 28 December 2016; Accepted 27 April 2017
1364-0321/

CPV or CPVT) [1,2].

Given the fact that concentrating solar systems are a promising technology with several advantages (in comparison to the solar systems without concentration) and interesting applications, Life Cycle Assessment (LCA) studies (and, in general, investigations which include environmental issues) can provide useful information about this technology. Studies based on LCA help for the evaluation of the environmental burdens from cradle-to-grave and facilitate fair comparisons of energy technologies [3]. In the literature, there are LCA studies and works which include environmental issues about concentrating solar systems. In the following paragraph, some of these investigations are presented.

Kreith et al. [4] presented a work about CO_2 emissions from fossil and solar power plants in USA. Several configurations, including high-concentration collectors, were discussed. The CO_2 estimations were based on a net energy analysis from operational systems and detailed design studies. It was demonstrated that energy-conservation measures and shifting from fossil to renewable-energy sources have considerable long-term potential for the reduction of the CO_2 produced because of energy generation. In the work of Ferriere and Flamant [5] several environmental advantages of the concentrating solar systems were presented (predicted reduction of the cost per kWh of produced electricity (on a long-term basis) due to the technological progress; the concentrating solar systems provide an eco-friendly solution (with low CO_2 emissions) instead of using nuclear power plants, etc.). Masanet et al. [6] highlighted the role of LCA within the sector of electric power systems. It was noted that the application of LCA to electric power technologies is a vibrant research field that is likely to continue given the fact that the world is searching for solutions to meet growing electricity demand with reduced impact (in terms of the environment and the human health) [6]. Ferriere [7] discussed several aspects about the environmental and social benefits of concentrating solar power systems (low CO_2 emissions per kWh of produced electricity; possibilities for multiple configurations in terms of hybridization (e.g. with biomass) and storage; creation of new job opportunities, etc.). On the other hand, an evaluation about the environmental performance of several PV technologies, including CPV, with emphasis on Canada, has been conducted [8]. It was highlighted that PV systems have considerably lower impact (in terms of CO_2 emissions and other environmental indicators) than the use of fossil fuels for electricity production [8].

In the literature there are also review studies which include LCA and, in general, environmental issues (e.g. reduction of CO_2 emissions and energy savings) about solar energy systems. In Table 1, selected review studies are presented and it can be seen that most of the review articles about solar energy systems give emphasis on:

a) PV LCA and there are few review studies which focus on environmental issues about CSP.

b) The technologies (characteristics of an installation, concentrators, materials for storage, etc.) and there are few review studies which include environmental issues about CPV and CPVT systems.

By taking into account that concentrating solar systems offer some characteristics which are interesting from environmental point of view, it can be seen that there is a need for a review article which presents an overview of studies about concentrating solar systems from environmental point of view. In the frame of this concept, the present study is a critical review which includes LCA studies and, in general, investigations with environmental issues about different types of concentrating solar systems (CSP, CPV, CPVT, etc.). The main objective of the present review is to approach concentrating solar systems from environmental point of view. In the frame of this goal:

Table 1
Review studies which partly include LCA or, in general, environmental issues about concentrating solar systems.

Reference	Year	Main content of the review
Raugei and Frankl [9]	2009	PV today and the future for PV Prospective life cycle analysis of selected PV technologies
Fthenakis and Kim [10]	2011	PV LCA, LCI (modules, BOS), EPBT, GHG emissions Criteria pollutants, heavy metal emissions Concentrating PV systems, Life-cycle risk analysis, Outlook
Parida et al. [11]	2011	Photovoltaic power generation, Hybrid PV power generation Light absorbing materials, Performance and reliability Environmental aspects Sizing, distribution and control Storage systems, Concentrators, Applications Problems related to PV technology, Future prospects
Peng et al. [12]	2013	LCA for PV systems Life-cycle energy requirements of PV systems Solar radiation and energy output EPBT and GHG emission rate of PV systems New technologies and their effects on EPBT and GHG emission rate
Gerbinet et al. [13]	2014	The LCA methodology (general issues about LCA stages, etc.) LCA of PV systems
Sahoo [14]	2016	Recent trends of PV progress in India Future prospects Government initiatives in order to promote solar energy in India
Chow et al. [15]	2012	PVT developments in the twentieth century Recent developments in flat-plate PVT and concentrator-type design Miscellaneous developments over the last years
Tyagi et al. [16]	2012	Solar thermal collectors (concentrating collectors, etc.) PV technology (types of solar cells, etc.) PVT technology (PVT/air, etc.) Novel applications of PVT
Zhang et al. [17]	2012	The concept of PVT and the theory behind PVT operation Classification of PVT modules Standards for PVT evaluation (from technical, economic, environmental point of view) R & D progress, practical applications of PVT, studies for the future
Chemisana [1]	2011	Building-integrated CPV
Sharaf and Orhan [18,19]	2015	Fundamentals, current technologies, design, PV cells, solar thermal collectors, solar concentrator optics and concentrated solar energy [18] Implemented systems, performance assessment, future directions, high- and low-concentration CPVTs [19]
Turney and Fthenakis [20]	2011	Characteristics of the installation and operation of solar power plants Metrics for environmental impact categories Environmental impacts, Net environmental impact
Burkhardt III et al. [21]	2012	Harmonization method Results and discussion for parabolic trough and for power tower Limitations of the analysis Recommendations for future work

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Table 1 *(continued)*

Reference	Year	Main content of the review
Bijarniya et al. [22]	2016	Concept and layout of CSP-based power generation Critical factors for site selection Classification of CSP Status of CSP in India Discussion and key issues in terms of CSP in India
Grágeda et al. [23]	2016	Solar technologies (CSP, PV, etc.) Solar energy projects in Chile Sustainability analysis of the solar plants
Fernández-García et al. [24]	2010	Parabolic-trough collectors and applications (CSP, domestic, etc.)
Kalogirou [25]	2004	Solar collectors (flat-plate, parabolic-trough, etc.) Thermal analysis of collectors Performance of solar collectors Applications of solar collectors
Ibrahim et al. [26]	2014	Review of water-heating systems (CPVT, flat-plate collectors, etc.)
Barlev et al. [27]	2011	Parabolic-trough collectors, heliostat-field collectors, linear Fresnel reflectors, CPV, etc. Thermal energy storage, Energy cycles, Applications
Xu et al. [28]	2015	PCMs for thermal storage and recent developments of PCM encapsulation Research and applications of latent-heat thermal energy storage for CSP Modeling and simulation of latent-heat thermal storage Operation of CSP using thermocline latent-heat thermal energy storage system; Cost analysis
Liu et al. [29]	2016	CSP plants and thermal energy storage; Recent developments in thermal energy storage systems; Compatibility of the containment materials with the storage media; Cost issues
Kuravi et al. [30]	2013	Plant-level design considerations; Component-level considerations; System-level considerations; Developments in thermal energy storage for CSP

– The references are presented classified based on certain criteria (type of system, methods/environmental indicators adopted, etc.) which are related with the environmental profile of the systems.
– Issues about the materials for CPV concentrators, factors which influence CPV and CSP environmental profile and future prospects, are also included, in order to provide a complete picture of the systems based on different points of view.
– A critical discussion is also provided, identifying gaps in the literature and proposing methods/indicators which can give useful information about the environmental profile of concentrating solar systems.

2. General information about methods and indicators

In Section 2, some information about LCIA (life cycle impact assessment) methods and environmental indicators (related to the references of Sections 3 and 4) is presented.

The concept of "embodied energy" presents the energy needed to process (and supply to the construction site) a material. In order to determine this embodied energy, an accounting methodology should be used for summing the energy inputs over the major part of the material supply chain or life-cycle e.g. of a system. In the same concept with embodied energy, the emissions of energy-related pollutants (for example CO_2 emissions which are associated to climate change and global warming) may be examined over the life-cycle. In this way, the notion of "embodied carbon" arises [31].

Table 2
Presentation of different methods (according to reference [33]).

Methods	Information
CED	Non-renewable and renewable impact categories
Greenhouse gas protocol	GHG emissions
IPCC 2013	GWP (global warming potential)
USEtox	Human and eco-toxicological impacts
Ecological footprint	Nuclear energy use, CO_2 emissions, Land occupation
CML-IA	Midpoint approach
IMPACT 2002+	Combination midpoint/damage approach
ReCiPe	Combination midpoint/damage-oriented (endpoint) approach
EPS 2000	Damage-oriented approach
EPD	Environmental product declaration
EI99	Damage-oriented approach

Primary energy (energy sources) is the energy that is embodied in the natural resources (coal, crude oil, etc.) and it does not include anthropogenic conversions. This primary energy should be converted (and transported) so as to become "usable energy". The embodied energy shows the energy used to produce a material substance, considering the energy utilized at the manufacturing facility, the energy utilized for the production of the materials that are used in the manufacturing facility, etc. [32].

Related with the above mentioned issues, CED (cumulative energy demand) method presents characterization factors for the energy resources divided into non-renewable and renewable impact categories [33].

The primary energy demand over the life-cycle of a system can be utilized for example for the calculation of the energy metric EPBT (energy payback time). EPBT presents the time required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself [10]. Within the concept of EPBT, GPBT (greenhouse-gas payback time) [34] can be also evaluated, by considering the $CO_{2.eq}$ emissions over system life-cycle. PBTs based on other types of methods such as ReCiPe and EI99 [35] can be also presented.

In Table 2 a presentation of different methods is provided. With respect to ReCiPe (successor of EI99 and CML-IA), it includes at the midpoint level 18 impact categories (ozone depletion, human toxicity, ionising radiation, photochemical oxidant formation, etc.). On the other hand, at the endpoint level most of the midpoint impact categories are multiplied by damage factors and they are aggregated into 3 endpoint categories: human health, ecosystems and resource surplus costs. The three endpoint categories are normalized, weighted and aggregated into a single-score result [33]. The impact categories which refer to human health (endpoint results with characterization) can be presented in DALY (disability adjusted life years).

Finally, it should be noted that there are some investigations which present cost issues (for example reference [4]). In addition, there are studies that are based on multiple LCIA methods and environmental indicators (e.g. reference [36]).

3. Literature review: CPV

3.1. LCA and environmental issues about CPV

In Table 3, literature studies about CPV are presented, classified into two main categories: 1) high-concentration PV and 2) low-concentration PV.

From the review about high-concentration PV (Table 3) it can be noted that:

Table 3
Studies including LCA and/or, in general, environmental issues about CPV systems: high-concentration PV and low-concentration PV.

Study/type of system	CR	Type of PV cells (for the concentration PV)	Studied issues/Methods	Location	Findings	Additional findings/comments
High-concentration PV						
CPVT, point-focus: Renno and Petito (2015) [37]	900×	Triple-junction (InGaP/InGaAs/Ge)	CO_2 emissions, energy savings, cost analysis, etc.	South Italy	Annual avoided CO_2: 3376 kg	Domestic applications; annual output: 2983 kWh (electrical), 13921 kWh (thermal)
Apollon optimized; Concentrix Solar Flatcon CX–75; Amonix 7700 CPV systems and roof-top flat-plate PV systems: de Wild-Scholten (2010) [38]	500–750×	Multi-junction	$CO_{2.eq}$ emissions, EPBT, etc.	Catania, Sicily (Italy)	For the CPV systems: EPBT 0.8–1.9 years; carbon footprint: 18–45 g $CO_{2.eq}$/kWh	The highest contribution to the life-cycle environmental impact is due to the tracking and module materials (the environmental profile of the system can be further improved with higher efficiencies and higher lifetime of the components)
High-concentration PV and multi-crystalline Si PV, 100 MW: Nishimura et al. (2010) [39]	550×	III–V multi-junction	LCA-NETS, CED, EPBT, etc.	Gobi desert (China) and Toyohashi (Japan)	The EPBT of the high-concentration PV was found to be 0.27 years longer than that of the multi-crystalline-Si PV system	The impact of the tracking system (manufacturing) is the highest for all the life-cycle stages of the CPV, for both locations (the adoption of recycling is important for the reduction of this impact)
Amonix 7700, 53 kW_p: Fthenakis and Kim (2013) [40]	500×	Multi-junction GaInP/GaInAs/Ge cells grown on a germanium substrate	Primary energy demand, EPBT, $CO_{2.eq}$ emissions, land and water usage, etc.	Phoenix, AZ, USA	EPBT 0.9 years; 27 g $CO_{2.eq}$/kWh (over 30 years) (operation: Phoenix, AZ)	Although high-concentration PVs need considerable maintenance, their life-cycle environmental burden is much lower than that of flat-plate c-Si systems (operating in the same high-insolation regions)
FLATCON ®, 6 kW_p: Peharz and Dimroth (2005) [41]	500×	III–V multi-junction	CED, EPBT, etc.	Tabernas, Spain	EPBT: 0.7–0.8 years (for a concentrator built in Germany and operated in Spain)	The EPBT increases to 1.0–1.3 years for a system installed in Germany; the main energy demand in the production of such a high-concentration PV configuration is the zinced steel for the tracking unit
CPVs and flat-plate PVs: Halasah et al. (2013) [42]		Different types of PV cells were examined	Embodied energy, EPBT, CO_2 emissions, land use, etc.	Negev desert of southern Israel	High-efficiency CPV field installations show the shortest EPBTs, the highest energy-return factors and the highest life-cycle CO_2 offsets (under the condition that land availability is not a limitation)	A higher life-cycle energy-return and carbon offset per unit land area is yielded by locally-integrated non-concentrating configurations, despite the fact that they have lower efficiency per unit of module area
Solar power plants (including CPV) land use: Ong et al. (2013) [43]			Land-use requirements, etc.	USA	PV land use depends on the type of the PV system (fixed vs. with tracking, etc.)	
Low-concentration PV						
BICPVT 0.5 kW_p: Menoufi et al. (2013) [44]	10×	Mono-crystalline Si	EI99, EPS 2000, etc.	Lleida, Catalonia, Spain	Significant environmental impact reduction is achieved by replacing conventional BIPV by BICPV	The study was based on the phase of material manufacturing
BICPV 1 kW_p: Lamnatou et al. (2015) [34]	2.8×	Mono-crystalline Si	Embodied energy, EPBT, embodied carbon, GPBT, etc.	Exeter (UK); Barcelona and Madrid (Spain); Dublin (Ireland); Paris (France)	GPBTs: the highest values for Paris (27.2–33.1 years); Barcelona/Madrid: the lowest EPBTs (about 2.4 years); Madrid/Barcelona: 93–101 g $CO_{2.eq}$/kWh	Linear dielectric-based BICPV: two configurations (with and without reflective film) were examined; reflective film reduced EPBTs and GPBTs around 11–12%; annual $CO_{2.eq}$ savings for Madrid/Barcelona: 903 kg for the system with reflective film
BICPV	2.8×	Mono-crystalline Si	ReCiPe, ReCiPe PBT, EI99,	Barcelona (Spain);	For both configurations with/without	Linear dielectric-based BICPV: two

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Table 3 (*continued*)

Study/type of system	CR	Type of PV cells (for the concentration PV)	Studied issues/Methods	Location	Findings	Additional findings/comments
1 kW_p: Lamnatou et al. (2016) [35]			EI99 PBT, USEtox, Ecological footprint, etc.	Exeter (UK); Dublin (Ireland)	reflective film, Barcelona showed the lowest ReCiPe and EI99 PBTs: 3.6–5.8 years	configurations (with and without reflective film) were examined; by using reflective film ReCiPe and EI99 PBTs are reduced 0.5–0.9 years
BICPV 1 kWp: Lamnatou et al. (2017) [36]	3.6×	Mono-crystalline Si	CED; IPCC 2013 GWP 20a, 100a, 500a; ReCiPe; EI99; USEtox; Ecological footprint; EPBT, etc.	Barcelona, Seville (Spain); Marseille, Paris (France); London, Aberdeen (UK)	Among the studied cities, Barcelona, Marseille and Seville showed the lowest GWP and CED: less than 142 g CO2.eq/kWh and less than 2.9 MJprim/kWh, according to all the studied scenarios	For 30-years lifespan, Barcelona, Marseille and Seville showed 0.0107–0.0111 ReCiPe Pts/kWh while London, Paris and Aberdeen showed 0.0161-0.0173ReCiPe Pts/kWh
Low-concentration PVT, 1 kW electrical power: Cellura et al. (2011) [45]		Crystalline Si	Global energy requirement, GWP, acidification potential, EPBT, GPBT, etc.	Palermo, Italy	EPBT: 0.7 years; GPBT: 1 year	The system was installed on the roof of a building
Low-concentration PV vs. traditional PV: De Feo et al. (2016) [46]	2×	Poly-crystalline Si	ReCiPe, Ecological footprint, Carbon footprint, economic analysis, etc.	Different Italian cities	All the adopted methods verified the environmental convenience of the studied CPV system	For 1 kW_p, with traditional PV is needed a PV surface of 7.29 m^2 while with V-trough 2× an area of 5.6 m^2 is needed (to achieve the same power)

1) There are few investigations about CPVT.
2) Most of the references are about CPV with CR 500× and multi-junction PV cells.
3) The systems have been studied for several climatic conditions (Spain, USA, etc.).
4) Most of the investigations examine $CO_{2.eq}$ emissions, embodied energy and EPBT while there are few studies about land-use requirements.
5) Some references include comparisons of CPV systems with simple PV (without concentration) and the results of these comparisons depend on several factors (the insolation of the region, the type of the CPV system, etc.).
6) For most of the cases CPV systems show $CO_{2.eq}$ emissions less than 50 g/kWh and EPBTs less than 1 year.
7) Some investigations highlight the fact that the tracking system of a high-concentrating PV installation is responsible for a considerable part of the total environmental impact of the installation [38,39,41].
8) Most of the studies have been conducted between the years 2010–2015.

Based on the review about low-concentration PV (Table 3) it can be seen that:

1) There are few references about CPVT.
2) There are some investigations about CPV and CPVT for BI applications with CRs 2.8–10× and mono-crystalline PV cells.
3) The systems have been evaluated for several climatic conditions (Spain, UK, France, etc.).
4) The studies are based on multiple methods and environmental indicators: ReCiPe, EI99, $CO_{2.eq}$ emissions, GPBT, embodied energy, EPBT, Ecological footprint, etc.
5) Some investigations include comparisons of CPVs with simple PVs (without concentration).
6) The results show that the environmental profile of a CPV system depends on several factors such as the solar irradiance and the materials of the concentrator.
7) The studies have been conducted over the years 2011–2017.

Regarding high-concentration PV for domestic applications, Renno and Petito [37] proposed a model for choosing the proper modular configuration for a point-focus CPVT system. The scope of the investigation was the evaluation of different configurations according to their energy/economic performances and space occupied. The main CPVT components included the solar cells, the optics and the tracking system. The system considered was point-focus with parabolic mirrors, triple-junction cells and dual-axis tracking. It was found that the high-concentration level offers interesting solutions for domestic applications (from energetic and economic point of view) for southern Italy, taking into account CPVT life-cycle. In addition, significant reduction of CO_2 emissions was observed [37]. Concerning high-concentration PV for large-scale applications, several studies have been presented [38–43], highlighting that the tracking system shows a considerable environmental impact [38,39,41].

With respect to the specific case of low-concentration PV for BI applications, Lamnatou et al. [34,35] conducted an LCA for a BICPV (linear dielectric-based CPV with geometrical CR 2.8×). In Fig. 1, details about the studied system are presented. Two configurations (with and without reflective film) were evaluated. In Fig. 1(a) and (b), a sample of the concentrator made by polyurethane and the solar cell utilized in the BICPV system [34,35] are presented. In Fig. 1(c), the two configurations (left without reflective film and right with reflective film) are shown. By utilizing the reflective film, the rays escaping from the corner are trapped and thus, the PV output increases [34,35]. Furthermore, in Fig. 1(d) a configuration of the studied BICPV integrated into the façade of a building [35] is illustrated (the module

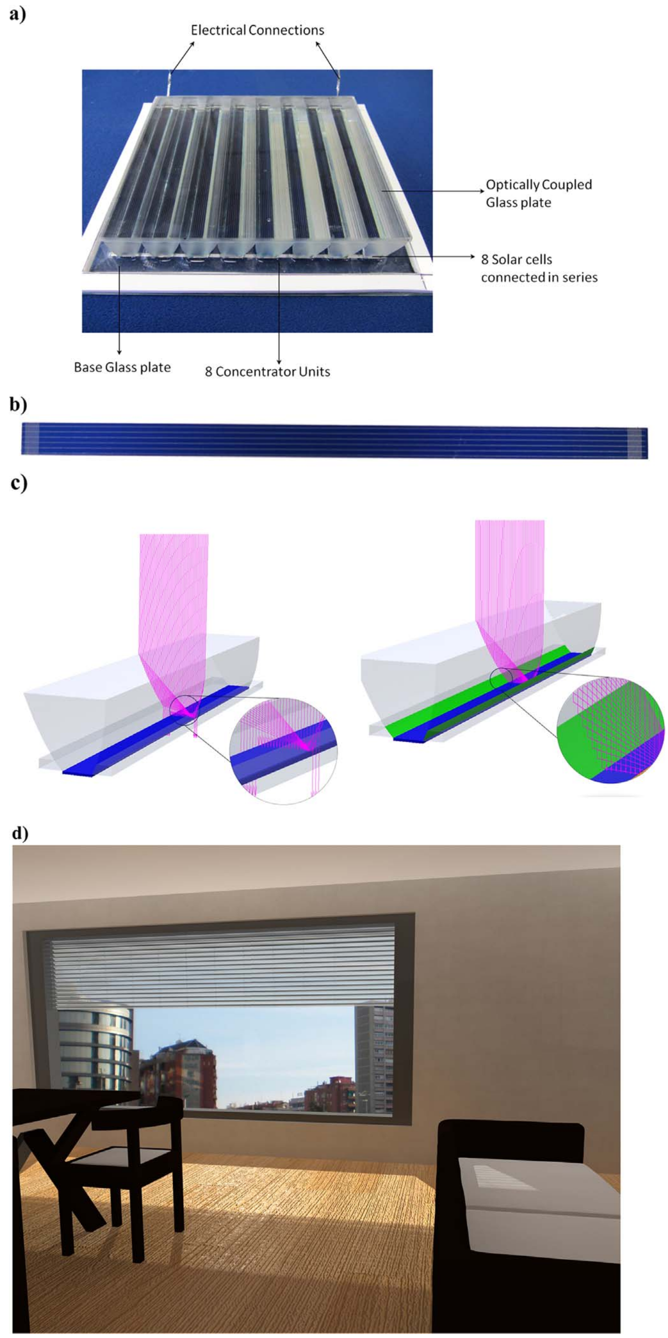

Fig. 1. The BICPV system studied from LCA point of view by Lamnatou et al. [34,35]: a) sample of the concentrator [35], b) solar cell [34,35], c) the system without reflective film (left) and the system with reflective film along the edges (right) [34], d) a configuration of the BICPV integrated into the façade of a building [35] (Sources: [34,35]).

is assumed to be vertically placed on a south-facing wall). From Fig. 1(d) it can be seen that the proposed BICPV offers (except of the shading effect) advantages from aesthetical point of view.

The study of Lamnatou et al. [34] was based on embodied energy and embodied carbon and the cities of Exeter, Barcelona, Madrid, Dublin and Paris were examined. The results for the GPBT showed that among the studied cities (and by taking into account both configurations) GPBT has the highest values for Paris (27.2–33.1 years) and the lowest values for Dublin (3.3–4 years). Certainly, the high GPBTs for Paris are related with the low CO_2 emissions of France´s electricity mix.[2] Concerning EPBT (average values based on two databases; CPV with reflective film), Barcelona and Madrid presented the minimum EPBTs (around 2.4 years) while Paris, Exeter and Dublin showed EPBTs 3.2–3.5 years. The utilization of reflective film results in 0.2% increase in system initial impact (embodied energy and embodied carbon; material manufacturing of the modules). Nevertheless, the results of the study [34] verify that, on a long-term basis, this additional impact is compensated (this is because the CPV with reflective film has higher electrical output in comparison to the CPV without reflective film). More specifically, it was found that the use of reflective film reduces around 11–12% the values of EPBT and GPBT. The EPBT was also evaluated with an alternative way by taking into account the replacement of the materials of a wall [34].

The above mentioned BICPV has been also evaluated by Lamnatou et al. [35] based on additional methods/indicators (ReCiPe, ReCiPe PBT, EI99, EI99 PBT, USEtox, Ecological footprint, etc.), for Barcelona, Exeter and Dublin, verifying that the reflective film remarkably improves the environmental profile of the reference system (system without reflective film). The results according to ReCiPe/endpoint with characterization (Fig. 2a) reveal that for all the components of the CPV system, climate change/human health, particulate matter formation and human toxicity are the categories with the highest impact (with climate change/human health showing the highest contribution to the total impact). By focusing on the total DALY impact for all the studied categories of Fig. 2(a), it can be observed that PVs are responsible for the major part of DALY. On the other hand, in Fig. 2(b) DALY impact (ReCiPe/endpoint with characterization) per kWh of produced electricity (for 25-years lifespan), is illustrated. From Fig. 2(b), it can be seen that, among the studied cities, Barcelona shows the lowest impact and the use of reflective film reduces the impact (for all the studied cases) [35].

3.2. Materials for concentrators of CPV systems and other factors which influence CPV environmental profile

Given the fact that the materials of the concentrator influence the profile (from environmental point of view) of a CPV system, in this section several aspects regarding these materials are presented, based on selected literature references.

With respect to the use of PMMA (polymethylmetacrylate) and SOG (silicone-on-glass) for Fresnel lenses for CPV applications, both materials present advantages and disadvantages. For example, PMMA has low weight but it has the drawback of the shape warp (which means shift of the lens focus). On the other hand, SOG is more resistant to erosion and scratching; however, it has low rigidity and it shows lens-facets deformation because of different thermal expansion of substrate and glass. Regarding the above mentioned issues, more information can be found in the studies of Cvetkovic et al. [47] and Hornung et al. [48]. In addition, Annen et al. [49] conducted a direct comparison of PMMA and SOG for Fresnel lenses for CPVs. In the literature there is also a review about the durability of Fresnel lenses, with emphasis on CPV applications: reference [50].

Moreover, French et al. [51] presented a work about the optical properties of polymeric materials for CPV systems. It was noted that certain fluoropolymers offer desirable optical and physical properties for optical applications within the field of CPV. Ethylene backbone polymers (for example, PVB sheet and EVA can be utilized as encapsulants for crystalline silicon (c-Si) and other flat-plate PV configurations. It was also mentioned that these materials are available with a big variety of polymer compositions and additive packages (which affect their optical properties, for example in terms of the UV absorption edge) [51].

[2] The low CO_2 emissions are associated with the fact that there is high penetration of nuclear energy (it should be noted that nuclear power plants include risks and other environmental issues related e.g. with nuclear waste management) [35].

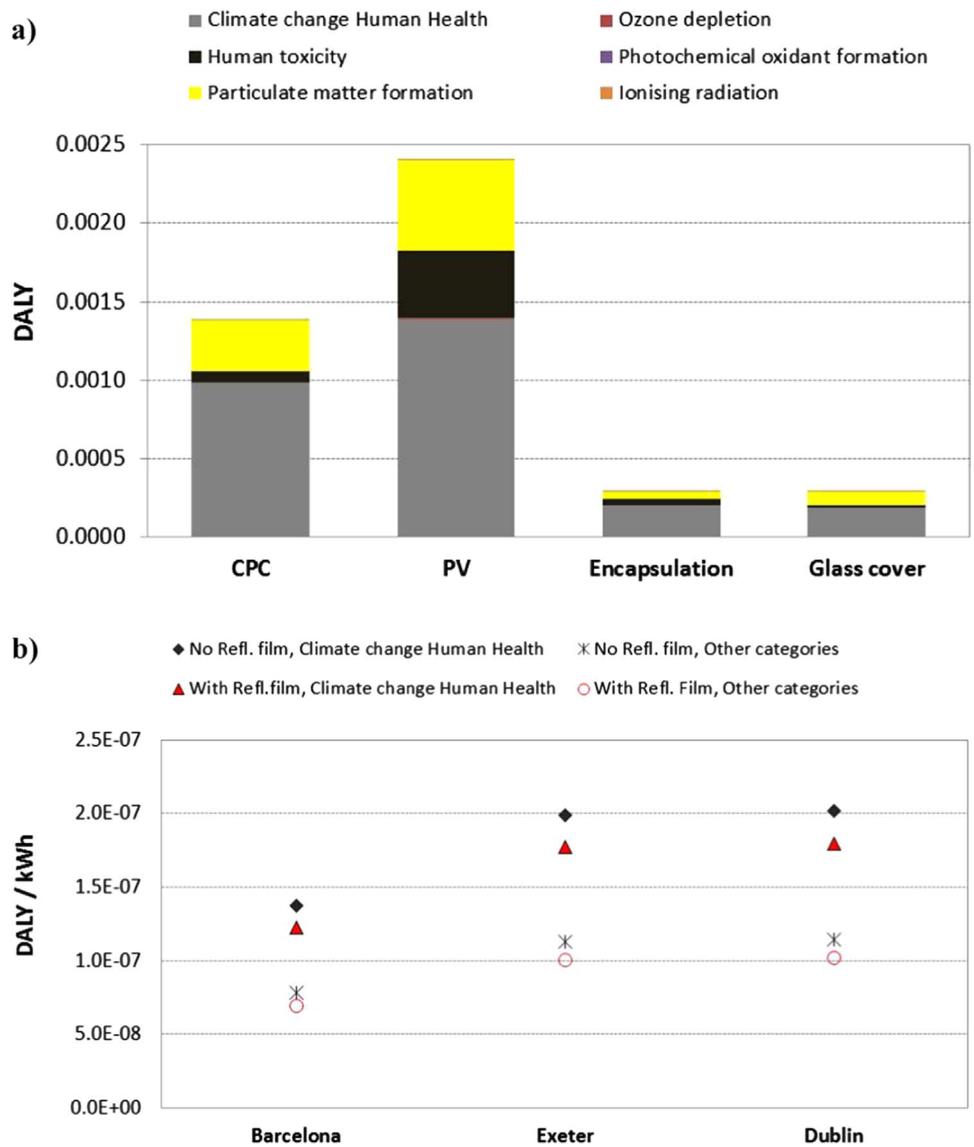

Fig. 2. ReCiPe endpoint/with characterization: a) The contribution of each component[3] to the total impact of material manufacturing (43 modules; configuration with reflective film) according to climate change/human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation (DALY); b) DALY per kWh of produced electricity for Barcelona, Exeter and Dublin, configurations with/without reflective film, 25-years lifespan, studied categories: i) climate change/human health and ii) other categories (ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation) (Source: [35]).

On the other hand, the concept of LSC (luminescent solar concentrator) for PV applications was proposed several years ago [52]. Bomm et al. [53] conducted a study about the fabrication and full characterization of LSCs comprising CdSe core/multishell quantum dots (QDs). Transmission-electron-microscopy analysis revealed that QDs are well dispersed in the acrylic medium while maintaining a high quantum yield of 45%, resulting in highly transparent and luminescent polymer plates. A detailed optical analysis of the QD-LSCs was presented [53].

Finally, it should be noted that in the literature there is a review study about coatings for concentrating solar systems [54], including CPV schemes. The aim of [54] was to focus on the underlying chemistry and stability of some of the main coatings that are in use (or that are currently under investigation) so as to identify issues such as gaps in the knowledge and prospects in terms of performance improvements [54].

In Table 4, issues related with concentrators of CPV systems, based on selected literature studies, are presented. In terms of the materials shown in Table 4, QD-LSCs need improvements in order to be commercially viable [53]. On the other hand, fluoropolymers (presented in [51]) have applications as encapsulants in crystalline-silicon and other flat-plate PV systems (detailed optical properties of these materials will be useful for the design of the geometrical optics of a CPV system [51]). With respect to PMMA and SOG for CPVs, (as it was previously mentioned) both lenses present advantages and disadvantages and thus, their evaluation (for CPV applications) from LCA/ environmental point of view depends on multiple factors (related for example with rigidity, thermal expansion and refractive index change as well as with the behavior of the lens in combination with the CPV on a lifespan-basis). Additional issues which influence the environmental profile of a CPV are related with: 1) the materials of the solar cells (the selection of the materials depends e.g. on the CR and the issue of building integration), 2) the direct solar radiation (since CPVs work with this part of the solar radiation), 3) the combination of CPV technology with other types of systems (e.g. with CSP).

[3] The reflective film is not illustrated in the graph because it presents a very small impact (less than 0.3% based on all the methods and impact categories studied in [35]) but it has been taken into account for the calculations.

Table 4
Selected literature studies about materials for concentrators of CPV systems and other factors which influence CPV environmental profile.

Study/topic	Findings/issues highlighted	Additional comments
Materials for concentrators of CPV		
Fresnel lenses: Cvetkovic et al. (2011) [47], Hornung et al. (2010) [48]	PMMA has low weight but it shows shape warp (thus, shift of the lens focus)	SOG is more resistant to erosion and scratching but it presents lens-facets deformation because of different thermal expansion of substrate and glass
Fluoropolymers: French et al. (2011) [51]	Several fluoropolymers were presented and it was noted that the detailed optical properties of these materials will be useful for the design of the geometrical optics of a CPV system and for the optimization of system optical throughput	UV: this absorption can influence radiation durability of the materials
QDs luminescent solar concentrators: Bomm et al. (2011) [53]	For QD-LSC concept to be commercially viable: the absorbance of QDs should be higher and extended further into NIR, and re-absorption losses should be drastically reduced	
Coatings for concentrating solar systems: Atkinson et al. (2015) [54]	Coatings for reflectors and glass receiver protector tubes: issues such as protection of reflector from corrosion, reflection losses and dirt were presented	
Other factors which influence CPV profile		
PV cell material: Chemisana (2011) [1]	For CPV applications different types of PV cells can be adopted (multi-junction, mono-crystalline, etc.), depending on the system	There are toxic products which are involved in the production of PV cells (depending on the type of the PV cell)
The issue of building integration: Chemisana (2011) [1]	Certain CPV systems are appropriate for BI applications	For BICPV another environmental issue is related with the fact that the system replaces the materials of a building component (e.g. of a wall) [1,34]
CR: Chemisana (2011) [1]	CR also determines if a CPV is appropriate (or not) for BI applications	CPVs with CRs less than 10× are interesting for BI applications (they do not require tracking)
Solar radiation: Renno et al. (2015) [55]	Since the optics should focus sunlight on the PV cells, CPV systems work by using direct solar radiation (thereby, it is important to have an accurate estimation of the global and direct radiation)	A methodological approach was proposed in order to evaluate the electric and thermal energy production of a point-focus CPVT
Combination of CPV with another system e.g. with a CSP: Cocco et al. (2016) [56]	A hybrid CSP–CPV system was proposed (in order to improve the dispatchability of solar power plants)	The results demonstrated the advantages of adopting an integrated management strategy in order to obtain a constant power output curve

4. Literature review: CSP

4.1. LCA and environmental issues about CSP and other types of concentrating solar systems

In Table 5, literature studies about CSP and other concentrating solar systems are presented and it can be noted that:

1) There are few investigations about dish-Stirling.
2) Most of the references are about CSP plants based on parabolic-trough and solar tower technologies.
3) Several studies examine scenarios which include hybridization of CSP plants with natural gas, biomass, etc.
4) There are few investigations which examine the effect of the storage materials on CSP environmental profile.
5) The systems have been evaluated for several climatic conditions (Spain, USA, etc.).
6) Most of the investigations examine $CO_{2.eq}$ emissions; however, there are several studies which are based on embodied energy, EPBT and LCIA methods with midpoint and/or endpoint approaches (ReCiPe, EI99, IMPACT 2002+, etc.). On the other hand, some investigations present economic issues.
7) For most of the cases CSP plants show $CO_{2.eq}$ emissions less than 40 g/kWh and EPBTs around 1 year.
8) Most of the CSP studies have been conducted between the years 2011–2016.
9) There are few references about concentrating solar systems based on parabolic-trough technology for small-scale applications for buildings. Most of these studies have been conducted in 2016 and they present $CO_{2.eq}$ emissions.

With respect to CSP, Piemonte et al. [62] presented an LCA study about a molten-salt CSP plant combined with a biomass back-up burner, developed by the Italian Research Centre ENEA. The LCA was performed by means of SimaPro7 software. The methods of EI99, IPCC and CED were adopted. Three different configurations of power plants were compared: molten-salt CSP plant, oil power plant and gas power plant. The functional unit "production of 1 kWh_e energy" was used and the system boundary was cradle-to-gate, including use phase. In Fig. 3, the solar part of the CSP plant consisting of a solar-collector field of parabolic mirrors and the receiver tube, is illustrated. In Fig. 4, findings from the work of Piemonte et al. [62] regarding LCA comparisons in terms of CED (Fig. 4a) and in terms of GWP evaluated on a 100-years basis (Fig. 4b), are presented. From Fig. 4(a) it can be seen that the CSP plant includes a high quantity of renewable energy while fossil energy requirements are around 85% less than those of the oil and gas power plants. These findings are in accordance with the remarkably lower GWP reported by the CSP configuration (in comparison to those of the oil and gas power plants): Fig. 4(b).

4.2. Multiple aspects related with CSP environmental impact

In Table 6, different factors which influence CSP environmental profile are presented, classified into categories. From Table 6 it can be seen that these factors include multiple issues:

Table 5
Studies including LCA and/or, in general, environmental issues about CSP and other types of concentrating solar systems.

Study/type of system	Studied issues/methods	Location	Findings/impact	Additional findings/comments
CSP				
CSP vs. coal-fired power plants: NREL (2012) [3]	GHG emissions, etc.		Coal-fired power plants: fuel combustion during operation emits the vast majority of GHGs	CSP plants: the majority of GHG emissions concern upstream of operation
CSP (parabolic trough) and the influence of hybridizing with natural gas: Corona et al. (2014) [57]	ReCiPe, CML, CED, EPBT, etc.	Spain	EPBT: 1.4 years	Water-cooled 50 MW_e CSP (parabolic-trough), solar-only scenario showed EPBT 1.4 years (hybridization with natural gas increases EPBT)
CSP plants (parabolic-trough and solar tower): Lechón et al. (2008) [58]	CED, EPBT, GWP, CML, etc.	Spain	EPBTs around 1 year for both power plants	17 MW central-tower CSP, 50 MW parabolic-trough CSP (GWP: around 200 g/kWh mainly due to the use of fossil fuels during operation)
CSP potential in Africa and Europe: Viebahn et al. (2011) [59]	$CO_{2.eq}$ emissions, cost issues, etc.	Africa and Europe	Emissions: 18 g $CO_{2.eq}$/kWh (scenario for 2050)	Scenario for 2050 (including transmission from North Africa to Europe)
CSP parabolic-trough: Burkhardt III et al. (2011) [60]	GHG emissions, CED, EPBT, water consumption, etc.	Daggett, CA, USA	Reference system: 26 g $CO_{2.eq}$/kWh EPBT about 1 year	Reference system: 103 MW, parabolic-trough, wet-cooled, two-tank thermal-energy-storage (alternative designs were also examined)
Thermal-energy-storage for CSP: Heath et al. (2009) [61]	GHG emissions, etc.		Two-tank: 17100 MT CO_{2e} (embodied emissions from the materials used)	Storage for 50 MW_e CSP plant with 6-h of molten-salt thermal storage, indirect, two-tank configuration (a thermocline system showed less than half emissions of those of the two-tank)
Molten-salt CSP combined with biomass back-up burner: Piemonte et al. (2011) [62]	EI99, IPCC, CED, etc.	Italy	The CSP plant has fossil-fuel requirements around 85% less than those for the oil and gas power plants	Molten-salt CSP plant, oil power plant and gas power plant were compared
Comparative LCA of four CSP plants: Kuenlin et al. (2013) [63]	IMPACT 2002+, cost issues, etc.	Southern Spain; AZ, USA (for Maricopa)	More than 86% of the impact is due to the phase of construction; Storage/heat transfer fluid may have as well a considerable impact (in particular for trough plants)	LCA comparison for: parabolic-trough (Andasol), tower (Gemasol), Fresnel (PE2), dishes (Maricopa); the comparison of CSP with their fossil competitors shows that CSP has much lower impact for most of the impact categories
CSP solar tower: Zhang et al. (2012) [64]	Embodied energy, CO_2 emissions, etc.	Beijing, China	CO_2 emissions: 36.3 g/kWh	1.5 MW Dahan solar-tower plant; heliostat field of 100 heliostats
Concrete thermal-energy-storage parabolic-trough CSP: Laing et al. (2010) [65]	Economic analysis, LCA, etc.		The impact of the hypothetical concrete-based Andasol-I decreased by 7% (for 1 kWh of solar electricity delivered to the grid)	LCA comparison of an Andasol-I type CSP with the original two-tank molten-salt storage with an hypothetical concrete storage configuration
CSP reference design: dry-cooled power tower: Whitaker et al. (2013) [66]	CED, EPBT, GHG emissions, etc.	Near Tucson, AZ, USA	The reference plant: 37 g $CO_{2.eq}$/kWh; By using synthetic salts there is 12% increase in GHG emissions	The reference system (106 MW_{net}) uses a mix of mined nitrate salts (heat transfer fluid and storage medium), two-tank thermal energy storage (6 h), auxiliary power from the local electric grid; design alternatives: thermocline-based storage system, synthetically derived salts and natural gas auxiliary power
CSP parabolic-trough, hybridization with natural gas: Adeoye et al. (2014) [67]	EI99, etc.	United Arab Emirates	Concrete thermal energy storage shows higher impact than molten-salt one	Shams-1: 100 MW, natural gas hybridization, parabolic-trough (the study [67] is a comparative LCA of concrete vs. molten-salt thermal energy storage)
Compact linear Fresnel reflector CSP: Hang et al. (2013) [68]	CO_2 emissions, etc.	India	31 g CO_2/kWh_e EPBT 0.7 years	AREVA Compact Linear Fresnel Reflector

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Table 5 *(continued)*

Study/type of system	Studied issues/methods	Location	Findings/impact	Additional findings/comments
Distributed concentrating solar combined heat and power: Norwood and Kammen (2012) [69]	GWP, economics, etc.	Richmond, CA, USA	GWP: around 80 g $CO_{2.eq}$/kWh of electricity and 10 g $CO_{2.eq}$/kWh thermal	Issues related with water (for desalination and water-use in operation) were also examined
CSP parabolic-trough: Ehtiwesh et al. (2016) [70]	EI99, cumulative exergy demand, thermo-economic analysis, etc.	Libya	Human health damage category shows the highest impact 69% (followed by Resources with 24%)	Respiratory inorganics category shows the highest percentage 45.48% (followed by fossil fuels (20.4%) and carcinogens (14%)); the analysis focused on a 50 MW_e parabolic-trough CSP
CSP solar tower: Koroneos et al. (2008) [71]	Eco-indicator		For construction and operation: the maximum impact is in terms of the GHG effect (followed by acidification)	Coal consumption is 46.9% of the overall energy consumption
Solar-aided coal-fired power plant (with and without heat storage): Zhai et al. (2016) [72]	Primary energy consumption, GWP, acidification potential, cost issues, etc.	Lhasa, China	For all the studied systems, pollutant emissions and primary energy consumption are mainly because of the fuel and the operational phase	CO_2 is responsible for the major part (about 79.5%) of the GWP; The performances of a coal-fired power system, a solar-aided coal-fired power system with thermal storage and a solar-aided coal-fired power system without thermal storage, with three capacities of each kind of system, were examined (over their entire lifespan)
CSP with unfired Joule-Brayton cycle: Rovense (2015) [73]	Energy output, CO_2 emissions, etc.	Seville, Spain	Electricity production more than 75 GWh/year, with a considerable sparing in terms of fossil fuel consumption and avoided CO_2 emissions	The studied CSP could be used for grid feeding, in the frame of decarbonizing the electric sector
CSP HYSOL, solar tower with steam turbine and gas turbine with biomethane: Corona et al. (2016) [74]	ReCiPe midpoint, CED, etc.	Spain, Chile, Kingdom of Saudi Arabia, Mexico, South Africa	HYSOL operating with 55% natural gas hybridization: 294 kg $CO_{2.eq}$/MWh	The environmental performance of the HYSOL is improved considerably (27.9 kg $CO_{2.eq}$/MWh in comparison to 45.9 kg $CO_{2.eq}$/MWh in the climate change category) when the study takes into account that the digestate from the production of the biomethane fuel is utilized to replace synthetic fertilizers
CSP plants: Caldés and Lechón (2012) [75]	LCA, socio-economic issues, etc.		A general introduction to the major environmental and socio-economic aspects related with CSP systems was presented	The state-of-the-art in terms of the methods available to quantify the main environmental impacts of CSP was presented
CSP hybridizing with biomass/waste: Peterseim et al. (2014) [76]	CO_2 emissions, economic analysis, etc.	Australia	The energy-from-biomass or energy-from-waste components of the hybrid plants considered were assumed to allow base load operation with the CSP components (offering additional capacity during day)	The generation potential and the most prospective regions for 5–60 MW_e CSP hybrids utilizing forestry residues, stubble, bagasse, wood waste and refuse derived fuels were examined
Solar-hybrid power plants: Giuliano et al. (2011) [77]			Comparing to a conventional fossil-fired combined-cycle configuration, the potential for reduction of CO_2 emissions is high for solar thermal power plants working in base-load, especially with large solar fields and high storage capacities	For dispatchable power generation and supply security, in any case additional fossil fuel is needed
Production of enriched methane by a molten-salt CSP: Piemonte et al. (2012) [78]	EI99, CED, GWP, etc.	Italy	The results demonstrated the lower environmental impact of this innovative plant compared to two traditional plants	The conventional plants presented GWP around 75% higher than that of the molten-salt-CSP-steam-reforming-reactor plant
Several electricity generation systems (CSP, etc.): Aden et al. (2010) [79]	CO_2 emissions, water input, energy input, cost analysis, etc.	China	From a reference to 450 ppm (global atmospheric carbon concentration) electricity generation trajectory, China can achieve remarkable energy, water and emissions savings	A comparative LCA of non-fossil electricity generation technologies was presented, based on China 2030 scenario analysis
CSP (parabolic trough, solar tower, etc.), Romero-Alvarez and Zarza (2007) [80]	Principles and limitations of CSP, CO_2 emissions, market opportunities, etc.		Solar thermal power plants are very promising for offering a considerable share of solar bulk electricity by the year 2020 (their strong point: they are flexible for adapting to dispatchable and distributed markets)	Aspects related to the avoided CO_2 emissions of CSP plants and the fossil fuel savings (comparing to conventional plants) were also presented

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Table 5 (continued)

Study/type of system	Studied issues/methods	Location	Findings/impact	Additional findings/comments
CSP parabolic trough: Poullikkas (2009) [81]	Cyprus current energy system, solar thermal power technologies, etc.	Cyprus	A feasibility study was conducted to evaluate whether parabolic-trough solar thermal technology for power generation in the Mediterranean region is economically feasible	The study also included issues about the CO_2 emissions of the systems
CSP plants: Stoddard et al. (2006) [82]	CO_2 emissions, economics, etc.	California, USA	Each CSP plant offers reductions of the emissions in comparison to its natural-gas counterpart (the 4000 MW scenario offsets at least 300 t/year of NO_x emissions, 180 t/year CO emissions and 7600000 t/year CO_2	Economic, energy and environmental benefits of CSP in California were presented
CSP plants: Purohit et al. (2013) [83]	CO_2 emissions, economics, etc.	Northwestern India	The CSP projects in Northwestern India present high potential due to the high solar radiation and the availability of desert areas	Several aspects were examined such as policy framework for promoting CSP in India, resource assessment of CSP in Northwestern India, energy yield and potential of CSP technologies in Northwestern India and CO_2 emissions mitigation benefits related to CSP
CSP plants: Viebahn et al. (2008) [84]	CO_2 emissions, economic issues, key emissions and land use, etc.	Several countries (Spain, Germany, etc.)	Emissions produced mainly due to fossil fuels (CO_2 and CH_4) decrease by around 80–90% with switching from hybrid to solar-only scenario	Several configurations (parabolic trough, Fresnel, solar tower, etc.) were examined, for different cases
CSP parabolic-trough hybrid with natural gas: Corona et al. (2016) [85]	Life-cycle cost, marginal damage costs for GHG emissions, etc.	Ciudad Real, Spain	Hybrid CSP with natural gas: showed higher overall power outputs but also higher internal costs	External unit costs of hybrid CSP with 30% natural gas were found to be up to 8.6 times higher than for solar-only operation (mainly because of the increase of the GHG emissions)
CSP vs. PV: Desideri et al. (2013) [86]	EI99, EPBT, CO_2 emissions, etc.	Sicily, Italy	GWP100: 29.9 g CO_{2eq}/kWh for the CSP plant; 47.9 g CO_{2eq}/kWh for the PV plant	EPBT: around 2 years for the CSP plant and 5.5 years for the PV plant; for the CSP plant with parabolic-trough collectors a score of 2.32 Pt was found, in comparison to 2.72 Pt for the PV system (these values regard life-cycle impact of 1 MWh, based on EI99)
Dish-stirling: Cucumo et al. (2012) [87]	EI99, EPD 2007, etc.	Italy	The environmental impact of a concentrating system, in comparison to a PV system (placed on a sloped roof with a retrofit system) was presented	The calculations were based on the Italian energy mix
Dish-stirling: Bravo et al. (2011) [88]	EI99, CML 2, CO_2 emissions, etc.	Europe	Dish-Stirling (10 kW) vs. monocrystalline PV (10 kW): CO_2 emissions show the same order of magnitude, with not significant balance favorable to the PV system	The damage categories (ordered by signification) for dish-Stirling and PV were found to be: Resources, Human health and Ecosystem quality
Dish-stirling: Cavallaro and Ciraolo (2006) [89]	EI99, primary energy, $CO_{2.eq}$ emissions, etc.	Sicily, Italy	The most critical phase (in terms of the environmental impact) is the construction/assembly of the solar power plant, followed by shipping of the solar dishes from Australia (manufacturing) to Sicily (installation)	The aim was to assess the environmental impact of electricity production by means of a system that is hypothetical (1 MW solar thermal power plant; paraboloidal dish)
Solar power plants (including CSP) land use: Ong et al. (2013) [43]	Land-use requirements, etc.	USA	CSP land use depends on the technology (parabolic trough, solar tower, etc.)	
Other types of concentrating solar systems				
Parabolic trough lighting and thermal system: Li and Yuan (2016) [90]	Optimization of critical components, GHG emissions, cost issues, etc.	USA cities	Based on the GHG emission rate of unit electricity and gas consumption (for each of the studied cities of USA), the GHG reduction was evaluated: for most of the cities, the reduction was found to be more than 4500 kg/year	The results demonstrated that the proposed system will be competitive in comparison to traditional solar energy systems when adopted in Sunbelt region

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Table 5 (*continued*)

Study/type of system	Studied issues/methods	Location	Findings/impact	Additional findings/comments
Micro-combined-heat-and-power system including a parabolic-trough collector: Bouvier et al. (2016) [91]	Overall performance of the system, etc.	La Rochelle, France	The temperature of the supply water for the building was about 60°C (values above 80°C can be achieved); thus, sufficient for hot water production or heating applications	Micro-combined-heat-and-power systems are promising for the reduction of CO_2 emissions and fossil-fuel consumption in buildings
Multi-generation system which includes parabolic solar collector: Ozlu and Dincer (2016) [92]	CO_2 emissions, NO_x emissions, SO_2 emissions, cost issues, etc.	Toronto, Canada	The proposed system saves 1398 t/year CO_2 in comparison to a conventional system for the production of the same outputs (demand of 94 suites)	The multi-generation system proposed provides heating, cooling, electricity and hydrogen by means of solar energy
A system based on parabolic-trough solar collectors for an ice-cream factory: Kizilkan et al. (2016) [93]	CO_2 emissions, energy analysis, etc.	Isparta, Turkey	The CO_2 emissions of the actual system are 1.23 t/year while those of the proposed system are 0.02 t/year	A case study (proposed solar system) aiming to convert an existing conventional system to a solar energy system for an actual ice-cream factory was presented
Parabolic-trough collectors with CR 19.89×: Valan Arasu and Sornakumar (2008) [94]	Life-cycle cost, etc.	Madurai, India	The present worth based on the life-cycle solar savings was calculated for the solar system (that replaces an existing electric water heating system)	The application was water heating for a restaurant

Fig. 3. CSP plant from the study of Piemonte et al. [62]: solar parabolic mirrors and receiver tube (Source: [62]).

1) Cooling and water use (there is a big difference in terms of the water consumption of a CSP based on a water-cooling systems and that of a CSP based on a dry-cooling system).
2) Materials (for storage, for the concentrating devices, etc.): e.g. nitrate salts, silver and steel alloys.
3) Soiling and atmospheric aerosol loads (for example, soiling causes optical losses to the solar field of a CSP plant).
4) Combination of CSP with other systems (desalination systems, PVs, etc.).
5) Land use, lifespan of system components, operation and maintenance needs, etc.

Finally, it should be noted that another factor is related with the location of the CSP plant since the location determines critical issues such as solar irradiance, soiling and land use.

5. Several issues related with concentrating solar systems and future prospects

5.1. End-of-life materials and recycling

In the frame of an LCA study, scenarios which examine the effect of material recycling are of great interest since recycling can lead to considerable reduction of the impact (depending on the materials which are considered for recycling and depending on the studied systems). Scenarios which include recycling can refer, for example, to copper, aluminium and glass components of solar thermal systems [114].

Other aspects, interesting from environmental point of view, are related with the recovery of valuable materials from end-of-life PVT [115] or PV panels [116], the identification of weak points of the recycling processes of PV panels (conventional vs. innovative scenarios of recycling can be examined) [116] and PV panel disposal in a landfill site [116]. Moreover, in the work of Halasah et al. [42] it was noted that by comparing CPV and flat-plate configurations, it is clear that for crystalline silicon-based PVs, the main contributors to embodied energy are PV cells since the process of producing the silicon is very energy-intensive. Thereby, reducing the required energy is related with technological improvements [42]. Halasah et al. [42] also mentioned that aluminium frame is another significant contributor which effect can be reduced by increasing the amount of recycled aluminium utilized.

On the other hand, in the LCA studies of Lamnatou et al. [34,35] about a BICPV system, recycling for the aluminium frame of the BOS was taken into account. Within the field of BICPV, in the review of Chemisana [1] it was noted that among the advantages that CPV offer (in comparison to conventional flat panels without concentration) is related with the ease of recycling of the constituent materials. Furthermore, in the study of Kammen et al. [117] issues about recycling of CPV systems were presented.

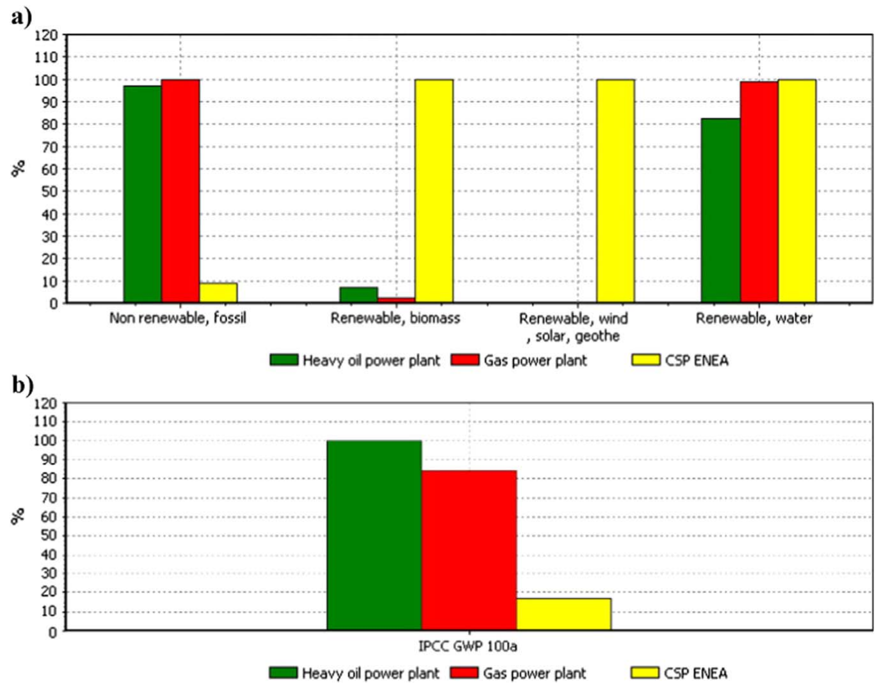

Fig. 4. Results from the study of Piemonte et al. [62]. LCA comparisons (heavy-oil power plant, gas power plant vs. CSP ENEA) based on: a) CED and b) GWP 100a (IPCC) (Source: [62]).

Regarding high-concentrating PV power generation systems, in the work of Nishimura et al. [39] several scenarios were examined, including recycling as treatment after system usage. Furthermore, in the investigation of Peharz and Dimroth [41] about the high-concentrating PV System FLATCON® it was mentioned that the recycling of the FLATCON® concentrator is specifically easy since the greatest part of the materials refers to steel (for the tracking) and glass (for the modules). In addition, the solar cells are mounted on single copper heat spreaders (which can also be removed at the end of the system lifespan) [41]. Peharz and Dimroth [41] highlighted that recycling of raw materials can have a significant influence on the calculations of the EPBT.

Moreover, in the study of Romero-Alvarez and Zarza [80] about CSP installations, it was noted that most of the solar field materials/structures can be recycled and in this way, they can be used again for other plants. Furthermore, in reference [118] a CSP plant based on Fresnel mirrors it was proposed and it was mentioned that the system has low environmental impact since it consists of fully recyclable materials (glass and steel).

Issues related with recycling for the case of CSP systems are also included in the studies of Desideri et al. [86], Ferriere [7], Whitaker et al. [66], Burkhardt III et al. [60], Corona et al. [57], Lechón et al. [58], Pihl et al. [104], Calvet et al. [102] and Burkhardt III et al. [21].

In addition, Py et al. [119] presented a work about thermal storage for solar power plants, based on low-cost recycled materials. It was noted that the storage of large amounts of heat requires large amounts of materials (and thus, there is high cost and high environmental impact).

Moreover, in the comparative LCA study of Adeoye et al. [67], regarding thermal-energy storage configurations for CSP plants, several scenarios were examined including material recycling and water recycling. In terms of material recycling, recycling of steel, glass, polyethylene and polyvinylchloride were considered. The energy required for dismantling the plant was taken into account while the energy needed for separating the dismantled materials was not taken into account. Regarding water recycling, an on-site membrane bio-reactor was considered for the treatment of the water used for cleaning the mirrors. Construction, operation and maintenance of the membrane bio-reactor were taken into account. It was noted that this almost eliminated the use of desalinated water [67].

5.2. Comments and future prospects

By taking into account the literature review presented (Sections 3 and 4), some comments (which can be also viewed as future prospects for research) are following presented:

1) Regarding CPV, there is a need for more studies which examine:

- A range of different CRs (in order to investigate the effect of CR and the effect of the optical losses on the environmental profile of a CPV system).
- CPVT systems for production of both electricity and thermal energy.
- Low-concentration CPV.
- Strategies to reduce the impact (e.g. by recycling and by adoption of manufacturing processes with lower impact) of certain components such as the tracking (especially for the large-scale installations), the concentrators and the PV cells.

2) Concerning CSP, there is a need for more investigations about:

- Dish-Stirling systems.
- The effect of the storage materials on the environmental profile of the whole CSP plant.
- Strategies for water savings (water-efficient coolers, etc.) in CSP cooling system.
- The effect of soiling on CSP performance (from energetic and from environmental point of view).

3) In general, within the field of concentrating solar systems, there is a need for more studies:

- Based on Fresnel lenses and reflectors.
- For small-scale systems for buildings, for example for BI configurations.
- For multiple final applications (desalination, drying, etc.).

Table 6
Several factors which influence CSP environmental profile.

Study/topic	Location	Findings/issues highlighted	Additional comments
Cooling and water use			
Dry-cooling vs. wet-cooling CSP plants: Martín (2015) [95]	Almeria, Spain	For the selected location, the wet-based system produces slightly less CO_2 than the air-cooled system	The plant was located in Almeria (Spain) because of the high solar irradiation
Reduction of water use in CSP: Damerau et al. (2011) [96]	North Africa	For the studied cases, the wet-cooling systems would likely be unsustainable (while dry cooling and sourcing of alternative water supplies would offer sustainable solutions)	Four representative locations were evaluated in terms of their ecological and economical drawbacks (based on conventional and alternative cooling systems)
Water use in CSP: Fthenakis and Kim (2010) [97], Meldrum et al. (2013) [98]	USA [97]	Fthenakis and Kim [97] presented life-cycle uses of water in U.S. electricity generation, analyzing several data, including water use of multiple systems (CSP parabolic trough, solar tower, etc.)	CSP water consumption: considerable differences between wet-cooling and dry-cooling configurations [97,99,100]
Materials (for storage, etc.)			
CSP oil-cooled plants, with/without heat storage in molten-salt tanks: De Luca et al. (2015) [101]	Almeria, Spain	The adoption of thermal storage almost doubles the production (annual electrical energy), the charge factor and the value of the capital cost (comparing to a plant without storage and with the same power block); the main benefit of a plant with storage is the higher flexibility to dispatch electrical energy when it is needed (and also during the absence of solar radiation)	The most used thermodynamic solar plants (in the world) adopt linear parabolic collectors and oil as heat transfer fluid (in the receiver tubes)
Materials for thermal storage (based on sensible heat) for CSP systems: Calvet et al. (2010) [102]		The material COFALIT® resisted brutal and repeated changes of the temperature, confirming its ability to store/destock sensible heat over a wide range of temperatures (up to 1000°C)	A material from industrial vitrification of asbestos waste was characterized (under concentrated solar flux in order to be evaluated as storage material (sensible heat) for CSP plants)
Use of nanofluids and molten salt in CSP: Abid et al. (2016) [103]		The studied nanofluids presented higher energetic and exergetic efficiencies comparing to the studied molten salts; parabolic-dish and parabolic-trough collectors were utilized	The overall performance of a parabolic-dish solar collector was found to be higher with the adoption of nanofluids as solar absorbers
CSP constraints in terms of the materials: Pihl et al. (2012) [104]	Almeria, Spain; California, USA	In general, most of the materials required for CSP are common; however, certain CSP material needs become considerable in comparison to the global production; the requirements for nitrate salts, silver and steel alloys in particular would be considerable if CSP becomes a major global electricity supply	Two CSP case studies were examined based on: 1) parabolic-trough (Plataforma solar de Almería), 2) solar tower (Sierra SunTower, California)
Soiling and atmospheric aerosol loads			
Soiling of CSP solar reflectors: Bouaddi et al. (2015) [105]	Southwest Morocco	The accumulation of the dust particles on the solar reflectors of CSP plants, reduces the reflectance	Soiling causes optical losses to the solar field of a CSP plant
The impact of atmospheric aerosol loads on CSP production in arid/desert places: Polo and Estalayo (2015) [106]	Spain	The accurate quantification of the direct normal irradiance is important for CSP design	One source of uncertainty for satellite-derived direct normal irradiance is the accuracy in terms of the quantification of the aerosol optical depth
Combination of CSP with other systems			
Combination of CSP with desalination: Palenzuela et al. (2015) [107], Ortega-Delgado et al. (2016) [108]	Mediterranean Sea and the Arabian Gulf [107]; Almeria, Spain [108]	The best coupling was found to be "reverse osmosis unit connected to the local grid" (this option presented the lower levelized water cost [108])	Although the low-temperature multi-effect distillation with thermo-compression was not so favorable for the Mediterranean, the differences with the CSP with reverse osmosis were not too big (for some cases even negligible) [107]
Combination of wind turbines, CSP, hydroelectricity and wave power: García-Olivares et al. (2012) [109]	Subtropical regions	A global alternative mix to fossil fuels was examined, based on renewable energy technologies that do not use scarce materials	Overall, the proposed alternative to fossil fuels seems feasible from technical point of view
Hybrid PV-CSP plants: Parrado et al. (2016) [110]	Atacama Desert, Chile	PV-CSP plants are a feasible solution for a continuous delivery of sustainable electricity in northern Chile	PV-CSP plants can have a positive effect on the stabilization of the electricity price and they can also reduce the carbon footprint of Chile

(continued on next page)

Table 6 *(continued)*

Study/topic	Location	Findings/issues highlighted	Additional comments
Land use and other factors			
CSP land use: Ong et al. (2013) [43]	USA	CSP land use depends on several factors e.g. on CSP type (parabolic trough, solar tower, dish-Stirling, etc.)	Land-use requirements for PV and CSP projects in USA were presented
Land use, lifespan, etc. (CSP and other systems): Aman et al. (2015) [111]		Several issues (environmental, etc.) about CSP (and other systems) were presented, including land-use, lifespan, operation and maintenance needs, capacity factor, etc.	A review about safety, health and environmental issues, with emphasis on solar energy systems, was presented
Inspection and health monitoring for CSP: Papaelias et al. (2016) [112]		There are certain evaluation techniques that can be used for the inspection of solar receivers and insulated pipes	Further research work is necessary to develop appropriate inspection technologies for the reliable assessment of some CSP components which are critical (particularly, solar absorbers and insulated pipes)
Dual receiver for solar tower CSP: Luo et al. (2015) [113]		A novel central receiver was proposed in order to improve the efficiency of the solar tower	The proposed configuration combines an external and a cavity receiver, for the boiling and superheating sections, respectively

4) In terms of the adopted methods/environmental indicators, certainly $CO_{2.eq}$ emissions, embodied energy and EPBT can provide useful information for CPV, CSP (and, in general for concentrating solar systems); however, there is a need for use of additional methods which can also provide useful information (e.g. LCIA methods which combine midpoint with endpoint approach such as ReCiPe and IMPACT 2002+).

6. Conclusions

The present article is a critical literature review about studies which are based on LCA and about studies which include environmental issues about concentrating solar systems. The references are presented according to certain criteria (type of the system (CSP, CPV, CPVT), etc.). Additional issues related to the environmental profile of concentrating solar systems are also presented.

Based on the literature review about high-concentration PV it can be mentioned that most of the investigations have been conducted between the years 2010–2015, they examine $CO_{2.eq}$ emissions, embodied energy and EPBT. In terms of the impact of these systems, for most of the cases high-concentrating CPV systems present $CO_{2.eq}$ emissions less than 50 g/kWh and EPBTs less than 1 year.

According to the literature review about low-concentration PV, it can be noted that most of the studies have been presented between the years 2011–2016 and they are based on different methods/environmental indicators (ReCiPe, EI99, embodied energy, EPBT, $CO_{2.eq}$ emissions, GPBT, etc).

Moreover, the results demonstrate that CPV environmental profile depends on several factors such as the direct solar radiation, the materials of the concentrator (PMMA, SOG, etc.) and the materials of the PV cells.

On the other hand, the literature review about CSP shows that most of the references are about parabolic-trough and solar tower technologies and they have been conducted between the years 2011–2016. In terms of the studied issues, most of the cases examine $CO_{2.eq}$ emissions; however, there are several studies which are based on embodied energy, EPBT and LCIA methods with midpoint and/or endpoint approaches and economic issues. For most of the investigations CSP plants present $CO_{2.eq}$ emissions less than 40 g/kWh and EPBTs around 1 year.

There are different factors which influence CSP environmental profile, including cooling and water use, materials (for storage, for the concentrating devices, etc.), soiling, land use, lifespan of system components, operation and maintenance needs, location, etc.

By considering the literature review presented it can be noted that:

1) With respect to CPV, there is a need for more studies which examine different CRs, CPVT systems for production of both electricity and thermal energy, low-concentration CPV, strategies to reduce the impact (e.g. by recycling) of certain components such as the tracking (especially for the large-scale installations) and the concentrators.
2) Regarding CSP, there is a need for more investigations about dish-Stirling systems, the effect of the storage materials on the environmental profile of the whole CSP plant, strategies for water savings in CSP cooling system, the effect of soiling on CSP performance (from energetic and from environmental point of view).
3) In general, within the field of concentrating solar systems, there is a need for more studies with Fresnel lenses and reflectors, for small-scale systems for buildings (e.g. BI) and for multiple final applications (desalination, drying, etc.).
4) Concerning the adopted methods/environmental indicators, certainly $CO_{2.eq}$ emissions, embodied energy and EPBT can provide useful information for concentrating solar systems; nevertheless, there is a need for adoption of additional methods which can also offer useful information (e.g. LCIA methods which include midpoint and endpoint approaches such as ReCiPe and IMPACT 2002+).

Conclusively, the present review article provides an overview within the field of LCA/environmental investigations about concentrating solar systems, identifying gaps of the literature and critical issues related with the environmental profile of several concentrating solar technologies.

Acknowledgements

The authors would like to thank "Ministerio de Economía y Competitividad" of Spain for the funding (grant reference ENE2013-48325-R).

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