

Review article

Life cycle assessment of concentrating solar power systems and concentrating photovoltaic systems: A review

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ABSTRACT

In the context of decarbonization, the application of Life Cycle Assessment to renewable energy-based systems is a key step for quantifying their real environmental benefits. This paper reviews the scientific literature on the applications of Life Cycle Assessment to concentrating solar power systems and concentrating photovoltaic systems. The review shows a higher number of studies applied to concentrating solar power systems than concentrating photovoltaic systems (83 % and 17 % of the studies, respectively), and four concentration systems are examined specifically: parabolic, tower, Fresnel and dish-stirling. Key factors such as plant components and materials, presence of storage systems, hybridization, and geographic location were considered to evaluate their influence on environmental outcomes. The review highlights the contributions of individual materials and life-cycle stages, as well as the benefits of storage systems. However, no definitive conclusion can be drawn regarding which technology consistently provides superior energy and environmental performance, due to methodological variability and differences in technological configurations across studies. The analysis also identifies research gaps, particularly for CPV, dish-Stirling and Fresnel systems, emphasizing the need for more uniform LCA methodologies in future studies. This review offers a comprehensive synthesis of LCA applications in concentrated solar technologies, providing guidance for future research and supporting the development and optimization of CSP and CPV systems.

1. Introduction

The gradual depletion of fossil fuel reserves and the risk of climate change make renewable sources among the leading candidates for energy sustainability. Renewable energy sources grew by 5.7 % from 2021 to 2022. In 2022, they accounted for 41.2 % of gross electricity consumption in the EU, with solar energy being the most successful (EUROSTAT, 2025). Among renewable sources, power generation from concentrating solar power (CSP) systems and concentrating photovoltaic (CPV) systems are a rapidly expanding topic, as these technologies have a better environmental profile than others (Desideri et al., 2013), a high efficiency and low operating costs (Pelay et al., 2020). In particular, CSP technologies will play a key role in transforming the current energy model, providing up to 11.8 % of global energy demand by 2050 (Boie

and Del Rio, 2021).

CSP technology uses solar radiation to produce thermal energy. Heat is converted into electricity using thermodynamic cycles. Based on the location of the concentrating system relative to the receiver, different technologies can be distinguished: solar tower, linear parabolic collector, Fresnel lens, parabolic disk system (Dish-Stirling) (Malik et al., 2022).

Unlike CSP solar technologies, CPV systems exploit the photovoltaic effect. In the field of photovoltaic technology, CPV offers multiple advantages over the use of non-concentrating photovoltaic panels (Lamnatou et al., 2016): the possibility of reducing the amount of material used, thus lower costs, and at the same time, higher energy conversion efficiency (Fthenakis and Kim, 2013). In this general framework, the objective of this work is to conduct an analysis of the state of the art of Life Cycle Assessment (LCA) studies applied to CSP and CPV systems,

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Acronyms			
ADP	Abiotic resource depletion potential	EPBT	Energy Payback Time
BICPV	Building integrated concentrating photovoltaic system	GER	Global energy requirement
CPC	Compound parabolic concentrator	GHG	Greenhouse gas
CSP	Concentrating solar power	GWP	Global warming potential
CST	Concentrating solar thermal	HCPV	High concentration photovoltaic
CPV	Concentrating photovoltaic system	HTF	Heat transfer fluid
CPVT	Concentrating solar photovoltaic-thermal	LCA	Life Cycle Assessment
CPV - DSF	Double-skin facades integrated high concentration photovoltaic	PCU	Power conversion unit
CED	Cumulative energy demand	PV	Photovoltaic panel
		TCES	Thermochemical energy storage
		TE-FPV	Textile Envelope Integrated Flexible Photovoltaic
		TES	Thermal energy storage

in order to compare these technologies, identify the energy and environmental hotspots and clarify the potential environmental benefits that can be obtained from the use of these technologies. Life Cycle Assessment is a standardized method for quantifying the environmental impacts of a product or system throughout its entire life cycle, from raw material extraction to disposal (Schneider et al., 2023). In the context of photovoltaic systems, LCA provides a comprehensive evaluation of energy payback, carbon footprint, and resource use, offering critical insights into the true sustainability of solar energy technologies (Li et al., 2022).

The reviews available in the literature have generally focused on specific aspects of concentrating systems. Some studies, for instance, have addressed greenhouse gas emissions associated with these technologies (Kommalapati et al., 2017), while others have explored the environmental performance of different types of concentrating systems (Lamnatou and Chemisana, 2017) or have analyzed the environmental impacts related exclusively to CSP systems (Guillén-Lambea and Carvalho, 2021). However, few studies provide a systematic comparison between CSP and CPV systems, highlighting the significant methodological differences that exist, such as the definition of the functional unit, system boundaries, and the methods used to assess environmental impacts. This scenario underscores the need for a comprehensive and critical review, capable of thoroughly evaluating the existing literature, identifying knowledge gaps, and providing guidance for future LCA research.

This study, by contrast, adopts a broader and more integrated approach: in addition to considering the factors already explored by previous authors, it also compares key elements such as the functional unit employed, system boundaries, methodological choices, the most impactful life cycle stages, a variety of environmental indicators, as well as the role of storage systems and the influence of the geographical location of the plants. Particular attention will be given to the analysis of the environmental impacts associated with the various components that make up a concentrating plant, both CSP and CPV, with a specific focus on key elements such as the solar field, collectors, receiver system, and secondary components.

With this analysis, recommendations will be provided to guide and optimize future LCA evaluations in the field of concentrating systems.

The manuscript is structured as follows. Section 2 describes the methodology adopted, including the PRISMA approach for the systematic literature review. Section 3 presents the results, organized into several subsections: Search results, Functional unit and system boundaries, Inventory analysis, Impact assessment methods, Comparison of the technologies investigated and Hotspots, the latter further divided into subsections such as life cycle phases, plant components, construction materials, storage systems, use of salts and heat transfer fluids (HTFs), hybrid systems and geographical location of the plants. Finally, the concluding sections provide a discussion of the main findings and the study’s conclusions, highlighting research gaps and suggesting possible directions for future studies.

2. Concentrating solar power and concentrating photovoltaic

Concentrating solar technologies can produce electricity, heat, or both. A CSP or CST plant generally consists of a solar collector field, heat transfer fluids, a thermal energy storage (TES) system, and a power conversion unit. The key component of the collector system is the receiver or the reflecting mirror. These systems are often classified according to the type of receiver: parabolic troughs and Fresnel systems are examples of line-focus concentrators, while parabolic dishes and solar towers belong to the point focus category (Cellura et al., 2025). In particular, a solar tower requires the use of a solar tracking system or heliostats to concentrate solar radiation onto a receiver. In parabolic systems, the collectors consist of glass mirrors shaped as parabolic cylinders, which focus the solar rays onto a cylindrical receiver positioned at the focal point of the collector. In Fresnel systems, sunlight is reflected by rows of adjustable flat mirrors, known as Fresnel lenses. Finally, in the parabolic dish configuration, parabolic-shaped panels, through a rotational movement on two axes, concentrate the radiation onto a receiver located at the focal point (Cotana et al., 2011).

CSP systems generate electricity by concentrating sunlight using reflective devices to produce heat. The heat is transferred through a heat-transfer fluid, which in turn powers a steam cycle to generate electricity. Some plants integrate thermal storage systems, allowing heat to be stored and the heat-transfer fluids to be reused to produce energy even when sunlight is not available (Luu et al., 2024).

Alongside these technologies, there are concentrating photovoltaic systems, where sunlight is focused onto high-efficiency multi-junction cells using optical devices that direct solar rays onto very small cell surfaces. This approach not only reduces the amount of semiconductor material required but also increases the intensity of the incident radiation proportionally. A CPV system includes not only the photovoltaic cells but also concentrating optics, heat dissipation systems, and solar tracking devices (Ghoneim et al., 2018). Among the various types of CPV systems, high-concentration systems integrated into double-skin facades (CPV-DSF) can be mentioned, which are characterized by two structural layers separated by an air gap. Between these two layers, solar-absorbing materials are generally placed, such as solar collectors, CPV modules, external single glass, internal double glass, and metal plates, in order to capture and make the most of the available solar energy (Zhu et al., 2020). Fig. 1 shows a schematic of concentrating systems.

3. Method

3.1. Literature search

The review was conducted through the application of the PRISMA methodology. The use of this approach allows the results obtained during the analysis process to be reported clearly and transparently, using specific guidelines (Page et al., 2021).

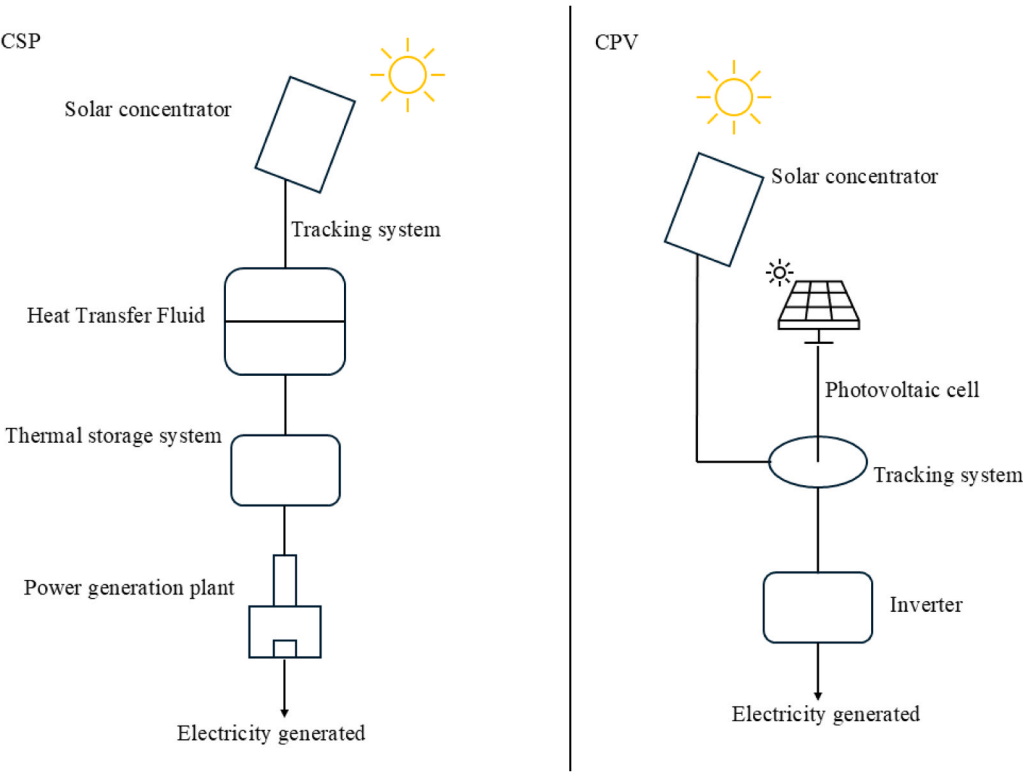


Fig. 1. Concentrating systems.

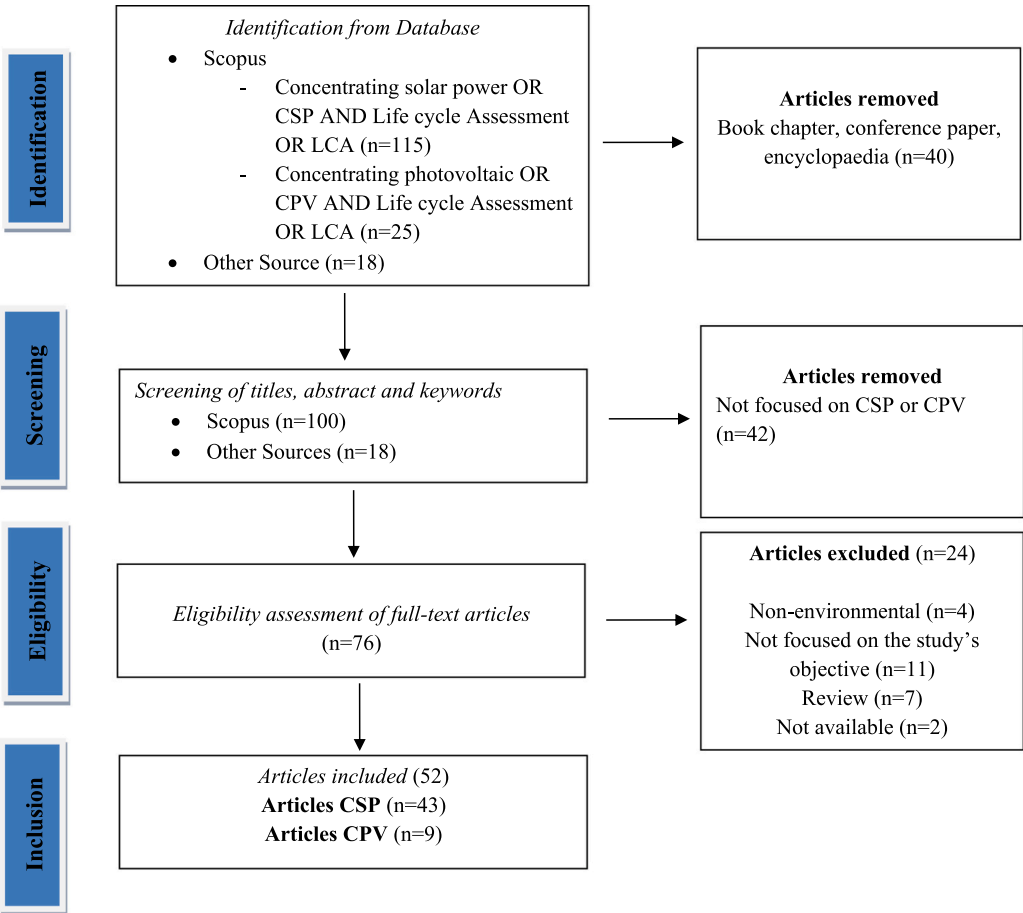


Fig. 2. PRISMA flow diagram.

The analysis of the state of the art was divided into the following phases:

- 1) First phase “Identification”: the search for studies was conducted through Scopus database by entering the following keywords: Concentrating Solar Power, Concentrating Photovoltaic and Life Cycle Assessment.

The search was conducted by combining the above words, for example:

- (CSP OR “Concentrating Solar Power”) AND (LCA OR “Life Cycle Assessment”);
- (CPV OR “Concentrating Photovoltaic”) AND (LCA OR “Life Cycle Assessment”).

In addition to the above databases, internet searches were conducted, to include additional published articles. At this phase, 158 articles were found, 40 of which were excluded because they fell into the following categories: book chapter, conference paper, encyclopaedia etc.

- 2) Second phase “Screening”: at this phase, titles, abstracts and keywords were reviewed and 118 articles were selected, of which 42 were excluded because they were not focused on the CSP or CPV.
- 3) Third phase “Eligibility”: consultation of the whole articles made it possible to select the publications most relevant to the research activity and to exclude articles not of interest. Specifically, 76 articles were selected and 24 articles were excluded.
- 4) Fourth phase “Inclusion”: with reference to the 52 selected articles, a division was made between those examining CSP and those examining CPV. At the end of this phase, 43 articles on CSP and 9 on CPV were selected.

Fig. 2 shows the flow diagram Prisma.

4. Results

4.1. Search results

The common objective of most publications is to evaluate the energy

and environmental performance of the examined technologies. Others have more specific objectives:

- To evaluate the energy and environmental impacts of different design alternatives and configurations, including various technologies or components;
- To assess the energy and environmental impacts, as well as the energy payback time (EPBT), with reference to different areas and energy supply conditions of the system;
- To analyse the energy and environmental impacts of the system under consideration with different natural gas input, different heat transfer fluids (HTF) and types of materials.

The selected articles were published between 2009 and 2025 (except for the year 2010). No filter was imposed on the year of publication, and no publications prior to this period were found. The year 2022 had the most publications. Between 2009 and 2012 only two articles were found, one for each year, except for 2011 when there was an increase in publications.

The graph shown in Fig. 3 indicates the number of selected articles per year of publication.

Only 30 studies specify the type of CSP (24 studies) or CPV (6 studies) examined, the remaining part does not clarify the type of system.

Specifically, among the various concentrating solar power technologies, those predominantly examined are: the solar tower system (10 studies), followed by the linear parabolic CSP system (10 studies), while 4 studies analyzed dish Stirling technology. The study conducted by Kuenlin et al. (2013). analyzes and compares four different types of CSP (parabolic, tower, Fresnel and dish-Stirling).

Two studies on CSP carried out a comparative analysis examining both solar tower systems and parabolic trough systems (Luu et al., 2024; Rangarajan et al., 2022).

With reference to concentrating photovoltaic systems, many of the authors analyze a parabolic CPV system (4 study). Fresnel technology is more common in a CPV system than in a CSP system, despite being the technology least investigated by the authors (2 studies). In other study contexts, since these are building-integrated concentrating photovoltaic systems, the type of CPV is not specified. The useful life of the analyzed plants averaged between 25 and 30 years.

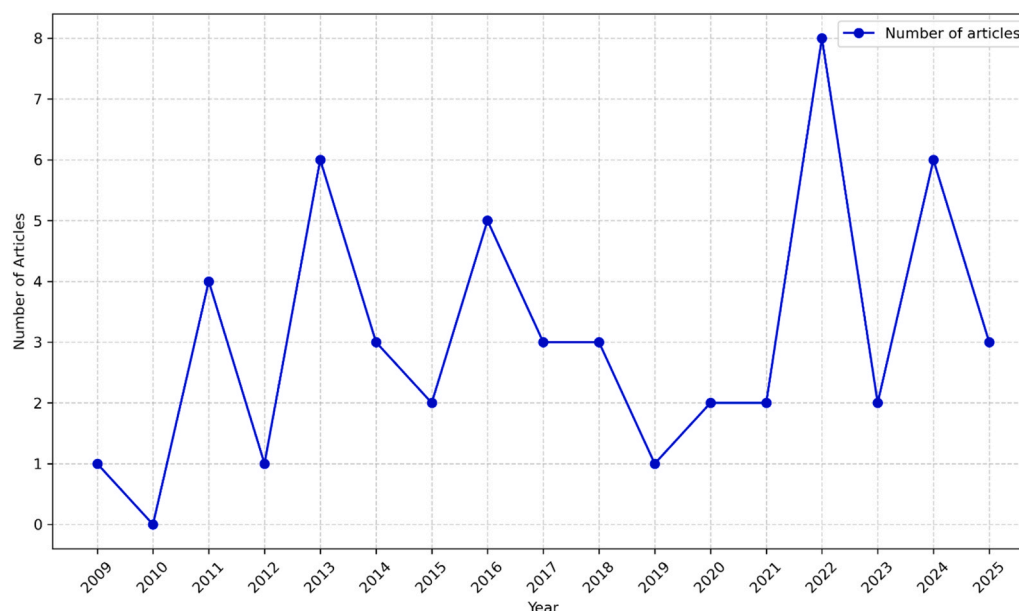


Fig. 3. Selected articles per year of publication.

4.2. Functional unit and system boundaries

Most studies have chosen electricity production as the functional unit, while others selected the plant power or the entire concentrating system. Some studies that examined the components of the systems identified one kilogram of product as the functional unit (e.g. 1 kg of steel or 1 kg of heat transfer fluid). Fig. 4 shows a summary of the functional units.

Fig. 4 shows that most of the authors of the selected studies chose kWh of electricity produced as the functional unit.

The diversity between the results highlights the need for a consistent choice of the functional unit among the studies. Since the main function of a concentrating system is electricity generation, choosing kWh of energy produced as the functional unit allows for a more accurate evaluation of the system’s performance, thus providing a clear and focused view of its impact. For the selection of system boundaries, the authors do not follow a uniform approach. Most publications follow a cradle to grave approach for system boundaries, (most include disposal and recycling of components), with the exception of the study conducted by Pelay et al. (2020), Mayo et al. (2018) and Batuecas et al. (2017) which use a cradle to gate approach. Backes et al. (2021) and Piemonte et al. (2011) adopted a cradle to use approach. In addition, the literature shows further variations, with approaches ranging from production to construction, operation, maintenance and decommissioning (Qi et al., 2025), others focusing on production, use and final decommissioning (Tursunović and Papurello, 2024) and others considering exclusively an approach from construction to decommissioning (Rangarajan et al., 2022).

4.3. Inventory analysis

The inventory analysis in the various studies shows different levels of detail (Table 1): some provide a thorough description of all plant components and the materials used, others are limited to the components without specifying the materials, while in some cases the analysis is not reported. To support the analyses, the authors used various software tools (mainly SimaPro) and secondary data databases, with Ecoinvent (Frischknecht, 2010) being the most commonly used source.

In other cases, however, the inventory analysis was not reported, creating a significant gap that makes it difficult to draw conclusions about the materials or components used. Without a detailed analysis, the

Table 1
Summary of inventory analysis approaches.

Aspect analyzed	Detail / Approach	Main studies
Inventory analysis	Detailed: all components and or materials (e.g., solar field, storage system, power block, concrete, polystyrene, glass, aluminium, etc.)	(Pelay et al., 2020; Lamnatou et al., 2016; Aurelie et al., 2013; Backes et al., 2021; Tursunović and Papurello, 2024; Gasa et al., 2021, 2022; Cellura et al., 2011; Ehtiwesh et al., 2016; Payet and Greffe, 2019; Palmero-González et al., 2025; Botejara-Antúnez et al., 2025; Yang et al., 2024; Le Roux et al., 2024; Puig-Samper et al., 2022; Colelli et al., 2022; Zhang et al., 2022; Qi et al., 2024)
Software and tool used	Components only (without specifying materials)	(Desideri et al., 2013; Herrera et al., 2020; Telsnig et al., 2017; San Miguel and Corona, 2014)
	Not explicitly reported	various studies
	SimaPro	(Backes et al., 2021; Ko et al., 2018; Mahlangu and Thopil, 2018)
	Gabi	(Gasa et al., 2021; Palmero-González et al., 2025; Matos et al., 2022)
	SAM	(Qi et al., 2025, 2024; Yang et al., 2024; Zhang et al., 2022)
	eFootprint	(Tursunović and Papurello, 2024; Le Roux et al., 2024)
Databases	Open LCA	(Shoaei et al., 2022)
	MATLAB	(Puig-Samper et al., 2022)
	EBSILON	(Aurelie et al., 2013; Frischknecht, 2010; Gasa et al., 2022; Telsnig et al., 2017; Xiao et al., 2022; Viebahn et al., 2011)
	Not explicitly mentioned	various studies
	Ecoinvent	(Lamnatou et al., 2015),
	ICE, ALCORN	(Herrera et al., 2020)
	Multi-regional IO	(Pelay et al., 2020; Gasa et al., 2021)
	LCA Food DK, USA Input	(Fthenakis and Kim, 2013)
	Output	(Yang et al., 2024; Zhang et al., 2022; Qi et al., 2024)
	Franklin	(Tursunović and Papurello, 2024)
	Chinese Life Cycle Database (CLCD)	
	Open-source Environmental Footprint database	

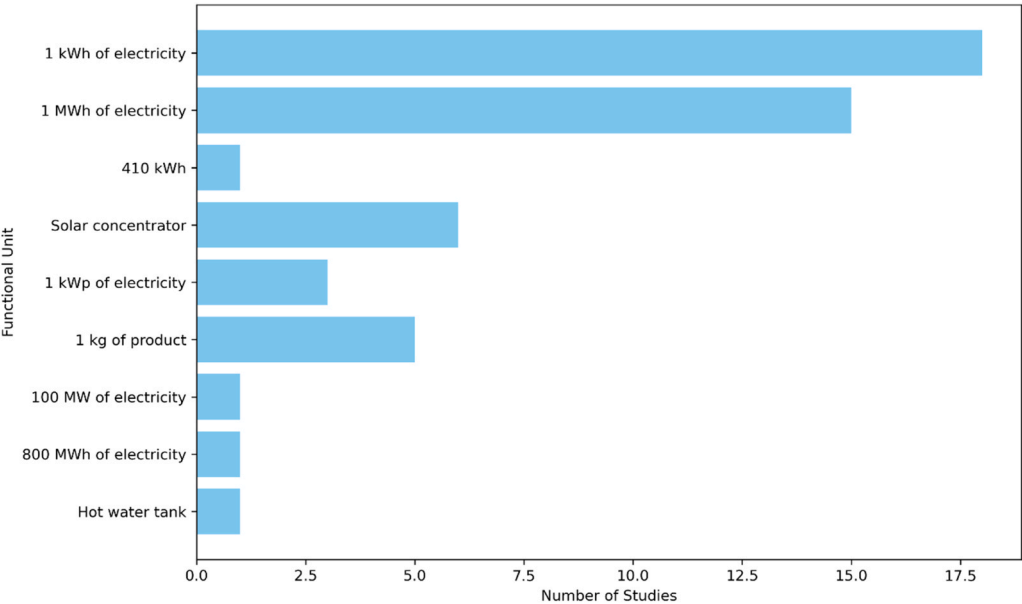


Fig. 4. Distribution of the types of functional units used in the considered LCA studies.

available information is less comprehensive, limiting the ability to identify potential strategies in choosing the type of material to use (Ko et al., 2018; Burkhardt et al., 2011; Cucumo et al., 2012; Corona et al., 2014; Corona and San Miguel, 2015; Corona et al., 2016a; Ordóñez Barreiro et al., 2009; Whitaker et al., 2013).

4.4. Impact assessment methods

About 45 % of the studies reviewed used a combination of different methods to assess the impacts. This methodological variety, applied within the same study, allows observing different environmental effects of technologies or quantifying the same impact with different reference substances, thus enriching the overall analysis. Table 2 shows the various methods used by the authors. In some studies the method used is not specified. Within the studies reviewed, the methodology adopted by the authors of one study proved to be of interest. Herrera et al. (2020) employed an integrated hybrid LCA, combining the LCA methodology with input-output economic sector analysis, resulting in an accurate and comprehensive assessment method as it provides a detailed evaluation of the impacts. This approach not only offered new analytical perspectives but also allowed for the exploration of innovative aspects that could be applied to other contexts.

4.5. Comparison of technologies investigated

Assessing the greenhouse gases emitted over the life cycle of CSP and CPV technologies is particularly important because they contribute significantly to climate change, one of the most serious and urgent environmental impacts to be addressed. Identifying technologies that can generate electricity while minimizing their greenhouse gas emissions is critical to guide the development of more sustainable energy solutions.

The studies examined highlight the complexity of determining the optimal technology from a CO₂ emissions perspective. The limited methodological consistency among the studies makes direct comparison challenging. Despite this limitation, a comparison was made with a selection of studies. In the studies shown in Table 3, all authors chose a cradle to grave approach, but differences emerged in the functional unit. Three studies selected 1 kWh of electricity fed into the grid (FITG), while six studies chose 1 kWh of electricity generated (G). In two studies (Corona et al., 2014) and (Corona and San Miguel, 2015) the functional units were converted from 1 MWh of electricity to 1 kWh of electricity to make the results comparable. The studies were compared, although they showed differences in the functional unit (FITG or G), as the discrepancy found was considered irrelevant to the analysis. It is important to emphasize that the comparison between CSP and CPV systems in this analysis is based on a limited and uneven number of studies (particularly for CPV), which reduces the robustness of the possible comparisons. Therefore, the results should be interpreted with caution.

The tower CSP system with thermal energy storage is responsible for the lowest emissions (9.8 gCO₂eq/kWh) (Gasa et al., 2021; Ko et al., 2018). HCPV systems show intermediate values between 16.4 and 26 gCO₂eq (Fthenakis and Kim, 2013; Payet and Greffe, 2019). The use of air cooling, auxiliary boilers powered by fossil fuels, or less efficient cycles further increases emissions up to 311 gCO₂eq (Corona et al., 2014).

4.6. Hotspots

Based on the studies that conducted a hotspot analysis (i.e., the critical points or elements with the greatest environmental impact in the life cycle of the system), it was useful to subdivide the results to make the identification and understanding of the various hotspots detected clearer. Accordingly, the results were organized as follows:

Table 2

Studies that simultaneously applied multiple methods for environmental impact assessment and characterization.

Authors	Method
(Adeoye et al., 2014).	-
(Backes et al., 2021).	CML
(Ordóñez Barreiro et al., 2009).	CML - CED
(Batuecas et al., 2017).	CML-IA
(Burkhardt et al., 2011).	-
(Botejara-Antúnez et al., 2025).	Recipe 2016
(Cellura et al., 2011).	EPD 2007
(Corona et al., 2014).	ReCiPe (Midpoint/Endpoint) Europe (H perspective), CML 2000, ReCiPeMidpoint Europe E, CED
(Corona and San Miguel, 2015).	ReCiPe Midpoint and Endpoint Europe (H), Cumulative Energy Demand
(Corona et al., 2016a).	Recipe Midpoint World H/CED
(Corona et al., 2016b).	Recipe Midpoint World (H perspective)/CED
(Corona et al., 2016c).	-
(Costa et al., 2024).	Environmental Footprint 3.1 (EF 3.1) and PEFCR
(Cucumo et al., 2012).	Eco-Indicator 99 and the EPD 2007
(Colelli et al., 2022).	CML 2001-IMPACT 2002 +
(Desideri et al., 2013).	Eco-Indicator 99
(Ehtiwesh et al., 2016).	Cumulative exergy demand and Ecoindicator 99
(Fthenakis and Kim, 2013).	CED
(Gamarra et al., 2023).	EMRIO (Extended Multi-Regional Input-Output), Environment Footprint
(Gasa et al., 2021).	ReCiPe and IPCC2013 GWP
(Gasa et al., 2022).	ReCiPe2016 and IPCC2013
(Herrera et al., 2020).	Environmental Footprint/ Input-Output Analysis (IOA)
(Klein and Rubin, 2013).	IPCC GWP 100a
(Ko et al., 2018).	CML
(Aurelie et al., 2013).	IMPACT 2002+
(Lambrech et al., 2023).	ReCiPe Midpoint (H) V1.09/Europe Recipe H
(Lamnatou et al., 2015).	The methodologies of Embodied Energy and Embodied carbon
(Lamnatou et al., 2016).	1) ReCiPe Endpoint (H) V1.10/Europe ReCiPe H/A; 2) Eco-indicator 99 (H) V2.09/Europe EI 99H/A; 3) USEtox /Europe 2004; 4) Ecological footprint
(Lamnatou et al., 2017).	1) Cumulative Energy Demand; 2) IPCC 2013 GWP 20a - IPCC 2013 GWP 100a - IPCC2013 GWP 500a; 3) ReCiPe Endpoint (H)/Europe ReCiPe H/A; 4) Ecological footprint; 5) USEtox /Europe 2004; 6) Eco-indicator 99 (H) /Europe EI 99 H
(Le Roux et al., 2024).	International Reference Life Cycle Data System (ILCD) 2016 midpoint
(Luu et al., 2024).	Product Environmental Footprint and ReCiPe
(Mahlangu and Thopil, 2018).	-
(Matos et al., 2022).	Recipe 2016 midpoint
(Mayo et al., 2018).	Recipe Midpoint H
(Menoufi et al., 2013).	Ecoindicator 99 and the EPS 2000
(Palmero-González et al., 2025).	Environmental Footprint (PEF) 3.0
(Payet and Greffe, 2019).	ILCD midpoint 2011, RECIPE, IMPACT 2002+ , CML, the Rabl and Spadaro, CED
(Pelay et al., 2020).	IMPACT 2002+
(Piemonte et al., 2011).	Ecoindicator, IPCC and CED
(Puig-Samper et al., 2022).	Environmental Footprint
(Qi et al., 2025).	IPCC, ReCiPe midpoint, CML2002, Impact2002+ , USEtox
(Qi et al., 2024).	ECER-135
(Rangarajan et al., 2022).	-
(San Miguel and Corona, 2014).	ReCiPe Midpoint Europe (H perspective) and ReCiPe Endpoint Europe H/H
(Shoei et al., 2022).	-
(Telsnig et al., 2017).	CML
(Tursunović and Papurello, 2024).	-
(Viebahn et al., 2011).	-
(Whitaker et al., 2013).	The Carnegie Mellon Economic Input Output (EIO) LCA tool
(Xiao et al., 2022).	-
(Yang et al., 2024).	ECER-135
(Zhang et al., 2022).	Integrated in eFootprint

Table 3

Comparison of studies with the same functional unit and system boundaries.

Authors	Technology	GWP	Functional unit	System boundaries	Capacity	Storage	auxiliary fuel usage
(Gasa et al., 2021).	CSP Tower	9.8 gCO _{2eq}	1 kWh electricity FITG	from cradle to grave	110 MW	yes	-
(Telsnig et al., 2017).	CSP tower	14.51 gCO _{2eq}	1 kWh electricity G	from cradle to grave	400 MW	yes	0 % diesel
(Ko et al., 2018).	CSP Tower	24.3 gCO _{2eq}	1 kWh electricity FITG	from cradle to grave	101 MW	yes	-
(Whitaker et al., 2013).	CSP tower	37 gCO _{2eq}	1 kWh electricity G	from cradle to grave	106 MW	yes	yes
(Luu et al., 2024).	CSP tower and parabolic	75–84 gCO _{2eq}	1 kWh electricity	from cradle to grave	20–50 MW	yes	-
(Qi et al., 2024).	PV-CSP hybrid	45.92 gCO _{2eq}	1 kWh electricity G	from cradle to grave	20 MW (PV)/19.9 MW (CSP)	yes	-
(Payet and Greffe, 2019).	CPV (H-C)	16.4 gCO _{2eq}	1 kWh electricity FITG	from cradle to grave	361.86 Wp–117.44 Wp	-	-
(Fthenakis and Kim, 2013)	CPV (H-C)	26 gCO _{2eq}	1 kWh electricity G	from cradle to grave	53–62 kWp	-	-
(Burkhardt et al., 2011).	CSP Parabolic	28 gCO _{2eq}	1 kWh electricity G	from cradle to grave	103 MW	yes	-
(Corona et al., 2014).	CSP Parabolic	26.6 gCO _{2eq}	1 kWh electricity	from cradle to grave	50 MW	yes	0 % natural gas
(Corona et al., 2014).	CSP Parabolic	311 gCO _{2eq}	1 kWh electricity	from cradle to grave	50 MW	yes	35 % natural gas
(Corona and San Miguel, 2015)	CSP Parabolic	125 gCO _{2eq}	1 kWh electricity	from cradle to grave	50 MW	yes	natural gas
(Ordóñez Barreiro et al., 2009).	Dish-stirling	89.4 gCO _{2eq}	1 kWh electricity G	from cradle to grave	10 kW	-	-
(Desideri et al., 2013).	CSP	29.9 gCO _{2eq}	1 kWh electricity	from cradle to grave	2 MW	-	-

1. Discussion of the influence of life cycle stages on the various indicators examined, by highlighting the significant heterogeneity in the results;
2. Incidence of components of concentrating power plants across different systems. For example, the solar field, storage systems, solar collectors etc. will be examined;
3. Where possible, focus on the impact of various materials used in the components;
4. Insight into incidence of the various storage systems and the types of salts used in them;
5. Analysis on the impact caused by the use of hybrid systems (e.g. hybrid system with natural gas or with coal, straw, biomethane, etc.). The results will be differentiated between a system operating in hybrid mode and one operating in solar-only mode;
6. Evaluation of the impact of the geographical location of the systems with a brief mention of energy payback time.

Table 4 shows a summary of the environmental hotspots identified in the different CSP and CPV systems.

4.6.1. Phases of the life cycle

The studies analyzed highlight how the environmental impacts of CSP and HCPV systems are primarily concentrated in specific phases of

their life cycle, with significant variations depending on the technology considered. Studies such as [Palmero-González et al. \(2025\)](#) highlight that the most impactful phases are material production and construction, confirming the findings of the study ([Qi et al., 2025](#)). In tower CSP systems analyzed in China ([Yang et al., 2024](#)), the production phase accounts for nearly all environmental impacts, while the operational phase has a minimal contribution and the end-of-life phase is important for recycling steel and glass. In CSP systems, the manufacturing phase is critical: in the study by [Mahlangu and Thopil \(2018\)](#), it accounts for 43.3 % of impacts on human health and 24.6 % on crop damage, contributing for 14.1 gCO_{2eq}/kWh to total emissions (32.2 gCO_{2eq}/kWh). In CSP HYSOL systems analyzed by [Corona et al. \(2016a, 2016b\)](#), bi-methane consumption during operation represents 32 % of the total life cycle energy consumption, affecting categories such as toxicity, climate change and acidification. In a tower system, during the operation and maintenance phase, 97 % of the emissions come from the consumption of auxiliary ([Whitaker et al., 2013](#)). Conversely, in a tower CSP system, like those analyzed by [Gasa et al. \(2021\)](#), the efficiency of the systems and reduced energy use from the grid significantly lower the impact of the operational phase. Indeed, emissions from the operational phase could be reduced in a CSP system with a TES, as evidenced by [Gasa et al. \(2022\)](#).

TES systems are components integrated into concentrating systems

Table 4

Summary of the environmental hotspots identified in the different CSP and CPV systems.

System type	Hotspot category	Most impactful life cycle phase	Impact categories
Tower CSP	Material production (steel), solar field and collector	Production, Construction and Installation	GWP, marine ecotoxicity, acidification, human toxicity
PV-CSP	Components (photovoltaic modules)	Production	GWP
Hybrid system	Consumption of auxiliary fuels	Operation	GWP, terrestrial acidification, cumulative energy demand
CSP systems (generic)	Solar field, support structure, mirrors	Production and Operation	GWP, damage categories, resource depletion
Systems with TES	Production of salts and tanks, hours of accumulation	Production and Construction	GWP, primary energy requirements, ecosystem quality
CPV	Photovoltaic cells & concentrators, tracking system, reflectors and materials (copper)	Production	Embodied energy and carbon, human toxicity, energy consumption, GHG

and, depending on the type of storage, they influence different stages of the life cycle.

In the TES systems analyzed by Adeoye et al. (2014) (in this case, the authors examined the environmental performance of two storage systems: one consisting of binary salt and the other consisting of a concrete tank), the manufacturing and construction phase, heavily influenced by air transportation of materials (an impact that could be reduced by opting for maritime transport), represents one of the main sources of emissions, contributing approximately 50 % to the total impact (expressed as a single score). The disposal phase, on the other hand, associated with landfilling, has a significant influence on carcinogenicity and ecotoxicity (around 15 %).

Regarding the raw material extraction phase, only the study by Corona et al. (2014) and San Miguel and Corona (2014) highlights a significant impact on climate change emissions: in Corona et al. (2014), about 79 % of the impact originates from the extraction and maintenance phase.

In the CSP analyzed by Ko et al. (2018) metal recovery during disposal reduces the impact on resource use (ADP) to less than 10 %, while the transportation of hazardous materials such as solar salt, highlighted in the study by Mahlangu and Thopil (2018) increases impacts related to this phase.

In the parabolic CSP studied by Desideri et al. (2013), the end of life phase contributes 0.57 Pt of a total of 2.3 Pt. For all concentration systems examined by Aurelie et al. (2013), the end of life phase has a negligible impact on the total, which is mainly attributable to the construction phase (between 86 % and 99 %). With reference to the disposal phase, it has emerged that this phase has a significant influence on the EPBT: with the reuse/recycling of materials, the EPBT is 4 years, while when these processes are not included, the EPBT is approximately 11 years (Cucumo et al., 2012).

Regarding concentrating photovoltaic-thermal (CPVT) systems (system composed of a concentrating thermal collector with a photovoltaic module), according to Cellura et al. (2011), the production phase is the largest contributor to global energy requirements (GER), accounting for 85 %, followed by the transportation phase at 14.6 % and the end of life phase at 0.5 %. The impact of the operational phase can vary significantly depending on the technological configuration.

In the case of the HCPV, Fthenakis and Kim (2013) report a low operational phase impact, with an EPBT of only 0.9 years and a reduction in emissions from 27 to 16 gCO_{2eq}/kWh over 50 years.

4.6.2. Plant components

The configuration of concentrated solar systems has a significant influence on the overall environmental impact, with the results highlighting the varying contributions of individual components to each category of environmental impact. The difference in the choice of functional unit and system boundaries proposed by the authors make it complex to identify and classify the component most responsible for the impact. Although the same concentrator system consists of the same components, the variability in the results highlights that each system has a unique environmental profile that is not easily comparable. The authors of the studies examined the energy and environmental impacts associated with the following components: solar field, solar tracker, the foundation, parabolic concentrator and photovoltaic cells, TES, dish-carrier, electronic components, power conversion unit (PCU), structures, reflector panels, the receiver tubes and collectors.

4.6.2.1. Solar field. The operation and maintenance phase of the solar field impacts various environmental categories differently. The solar field contributes 12–17 % to the total impact in hybrid PV-CSP systems (Qi et al., 2025).

Looking at 15 impact categories (GWP, carcinogens, non-carcinogens, ionizing radiation, ozone layer depletion, respiratory organics and inorganics, aquatic ecotoxicity, terrestrial ecotoxicity and

acidification, land occupation, aquatic acidification and eutrophication, non-renewable energy, mineral extraction), the impact generated by the solar field is between 10 % and 70 % (Pelay et al., 2020).

In a tower system, solar field maintenance is responsible for 42 % of Abiotic Depletion Potential (ADP) (Ko et al., 2018) while the solar field alone contributes 30 % to the GWP (similar percentages are also observed in the case of a parabolic system (Puig-Samper et al., 2022)). In a parabolic CSP 79.5 % of the total impact is caused by the solar field (Ehtiwesh et al., 2016).

There are no significant differences in the comparison of environmental performance of four plants (parabolic, tower, Fresnel and dish Stirling). For all types of plants, the solar field is the main contributor to the impact on GWP and damage categories: human health, resources, and ecosystem quality (Aurelie et al., 2013). Regardless of the method used for impact assessment, the collector field is among the main contributors to the analyzed impact categories (Luu et al., 2024). Table 5 summarizes the main environmental impacts attributable to the solar field.

The results show that, regardless of methodological differences, the solar field is the main contributor to environmental impacts, both in terms of GWP and other impact categories.

4.6.2.2. Collector system, receiver system and other components. The collector system has a notable impact, especially on aquatic ecotoxicity, GWP and acidification. With reference to GWP, the installation phase of the collectors is the most responsible (Matos et al., 2022). In a hybrid PV-CSP system, during the production phase, the contribution of the receiver system is almost negligible (1.11 %) (Qi et al., 2025) (in this system, the photovoltaic modules account for 57 % of the total impact). Moreover, mirror fields, generators and water bodies dominate the land use impacts (Rangarajan et al., 2022). 95 % of greenhouse gas emissions are attributable to the installation phase, with the largest contribution coming from the collector field (Matos et al., 2022). Regarding GWP, in a Dish Stirling plant (Ordóñez Barreiro et al., 2009), the structure accounts for 0.021 kgCO_{2eq}/kWh. Within the Dish Stirling system, the foundation has the greatest impact, contributing 0.028 kgCO_{2eq}/kWh, followed by the concentrator at 0.022 kgCO_{2eq}/kWh, and the PCU at 0.019 kgCO_{2eq}/kWh (out of a total of 0.089 kgCO_{2eq}/kWh). The main contribution to emissions comes from the parabolic dish (4300 kg CO_{2eq}), followed by the hot water tank (861 kg CO_{2eq}) and the receiver (164 kg CO_{2eq}) (Tursunović and Papurello, 2024). In the work of Backes et al (Backes et al., 2021) both dish carrier and electronic components cause 16 % of total CO_{2eq} emissions, while power conversion unit components are responsible for 11 % of GHG emissions. On fossil abiotic depletion, electronic components, solar tracker, and PCU affect less than 22 %. Table 6 summarizes the main environmental impacts attributable to the collector system, receiver system and other components.

4.6.2.3. Components of CPV plant. In CPV systems, multi-junction photovoltaic cells and concentrator are the components that most affect embodied energy and carbon, and damage categories. The rest of the components contribute to the total impact with a negligible percentage for both indicators (between 0.2 % and 6 %) (Lamnatou et al., 2015).

Also in the study conducted by Lamnatou et al. (2017) photovoltaic cells and the concentrator are the components that generate the greatest impact on resources depletion, human health and ecosystem quality (between 26 % and 63 %).

In the study conducted by Payet and Greffe (2019) in a mirror system and an achromatic lens system, the tracker (25 %) is the main contributor to the total weighted impact. In the mirror system, in addition to the tracker, composite (17 %) and copper (16 %) also contribute to the impact. In the achromatic lens system, the impact comes from electrical systems (15 %), solar cells (14 %) and the glass plate (12 %). Photovoltaic panels have a significant impact (from 68.3 % to 93.3 %) on the

Table 5
Summary of the main environmental impacts attributable to the solar field.

System Type	Functional unit	System boundaries	Component	Categories	(%)
Tower CSP (Gasa et al., 2021)	1 kWh electricity FITG	from cradle to grave	Solar field	GWP (ReCiPe)	30 %
Tower CSP (Gasa et al., 2021)	1 kWh electricity FITG	from cradle to grave	Solar field	GWP (IPCC)	45 %
Hybrid PV-CSP (Qi et al., 2025)	1 MWh	from cradle to grave	Solar field	Total impact	12–17 %
Tower CSP with TES (Gasa et al., 2022)	1 kWh electricity FITG	from cradle to grave	Solar field	Total impact	~40 %
CSP (Klein and Rubin, 2013)	1 MWh	from cradle to grave	Solar field	GWP	~50 %
CSP (Pelay et al., 2020)	100MWel	from cradle to gate	Solar field	15 impact categories	10–70 %
Tower CSP (Ko et al., 2018)	1 kWh electricity FITG	from cradle to grave	Solar field (maintenance)	ADP	42 %
Parabolic CSP (Puig-Samper et al., 2022)	1 kg of hydrogen	from cradle to grave	Solar field	GWP	30 %
Parabolic CSP (Ehtiwesh et al., 2016)	Plant	from cradle to grave	Solar field	Total impact	79.50 %

Table 6
Summary of the main environmental impacts attributable to the collector system, receiver system and other components.

System Type	Component	Main Impact Category	%
Tower CSP (Telsnig et al., 2017)	Collectors, receivers	Aquatic ecotoxicity	~82 %
Tower CSP (Whitaker et al., 2013)	Collectors	Greenhouse gas emissions	54 %
Hybrid solar power plant (Herrera et al., 2020)	Collectors	Acidification	~50 %
Parabolic CSP (Desideri et al., 2013)	Support structure	Ecosystem quality, Human health	55 % and 38 %
Parabolic CSP (Desideri et al., 2013)	Mirrors, tracking system, support structure, receiver tubes	Resources	30 % (each) and 10 % (receiver tubes)
Dish Stirling (Ordóñez Barreiro et al., 2009)	Concentrator	Human toxicity	~50 %
Dish Stirling (Ordóñez Barreiro et al., 2009)	PCU	Ozone layer depletion	~95 %
Dish Stirling (Backes et al., 2021)	Electronic components	Abiotic depletion	61 %
Dish Stirling (Backes et al., 2021)	Electronic components	Ozone depletion potential	54 %
Dish Stirling (Backes et al., 2021)	Electronic components	Photochemical zone creation potential	48 %

category of human toxicity (cancer and non-cancer) and along with CPC, encapsulation, glass cover (components/elements of a building-integrated CPV) affect climate change (percentages range from 58 % to 83 %) (Lamnatou et al., 2016). Table 7 summarizes the main environmental impacts attributable to the components of CPV system. Despite many similarities in the basic materials between PV and CPV systems, the component differences, such as the presence of concentrators, lenses, or mirrors in CPV systems, involve additional materials. Since many CPV materials are similar to those of PV, LCA analyses on PV can in some cases serve as a valuable reference for studies on CPV systems. For example, organic solar cells are not suitable for Textile Envelope Integrated Flexible Photovoltaic (TE-FPV) systems due to their low efficiency, whereas perovskite cells integrated into Ethylene Tetrafluoroethylene (ETFE) façades show great environmental potential, being able to offset greenhouse gas emissions (Li et al., 2024a). Furthermore, TE-FPV systems generate economic benefits and produce clean renewable energy, with advantages also for building owners, as demonstrated by cases in Bergen, Norway (Li et al., 2023). The use of

Table 7
Summary of the main environmental impacts attributable to the components of CPV system.

System Type	Component	Impact Category	(%)
CPV (Lamnatou et al., 2015)	Multi-junction PV cells	Embodied energy	54.1 %
CPV (Lamnatou et al., 2015)	Multi-junction PV cells	Embodied carbon	54.8 %
CPV (Lamnatou et al., 2015)	CPC	Embodied energy	33.5 %
CPV (Lamnatou et al., 2015)	CPC	Embodied carbon	34.2 %
CPV (Lamnatou et al., 2017)	CPC	Primary energy demand	54 %
CPV (Lamnatou et al., 2017)	PV cells	Primary energy demand	36 %
BICPV (Menoufi et al., 2013)	Reflectors	Total impact (EPS 2000 and Ecoindicator 99)	23 % - 45 %
BICPV (Menoufi et al., 2013)	PV cells	Total impact (EPS 2000 and Ecoindicator 99)	6.5 % - 9.6 %
HCPV (in a mirror system and an achromatic lens system) (Payet and Greffe, 2019)	Tracker	Weighted total impact	25 %
HCPV (Fthenakis and Kim, 2013)	Concentrator & Tracker	Energy consumption & GHG emissions	91 %

cushion-integrated transparent solar cell (EC-TSC) systems proves to be more cost-effective and low impact than glass PV skylights, as long as they are manufactured according to the intended design specifications (Li et al., 2024b).

4.6.3. Construction materials

The use of materials such as steel and copper in CSP systems contribute to the worsening of their energy and environmental performance, especially on GWP and marine ecotoxicity. In particular, the use of steel causes 54 % of GWP emissions (Backes et al., 2021) and is responsible for 46.9 % of the total impacts of all categories examined (results expressed as a single score) (Ehtiwesh et al., 2016). In the study conducted by Piemonte et al (Piemonte et al., 2011), the use of steel mainly affects human toxicity, eutrophication and acidification.

The impact of parabolic CSP on marine ecotoxicity is mainly attributable to the use of steel (33 %) in various components of the plant, the use of copper in the energy storage system and power block (17 %), the use of chrome-plated steel in the solar field (12 %) and the production of the heat transfer fluid (8 %) (Corona et al., 2014). Similar results were obtained in the study conducted by San Miguel and Corona (San Miguel and Corona, 2014): the marine ecotoxicity category is primarily influenced by the use of steel (37 %) and chromium (12 %) in the solar field, by copper (18 %) in both the thermal energy storage (TES) and power block, and by heat transfer fluid (9 %). Using AISI 347 H stainless steel can reduce the environmental impact compared to INCONEL 617 (Mayo et al., 2018).

The use of stainless steel reduces GWP by about 60 %. Regarding

resources, the main tank materials (aluminium, stainless steel, and concrete) have a significant impact (Aurelie et al., 2013), while copper mainly affects CPV systems.

Targeted management of structural steel quantities and the adoption of low-carbon alternative materials can significantly reduce overall environmental impact (Yang et al., 2024). Materials such as multi-Si cells, glass, aluminium and polyethylene are particularly critical due to their high sensitivity to environmental indicators (Qi et al., 2024). Furthermore, steel and copper production stages represent the most energy-intensive processes in the entire production cycle (Tursunović and Papurello, 2024).

The impact of achromatic lens (5.48×10^{-4}) and Fresnel lens HCPV systems on aquatic biodiversity is greater than that of mirror systems (4.67×10^{-4}), primarily due to the materials used: copper (65 %) and zinc (22 % on average) (Payet and Greffe, 2019). Although the amount of copper used in the production of cooling tubes and U-shaped support structures in a CPV plant (integrated into a building) is relatively small (about 2 kg), it accounts for 59 % of the total impact (Menoufi et al., 2013). Copper (Herrera et al., 2020), when used in the balance of system (in a CSP system), has a significant impact, contributing approximately 20 % to non-cancer human toxicity. In this section, the materials typically used for photovoltaic cells are not considered, as they have not been explored in the studies selected for this analysis. In any case, material recovery thus proves to be a choice capable of delivering significant environmental benefits (Qi et al., 2025; Costa et al., 2024).

4.6.4. Storage systems, use of salts and heat transfer fluid

The presence of storage affects different environmental impact categories differently, depending on the type of storage, the fluid used and the materials.

In particular, in the study by Ehtiwesh et al. (2016) the storage system accounts for 20 % of the overall impact, compared to other components of the concentrating system.

The study conducted by Adeoye et al. (2014) examined the environmental impacts of two thermal energy storage systems, one consisting of binary salt called Molten salt TES and the other, Concrete TES, consisting of a single concrete tank. The thermal storage system consisting of binary salt generates a lower single score environmental impact than the concrete thermal storage system (48.2 % lower).

The study conducted by Burkhardt et al. (2011) showed that the use of salts extracted from natural deposits has a lower environmental impact in all categories examined than the use of synthetic salts (the use of synthetic salts results in a 52 % increase in greenhouse gas emissions, a 24 % increase in primary energy requirements and a 3 % increase in water consumption).

To mitigate the major environmental impacts associated with synthetic salts, the use of a thermocline storage system is essential, as compared to two-tank storage systems, a reduced amount of salt is expected due to the presence of only one tank.

In addition, the authors showed how the use of a thermocline storage system, compared to the use of a two-tank storage system, reduces greenhouse gas emissions by 7 % and water consumption by 2 %.

What has been stated above demonstrates the importance of using a storage system and the energy and environmental benefits induced by the use of salts extracted from natural deposits. In any case, the adoption of a thermocline storage system turns out to be the strategic choice, even with the use of synthetic salts.

Some approaches (such as improving lifetime or efficiency) have a significantly positive effect on emissions (a reduction of approximately 15 % on GHG), while others (such as increasing storage capacity) may have a negative impact (13 % more on GHG) (Viebahn et al., 2011). For example, in the study conducted by Gasa et al. (2022) the results of the analysis highlighted that the increase in hours of accumulation in a system leads to a reduction in environmental impacts, especially on the categories of resources and human health. However, the increase in accumulation hours determines an increase in the environmental impact

on the ecosystem quality category. This result is likely due to a trade-off between the plant's manufacturing and operational phases. A greater storage capacity increases the impact of the manufacturing phase due to the need for more materials for the TES system. Conversely, it reduces the impact of the operational phase by improving the plant's efficiency and decreasing its reliance on auxiliary power sources. The reduction of the environmental impact in the mentioned categories is more evident when considering a system with a storage capacity between 3 and 9 h, unlike a system with a storage capacity between 9 and 17.5 h, where no significant changes in environmental impact are recorded. When the impact is assessed using the ReCiPe and IPCC methods, the components of the system with the greatest impacts vary as the capacity of the storage system changes. The impact assessment (conducted using ReCiPe) shows that as the storage capacity increases, the percentage contribution of the solar field decreases while that of the storage system increases (Gasa et al., 2022).

A plant consisting of a storage system has also been shown to reduce the total environmental impact on all the damage categories examined, as demonstrated in the study conducted by Gasa et al. (2021), in which the plant without storage results in a greater total environmental impact (about 46 % greater) in the damage categories (human health, resources, and ecosystem quality) than the plant using an energy storage system.

In order to achieve a higher storage density, some authors have examined the environmental performance of Thermochemical Energy Storage (TCES).

With a particular configuration (turbine integration), the results of the study conducted by Pelay et al. (2020), showed a reduced impact on both GWP (between 6 % and 9 %) and in terms of energy return, compared with the other proposed alternatives (mass integration and thermal integration).

The TCES impacts of tower plant are dominant on the following impact categories: respiratory inorganics (about 50 %), terrestrial ecotoxicity (about 60 %) and mineral extraction (about 85 %), due to the use of CaO/Ca (OH)₂ in the system (Pelay et al., 2020).

Solar power cannot provide continuous electricity generation without an energy backup system.

In this context, Klein and Rubin (2013) evaluated the greenhouse gas emissions, water consumption and direct land use associated with power generation by CSP plants with dry cooling, wet cooling and three energy backup systems.

Systems with minimal backup generated lower lifecycle greenhouse gas emissions and lower direct water consumption than systems with TES and natural gas. Dry air-cooled systems produced slightly higher GHG emissions but lower water consumption (71–78 %) and similar land use compared to water-cooled systems. GHG emissions from systems using natural gas are 4–9 times higher than those from TES systems, while land use impacts in natural gas systems are 14 % lower than those from TES systems (Klein and Rubin, 2013).

Commonly, the impact of the storage system is evaluated together with the heat transfer fluid. The presence of a storage system and HTF determines 48 % of the impact on GWP (Gasa et al., 2021). The component of the HTF-TES system that causes the greatest total environmental impact in terms of score is the nitrate salt (84 % without storage and 90 % with storage) (Gasa et al., 2021).

In the study conducted by Batuecas et al. (2017), it was found that Hitec® salt compared to binary salt is the heat transfer fluid with the lowest environmental impact and that, in any case, both salts cause less environmental impact, especially in the human toxicity categories, than synthetic oil (Therminol® oil was used in the specific case).

Molten salt concentrating power plants have a lower environmental impact than both oil-fired and gas-fired plants (Piemonte et al., 2011). Additionally, using molten salt as the heat transfer fluid enables it to achieve higher operating temperatures than synthetic oil, thereby enhancing the efficiency of the thermal storage system. Although TES is a relevant component both from an environmental and an energy

performance perspective, the system can be optimized through the use of recycled materials, the selection of lower-impact fluids and more efficient design.

4.6.5. Hybrid systems

The hybrid (the integration, using different inputs of natural gas or using coal, fuel oil, biomethane, wood pellets, wheat straw, into the CSP system to support power generation) or non-hybrid operation of the plant is another aspect to consider when evaluating the energy and environmental performance of a concentrator plant. It is important to emphasize that, in the context of hybrid systems, studies focus exclusively on CSP systems.

It has been shown that operating the plant in hybrid mode results in a worse environmental impact on some categories than operating the plant without natural gas. The results can be summarized as follows:

1. The hybrid operation of the plant with various percentages of natural gas input (from 0 % to 35 %) showed a dual result (Corona et al., 2014). If on the one hand burning natural gas leads to a worsening of some impact categories such as climate change, land transformation, depletion of fossil fuels and terrestrial acidification, on the other hand, on some impact categories it has a beneficial effect: the environmental impact on human toxicity, marine ecotoxicity and freshwater eutrophication was reduced. This benefit is due to the fact that using natural gas increases electricity production, which improves the overall efficiency of the system;
2. Corona and San Miguel (2015) evaluated the environmental impacts of a CSP plant hybridized with 12 % of the following fuels: coal, natural gas, fuel oil, biomethane, wood pellets, and wheat straw. The results indicated that the hybrid plant's environmental performance was worse compared to its operation without fossil fuels. In any case, among the scenarios proposed by the authors, the renewable fuels scenario represents the best one. Using a single weighted indicator for evaluation, the environmental impact of renewable fuels is approximately half of the environmental impact in the renewable fuels scenario fossils. For example, the hybrid scenario with the lowest climate change impact is wheat straw (34.2 kgCO_{2eq}). The highest impacts are attributable to the use of coal (187 kgCO_{2eq}) and fuel oil (159 kgCO_{2eq}). Also for the acidification category, the highest impact is caused by the use of coal and fuel oil (1686 gSO_{2eq} and 1024 gSO_{2eq} respectively). These impact differences are driven by several factors. For greenhouse gas emissions, the higher impacts of fossil fuels are primarily due to combustion related emissions. In the biomethane scenario, some methane leakage occurs during the upgrading process (from biogas to biomethane). Regarding acidification, the high impacts observed in both the coal and fuel oil scenarios are mainly attributable to emissions produced during power plant operation;
3. The plant with a hybrid configuration that uses biomethane generates a lower total (normalized) environmental impact on all impact categories (with the exception of the marine ecotoxicity, human toxicity and water stress) compared to the hybrid configuration with natural gas (Corona et al., 2016a). This result is particularly evident for climate change (27.9 kgCO_{2eq} with the use of biomethane and 294 kgCO_{2eq} with the use of natural gas), terrestrial acidification (the use of biomethane causes 466 gSO_{2eq} compared to the use of natural gas, which causes 694 gSO_{2eq}) and cumulative energy demand (biomethane use results in 1159 MJ, while natural gas results in 6344 MJ). Identical results were obtained, on the other hand, in the case of water eutrophication (14.4 gP_{eq}). Considering a CSP plant (Corona et al., 2016b), where natural gas is used to increase the thermal energy of the HTF through an auxiliary boiler, the hybrid scenario involving natural gas usage shows an increase in emissions for GWP, terrestrial acidification and cumulative energy demand (392 kgCO_{2eq}, 891 gSO_{2eq}, 8484 MJ);

4. A plant, evaluated in both solar mode and hybrid configurations with different fuels, was studied by San Miguel and Corona (2014). The system in solar mode has better energy and environmental performance than the hybrid mode. In particular, hybrid operation results in decline in the environmental performance of the plant in the following categories: terrestrial acidification (215 gSO_{2eq}/MWh), natural soil transformation (0.020 m²/MWh), fossil depletion (48.4 kg oil eq/MWh) and climate change (124 kgCO_{2eq}/MWh).

Regarding solar operation, there is evidence of a reduction in the impact: 166 gSO_{2eq}/MWh for terrestrial acidification, 0.005 m²/MWh for natural soil transformation, 9.29 kg oil eq/MWh for fossil depletion, 26.7 kgCO_{2eq}/MWh generated for climate change. It has been observed that hybridization of CSP with natural gas results in a significant transformation of the environmental and economic profiles of CSP technology. The operation in hybrid mode leads to an increase in operating costs, mainly due to the consumption of natural gas and water. However, these additional costs are offset by higher revenues resulting from the increased electricity production, thanks to the use of natural gas to improve the system's efficiency (Corona et al., 2016c).

4.6.6. Geographical location of the plants

The geographical location of the plants significantly affects environmental performance mainly due to the strong differences in solar radiation, the electricity mix, the distance between component and material and the plant installation site. Among the countries where the analyzed solar concentrators are located, Spain is the country with the most installations, followed by Italy, in particular Sicily. Furthermore, there are plants located in various regions of the world, including Asia, Africa, Europe, North America and South America. Studies have analyzed a range of cities with very different characteristics. This approach revealed a wide range of environmental impacts, emphasizing how the peculiarities of each city, significantly influence the results. The diversity of urban settings examined provides a comprehensive overview of the variables that contribute to the observed environmental impacts: for example the efficiency of a solar concentration system would be lower in northern locations (due to the reduced amount of direct solar radiation) such as London, compared to cities like Shoubak - Saudi Arabia, where energy payback times are significantly lower (2.8) compared to London - UK (10.1) (Cucumo et al., 2012). In the case of a CSP system, for the examined categories, Saudi Arabia, followed by Chile, are the cities with the greatest impact (especially during the extraction phase) compared to Spain and Mexico (between 12 % and 17 % higher impact for each category) (Corona et al., 2016a). A study by Viebahn et al. (2011), compared greenhouse gas emissions from a CSP plant (virtual) located between Spain and Algeria. The results show a reduction in emissions over time:

- In Spain emissions decrease from 33.4 gCO_{2eq}/kWh (calculated in 2011 with solar-only operation) to 20 gCO_{2eq}/kWh in 2050;
- In Algeria, emissions drop from 30.9 gCO_{2eq}/kWh in 2011–18 gCO_{2eq}/kWh in 2050.

The difference in emission values between Spain and Algeria is due to the better solar irradiation conditions in Algeria.

Referring to a CPV system and the avoided CO_{2eq} emissions, higher values are estimated for Dublin - Ireland and lower values for Paris - France (Lamnatou et al., 2015) and Barcelona - Spain (Lamnatou et al., 2016). Furthermore, Barcelona is the city with the lowest energy payback time (from 3.6 to 5.8 years), while for Exeter - UK and Dublin, the payback time varies from 3.7 to 7.8 years. Among the studied cities, Barcelona, Marseille - France and Seville - Spain have the lowest impact on GWP and primary energy demand, compared to London, Paris and Aberdeen - UK (Lamnatou et al., 2017). The geographical location in which the systems are located also influences the water consumption and EPBT. In detail, in the study conducted by Corona et al. (2016a), the

authors highlighted that the water requirement for washing mirrors is influenced by meteorological and geographical factors. Water stress values are higher in Saudi Arabia and Chile due to the desert nature of the land where the plant is located. The water stress indices associated with Saudi Arabia, Chile, and Spain are very similar due to the limited availability of water resources (1–1–0.99, respectively). The various cities are characterized by local differences specific. Therefore, when making comparisons between different cities, these local differences limit the possibility of making direct and accurate comparisons, as conditions vary from one place to another. For a 3D CPVD system, the analysis conducted on six different cities (Bangkok, Mexico City, Cairo, Beijing, Rome, and Moscow) shows that, in most cases, the EPBT is less than 10 years (Zhang et al., 2022). In a solar tower CSP, the highest Energy Payback Time is in Dunhuang (4.88 years) and Tibet (3.92 years), while it is lower in Algeria (3.30 years) and Egypt (3.19 years) (Yang et al., 2024).

5. Discussion

The studies examined provided a wide range of results, which highlight the different methodological choices made by the authors. A detailed analysis was conducted on the selection of study objectives, functional units and system boundaries. In detail, a cradle to grave approach was chosen for most of the studies, in contrast to the choice of functional unit where it was not possible to identify an unambiguous choice.

A comparison was made, where possible, between studies in which the authors adopted similar choices, particularly with reference to functional unit and system boundaries.

It is important to note that this conclusion is based on an analysis of a limited number of studies comparing CPV and CSP systems. The study also evaluated the impact of geographic location on the environmental performance of the plants, focusing mainly on solar irradiance, which plays a crucial role in determining the emissions attributable to the plants.

In light of this, comparisons should ideally be made between cities with similar environmental and climatic conditions. This approach would allow for more accurate and representative results, ensuring that the comparison reflects real performance under comparable circumstances.

The differences highlighted in the studies, although they made a comparison difficult, allowed for the evaluation of secondary aspects that are sometimes overlooked. For example, the variety in the methodological choices, functional units and system boundaries adopted by the authors of the studies allowed for a clearer picture of the

environmental performance of the analyzed systems, thereby facilitating the identification of areas for improvement in these aspects, which might otherwise go unnoticed in a preliminary analysis. The following table (Table 8) summarizes the main environmental hotspots identified in the literature, together with methodological guidelines, recommended actions, and the expected benefits in terms of environmental performance.

With the advancement of 3D reconstruction technologies, several recent studies have shown that these can be successfully applied to the Life Cycle Assessment of photovoltaic systems, enabling more accurate material quantification and detailed system modelling (Li et al., 2025a, 2025b). In the future, the use of 3D reconstruction methods could also be extended to CPV systems, improving the precision of component-level inventories and facilitating system-specific environmental assessments for each installation. However, it is important to highlight that the limited number of available studies represents a significant constraint. The literature on CPV systems remains scarce, both in terms of the number of studies conducted and the variety of configurations analyzed. For this reason, further LCA studies specifically focused on CPV systems are needed, using consistent and detailed methodological approaches, in order to strengthen the robustness of the data and enable more reliable comparisons between different technologies and configurations.

6. Conclusions

This article describes a review of the scientific literature with special reference to the applications of LCA methodology to concentrating solar power systems and concentrating photovoltaic systems.

The methodology adopted resulted in the collection of 76 articles, of which 52 were selected. Most of the selected studies were published between 2009 and 2025.

The comparative analysis between tower CSP systems and high-concentration CPV systems showed that both are low-carbon solutions, with a slightly greater environmental advantage for tower CSP systems. However, it is important to note that CSP systems account for approximately 83 % of the systems examined in this analysis, significantly influencing the predominance of the results obtained.

In addition to CPV systems, further investigation is needed on both dish-Stirling and Fresnel technologies, particularly within the CSP field. The comparison between different concentrating solar technologies is currently hindered by significant differences in key aspects, such as technological configurations and material choices. Therefore, it will be essential to reduce these gaps in future research, as this will lead to more meaningful comparisons and a clearer understanding of the strengths of each technology. Future studies should adopt more uniform

Table 8
Summary of the environmental hotspots identified in the analyzed studies and the proposed strategies for their mitigation.

Hotspot Category	Guideline	Recommended Action	Benefit or environmental impact
Life Cycle Phase	Impacts are concentrated in specific phases, with significant heterogeneity in results.	Production/Construction: focus on material production and assembly, as they are the most impactful phases (e.g., Tower CSP, CPV).- Operation: reduce the use of auxiliary fuels in hybrid systems. End-of-Life: implement recycling of materials like steel and glass to reduce EPBT.	Production can account for almost all environmental impacts. Hybrid operation worsens impacts on GWP and acidification. Recycling can reduce EPBT from 11 to 4 years.
Plant Components	The configuration of concentrating systems has a significant influence on overall impact.	Solar Field: reduce the impact of the steel structure and mirrors. Photovoltaic Cells: improve the production efficiency of concentrating cells. Storage Systems (TES): optimize the choice of materials for tanks and salts.	The solar field can contribute 30–79.5 % of the total impact. CPV cells and concentrators are responsible for most of the embodied energy and carbon emissions. TES systems reduce operational impacts but increase production impacts.
Construction Materials	The use of specific materials such as steel, copper, and salts strongly affects environmental performance.	Steel/Copper: manage quantities and use low-impact materials. Salts/Fluids: prefer salts extracted from natural deposits over synthetic ones and adopt single-tank systems.	Steel accounts for 54 % of GWP. Copper is a hotspot human toxicity (n-c). The use of synthetic salts results in a 52 % increase in greenhouse gas emissions
Hybrid Systems	Hybrid operation worsens the impact in some categories compared to solar-only mode.	Substitute fossil fuels: use biomass (e.g., biomethane, straw) instead of natural gas or coal. Carefully evaluate percentages: monitor the share of auxiliary fuel to avoid compromising the environmental balance.	Hybrid configuration worsens environmental performance in terms of climate change, acidification and fossil fuel consumption. Renewable fuels can reduce impacts to about half compared to fossil fuels.

methodological choices (with reference to the selection of the functional unit, system boundaries, and impact categories) to facilitate the identification and evaluation of the energy and environmental impacts of different CSP or CPV systems. This approach will contribute to the development and optimization of these technologies, ensuring more reliable and easily comparable results.

CRedit authorship contribution statement

Maria Laura Parisi: Writing – review & editing, Validation, Supervision. **Adalgisa Sinicropi:** Writing – review & editing, Validation, Supervision. **Roberta Rincione:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Sonia Longo:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Federico Rossi:** Writing – review & editing, Validation, Supervision. **Maurizio Cellura:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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