Renewable Energy 249 (2025) 123203

Contents lists available at ScienceDirect

Renewable Energy

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

A review on life cycle assessment of concentrating solar energy technologies

Maurizio Cellura, Le Quyen Luu [*], Francesco Guarino, Sonia Longo

Department of Engineering, University of Palermo, Viale delle Scienze Ed.9, 90128, Palermo, Italy

A R T I C L E I N F O

Keywords:
Concentrating solar technology
LCA
Eco-design
Solar power
Solar thermal

A B S T R A C T

Solar energy technology is identified as one of the most important contributors to the decarbonization of the energy system and the economy, which requires the further development of these technologies with higher efficiency, and lower environmental impacts. The paper systematically reviews the energy and environmental impacts and costs of concentrating solar technologies, applying the life cycle approach. The concentrating solar technologies are described technically, which is followed by an analysis of life cycle assessment methods being currently applied in this context. The life cycle energy requirement, greenhouse gas emissions, resource consumption, other environmental impacts and costs of the technologies are reviewed by the types of technologies and the choice of assessment methods. The obtained findings show that the lower cumulative energy demand (CED) and global warming potential (GWP) of concentrating solar power (CSP) and high concentrating solar photovoltaics in high solar radiation areas, while higher CED and GWP of CSP and concentrating solar thermal hybridized with fossil fuels. Furthermore, it is indicated through the dominance analysis that construction, material extraction and manufacturing are the largest contributors to the single endpoint impact. For specific midpoint impacts, the hotspot lies in manufacturing (for energy demand, material depletion and ecotoxicity), operation (for GWP) or both of these stages (for water consumption). Disregards of stages, the solar concentrator is the component causing the largest share of several midpoint impacts such as energy demand, GWP, material depletion and ecotoxicity. In term of costs, the levelized cost of energy from CSP system tends to decrease thanks to the reduction in solar concentrator cost, and the combination of CSP and PV brings the lowest cost with reduced GWP.

1. Introduction

Energy transition pathways require the increased deployment of solar technologies, both solar photovoltaics (PV) and concentrating solar power/concentrating solar thermal (CSP/CST). It is estimated that in order to limit the average global temperature increase at 1.5°C, the global annual investment into solar PV needs to increase from 130 billion USD to 333 billion USD by 2050, and that of CSP technologies shall increase from 1 billion USD to 89 billion USD by 2050 [1]. At the end of 2023, solar PV provided 8.3 % of global electricity demand, with 1.6 TW of installed capacity [2], while the global CSP's installed capacity was 6.5 GW as of July 2023 [3]. By 2050, these solar energy technologies will contribute to 20 % of the global energy supply, in which solar PV and CSP provides more than 23 PW h (petawatt hour) and 1.3 PW h, respectively, being equal to 35 % of the global electricity generation, totally [4].

With the increased share and installation capacity of solar energy technologies, it is expected that more resources are required for these technologies. On one hand, the demand for resources causes the risk of material (energy, and other resources) shortages for manufacturing these technologies themselves. On the other hand, there is a concern about natural resources for manufacturing the (intermediate) components and infrastructure that support the development of solar energy technologies. Besides, the development of solar energy technologies will somehow cause some environmental impacts. Therefore, it requires a comprehensive methodology such as Life Cycle Assessment (LCA) to quantify and assess the potential environmental impacts of solar energy technologies, covering from the material extraction to the end of life of the technologies. This concept is even more important in the case of innovative solar energy technologies, in which the innovative

---

* Corresponding author.
E-mail addresses: maurizio.cellura@unipa.it (M. Cellura), lequyen.luu@unipa.it (L.Q. Luu), francesco.guarino@unipa.it (F. Guarino), sonia.longo@unipa.it (S. Longo).

https://doi.org/10.1016/j.renene.2025.123203
Received 25 August 2024; Received in revised form 29 March 2025; Accepted 18 April 2025

technologies are deemed to be more efficient and deliver higher capacity, while it is unclear on the resource use and environmental impacts of the new technologies.

LCA quantified and assessed all potential impacts on the land, water and air from different stages of a product or service life cycle, from the exploitation of natural resources for materials and energy, material processing, component fabricating and product manufacturing, product use and waste treatment or recycle of unused product. Thanks to the comprehensive coverage of LCA, no impact will be missed or accounted for the incorrect life cycle stages [5]. With the application of LCA in concentrating solar technologies, various impacts of the technologies over its whole life cycle can be assessed considering the current context of climate risk, global temperature rise and resource shortage.

LCA and concentrating solar technologies have been studied and reviewed in several papers. Some papers studied the performance of a specific concentrating solar technologies technically, such as energy (or technical) analysis of CST [6], of Fresnel collector to provide hot air for industrial [7], of CSP [8], of CSP hybridized with natural gas [9], and of compound parabolic concentrator [10]. Others studied the life cycle environmental impacts of a particular solar related technology such as photovoltaics thermal system [11], solar gas turbine [12], hybrid water chiller and vacuum tube system [13], hydrogen from CSP [14].

Besides, various technologies for exploiting solar heat, including CST have been reviewed [15]. This paper reviewed the technical aspects of CST, with a clear description of its industrial applications and advancement of the components. Another review focused on the technical aspects of solar thermal technologies, providing the pathway of technology development, the rate and the stage of their maturity [16].

Two other review papers considered both technical and environmental aspects of concentrating solar technologies [17]. reviewed the environmental profiles of concentrating photovoltaics (CPV) and CSP and identified that the CPV environmental profiles are affected by the concentrators' materials and solar radiation. Besides, those of CSP depend on storage's material and water use. The review highlighted the importance of energy and greenhouse gas (GHG) related indicators as well as suggested the adoption of various life cycle impact assessment methods for a better understanding of the technologies' environmental profiles. Meanwhile, solar thermal technologies and their corresponding environmental impacts were studied in Ref. [18]. The authors pointed out that the lowest GHG emissions come from the parabolic trough, followed by linear Fresnel, solar dish, and solar tower.

The existing reviews covered the technical aspects of the technologies, while limited reviews were conducted on both technical aspects and relevant life cycle environmental impacts. In such cases that both technical and environmental aspects of CSP are studied, the most attracted environmental impact is GHG emissions, with limited studies on other environmental impacts. At the same time, the quantitative values of the life cycle environmental impacts of the technologies were not clearly reviewed. Therefore, the innovation of the paper has three points: (1) presenting the comprehensive environmental profiles of concentrating solar technologies; (2) reporting the quantitative results, with some comparisons, and links between the technological characters and their life cycle environmental impacts, and (3) conducting the economic analysis of concentrating solar technologies from life cycle thinking perspective.

This paper aims to provide a critical review of the various life cycle environmental impacts of concentrating solar technologies. The assessed impacts include those related to energy, GHG, resource (land, water and material) consumption and other life cycle environmental impacts such as acidification, eutrophication, ecotoxicity and human toxicity. Moreover, these life cycle impacts are discussed and analysed with some statistical evidence. The dominant stages/components which contribute the most to the whole life cycle impacts of the technologies are identified for each impact category. Finally, the economic aspects of CSP technologies are further studied and reviewed. All this information can be used by energy and environment engineers, as well as policy makers who aim at the eco-design of concentrating solar technologies with higher energy outputs, lower economic cost, and better environmental profile.

The next section will describe the research method with a logical flow and a detailed review procedure. The result section provides five pieces of information (1) different concentrating solar technologies, and categorizing them by types of receiver, heat transfer fluid (HTF), and thermal energy storage (TES), (2) life cycle methodological aspects of the LCA studies, as the selection of functional unit, system boundaries, and life cycle impact assessment method may induce diversity in the obtained results, (3) the life cycle environmental impacts of the concentrating solar technology, (4) the identification of hotspots during the life cycle of the technologies and (5) an economic assessment of concentrating solar energy technologies. The paper ends with a brief discussion, policy implications, and a summary of the main results in the conclusion section.

2. Materials and methods

The five steps for conducting a systematic review, as suggested in Ref. [19] are applied in this paper. Fig. 1 presents the logical flow of how the review has been developed. Starting from the rationale for conducting the review, all the existing review papers are searched for and studied to find out the literature gap and prepare a list of research questions. In the second step, the keywords, timeframe and other rules for searching for relevant studies are defined. The search and selection of reviewed articles follow the guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2000 [20,21]. Then, the information regarding the methodological aspects of reviewed articles such as product systems, system boundaries, functional units and impact categories of LCA studies are extracted and analysed in the third step, following the FLAVIA framework for conducting a systematic literature review from life cycle thinking studies [22]. Finally, the extracted data on technologies, environmental impacts and hotspots of concentrating solar technologies will be synthesized and interpreted in steps four and five.

The search for literature on the Science Direct database with keywords such as “concentrating solar power”, “CSP”, “concentrating solar thermal”, “CST”, “life cycle assessment” and “LCA”. Specifically, the search keywords “CSP or concentrating solar power and life cycle assessment or LCA” gave 142 research articles from 2010 to 2023, and the keywords “concentrating solar thermal or CST and life cycle assessment or LCA” gave 10 research articles from 2008 to 2022. The Science Direct database is selected because it is evaluated to be a suitable database for systematic review and meta-analysis [23], with more than 2650 journals and 43 thousand e-books [24].

An additional search was conducted in July 2024 to on Scopus database, which includes around 29 thousand indexed journals [25]. The search has double objectives, which are to update the studies from 2023 until now, and to extend the publication coverage to more diverse indexed journals and publishers. The search with “CSP or concentrating solar power and life cycle assessment or LCA” keywords in the articles' titles, abstracts and keywords indicates 116 documents, while the search with “concentrating solar thermal or CST and life cycle assessment or LCA” indicates 40 documents.

In March 2025, the search was extended to include studies on life cycle environmental impacts of CPV systems, with the keywords of “concentrated photovoltaics CPV life cycle” on Science Direct database. 718 publications were obtained, including 336 research articles. The screening of these articles titles and abstracts indicated that the majority of them are on the technical performance of CPV [26,27]. Sometimes, the studied system is named as CPV, but there is no solar concentrating mirror or reflector, but integrating a tracking system to increase the concentration of a PV system [28], using nanofluid based for concentrating solar energy [29]. Such systems are out of scope of the review paper. At the end of the search and selection of articles, only two articles

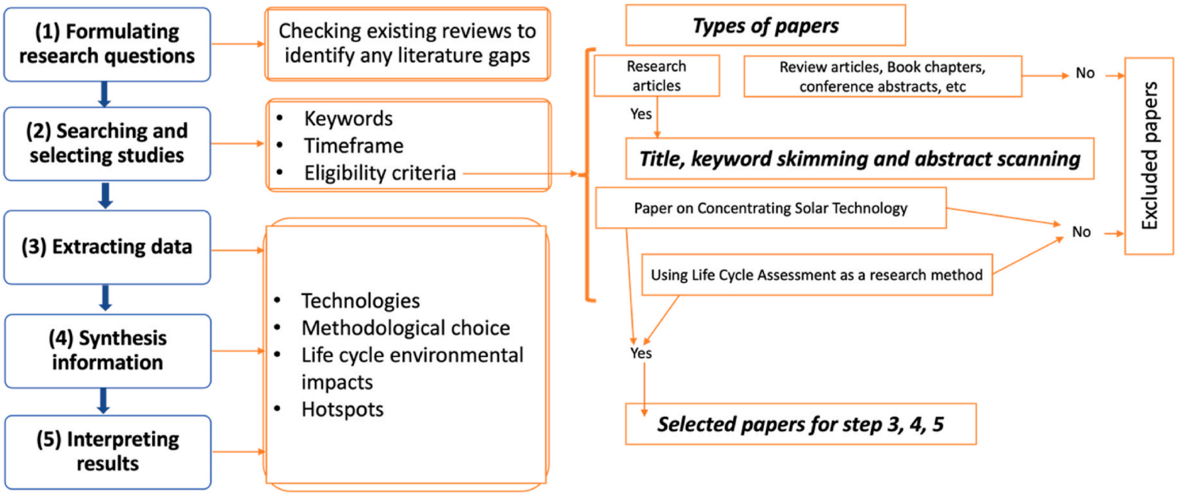


Fig. 1. Logical flow within the review development.

which reported the life cycle environmental impacts of CPV systems, were added to the review paper.

The documents obtained from both databases are skimmed, screened and selected if they are either research articles or case studies on concentrating solar technologies and using LCA methods. The reviews are not included for quantitative analysis, but it was cited and referred in the review in order to identify any literature gap. Books (and book chapters) were excluded as it is difficult to access to this type of literature. Conference papers were included in the review, but conference abstracts were excluded, as data from conference abstracts is insufficient for quantitative analysis of life cycle environmental impacts, and qualitative analysis of applied LCA methodological aspects such as functional unit, system boundary, life cycle impact assessment methods, environmental indicators, etc. At the end of the skimming and screening processes, 47 papers on concentrating solar technologies and LCA are selected for extracting data. The full texts of these selected papers are read and extracted for the following information, including:

- description of the concentrating solar technology,
- description of the life cycle assessment methodology, and
- report of life cycle environmental impacts
- identification of hotspots
- economic analysis/assessment

3. Concentrating solar technologies

Concentrating solar technologies can be utilized to generate electricity (CSP), heat (CST) or combined with solar PV (CPV) to generate both electricity and heat. Although CPV systems, by definition, do not generate heat, they frequently capture waste heat for latter applications. A concentrating solar system (CSP and CST) generally includes a solar collector system, HTFs, a TES and a power generation block (as illustrated in Fig. 2). The most important component of the solar collector system is the receiver or mirror. Sometimes, concentrating solar technologies are classified based on the types of receivers, for example, parabolic trough and linear Fresnel (or Fresnel trough/lens/reflector) are line focusing, while parabolic dish (or solar dish/mirror/reflector) and solar tower (or concentrating tower) are point focusing. The solar collector system concentrates the solar radiation which is then transported by the HTFs. There are several types of HTFs such as water, oil

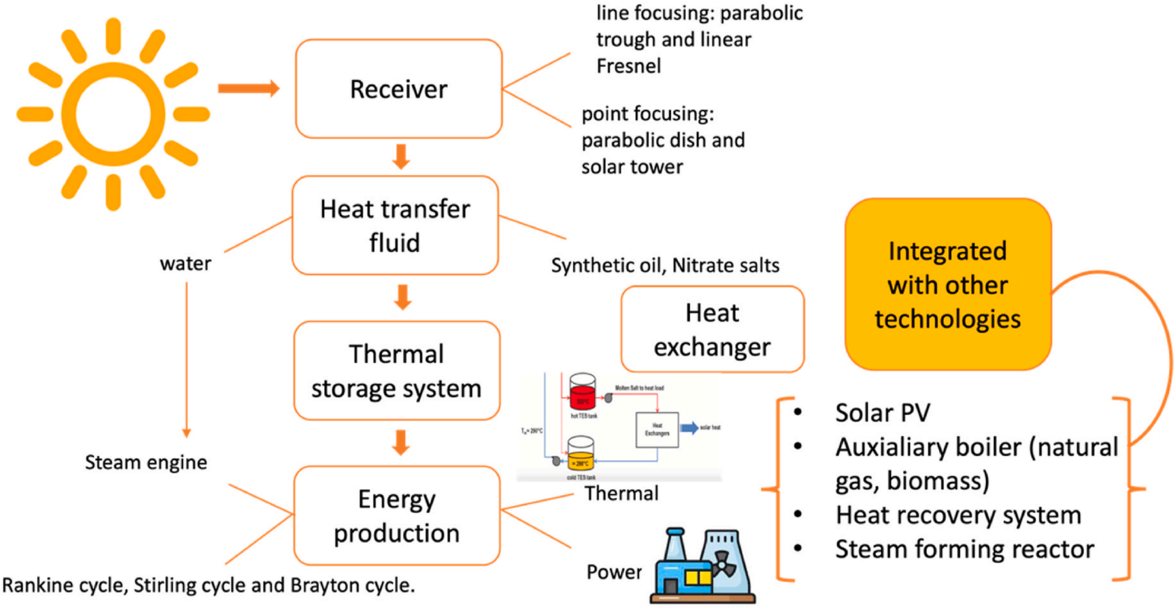


Fig. 2. Concentrating solar technologies.

and molten salts. The hot water, as an HTF, can be used to drive the steam engine and generate electricity. If the HTFs are molten salts, either mined nitrate salts or synthetic salts, a heat exchanger is required to generate superheated steam. In any case of HTFs, the steam engine, for examples Rankine cycle, Stirling cycle or Brayton cycle, is utilized to generate electricity.

3.1. Stand-alone concentrating solar technologies

In the reviewed case studies, different configurations have been assessed for their life cycle impacts (as specified in Table SI1). These configurations are both commercial and non-commercial systems, and the commercialization of the systems does not affect the analysis of their life cycle environmental impacts and costs. Considering the types of receivers, parabolic trough and solar tower are the most common receivers, with 13 papers studying parabolic trough, 12 papers studying solar tower, and five papers studying both types of receivers. This is reasonable as most of global CSP plants are based on either parabolic trough and solar tower, in which 70 % of currently operating CSPs are based on parabolic trough and 20 % are based on solar tower, with installed capacities of 4.46 GW and 1.31 GW, respectively [30,31].

In term of HTF or working fluid, water is normally used in conventional configurations for heating purpose, or to supply hot water. This conventional design may not require a lot of materials such as the concentrating solar system in Ref. [32] which is combined with solar PV panels, uses water as the working fluid, and there is no need for chemicals for HTF or TES. In this system, solar energy is collected by parabolic trough mirrors and reflective panels. The solar heat is transferred by a system of water tubes. This plant includes a support structure and a solar tracking system, but does not include TES [32]. Some other CPV systems which utilized water as the working fluid [33,34], was integrated with a tank to store hot water and PV modules to generate electricity.

At the same time, a concentrating solar system may utilize synthetic oil/fluid/salts or molten salts as HTFs and TES materials to increase the energy efficiency of the system. More than half of the reviewed case studies were conducted on CSP (or CST) plants with molten salts as either HTFs or TES materials. An example of this system is the solar tower plant, being cooled by air and integrated with a thermal energy storage which is assessed in Ref. [35]. Two types of HTFs have been studied, including mined nitrate salts and synthetic salts [35].

The most common TES is two-tank system including a hot and a cold tank, at different storage capacity. The thermocline tank is less common. For power engine, the most common one is the steam engine, Rankine cycle. Recent studies were conducted on CSP plants based on supercritical CO_2 or CO_2-SO_2 blended, with recompression cycle and Brayton cycle [36,37].

3.2. Hybridization of concentrating solar technologies with others

Sometimes, a concentrating solar system is combined with other technologies to maximize the solar energy potential and increase the energy efficiency. One example is the CPV technology which utilizes CST or CSP systems to concentrate the solar radiation and the PV cells to capture the solar irradiation. Common concentrating solar receivers are parabolic troughs and lens, while the most popular PV cells are crystalline silicon or thin films. The technical performance of hybrid CSP and PV plants were studied in the literature, indicating some evidence on the improvement of their performance compared to CSP alone. Vossier et al. studied the use of photovoltaic mirror acting as solar cell and reflector, and found that this system generated 50 %–130 % more electricity output compared to CSP [38]. Another study on THEMIS CSP plant in France indicated that both the daily or annual performance of hybrid system are higher than those of conventional plant, with energy gain from 20 % to 55 % higher, depending on pessimistic or optimistic scenario [39]. However, the choice of materials for balancing the electricity conversion of PV and CSP in different temperature conditions should be further studied [38]. In practice, the combination of CSP and PV is the technology development trend at commercial scale, as 7 out of 10 CSPs being under construction globally, are co-located with PV plants, with the total capacities of 1.16 GW of CSP and 2.09 GW of PV [30,31].

In the reviewed case studies, the hybrid configuration is available for both low and high concentration ratios. At a low concentrating ratio, CPV technologies are applied or integrated into a building. These CPV technologies increase conversion efficiency [40,41], or aims at generating electricity to provide the illumination function [42], or providing both electricity and hot water [34].

The high concentrating CPV technology is frequently applied in power plants, such as those being studied by Refs. [43,44]. In Ref. [43], the environmental profile of a high CPV plant is assessed. This plant is called Amonix 7700, which is a combination of acrylic Fresnel lens and multijunction solar cells with a power conversion efficiency of 37 %. Similarly [44], studied the life cycle environmental impacts of high CPV with four junction GaInP/GaAs/GaInAs/Ge cells mounted on three different concentrating bases, including a mirror, Fresnel lens, and achromatic lens [45]. studied the life cycle impacts of a CPV plant which combine solar tower and multi-Si PV in China [46]. studied the climate change, levelized cost of electricity and levelized cost of heat of energy from CPV over its whole life cycle. In this plant, PV cells are integrated into parabolic trough concentrating solar technologies with a central receiver tube. The CPV system is illustrated in Fig. 3.

Another option is to integrate an auxiliary boiler into the concentrating solar system [47]. The purposes of this boiler are to provide heat for starting up the system, to avoid freezing the HTFs, and to generate additional steam and heat. Both fossil fuels (natural gas (NG)) and biomass-based fuels such as biomethane, biogas and biowaste can be used to operate the boiler [47–50]. An example of NG-fueled boiler can be found in Ref. [48], in which a NG boiler, with different percentages of NG ranging from 0 %, 5 %, 10 %, 15 %, 20 %, 25 %, 30 %, and 35 %, is applied in a parabolic trough CSP plant. Other studies compared the life cycle environmental impacts of CSP plants with NG, biogas provided by a nearby plant and biomethane produced from mixed sources of biowaste, sewage sludge, grass, and animal manure [47], and solar only CSP and hybridized CSP with 12 % of electricity generated by NG, coal, fuel oil, wheat straw, wood pellets and biogas [50].

In more advanced systems, heat recovery system (HRS) is included in CSP plants to further increase efficiency [49,51,52]. In these plants, being called hysol CSP plants, solar radiation reflected by the 9151 heliostats is directed to an external central receiver. The solar thermal energy is then transferred by the nitrate molten salt and stored in the hot tanks of the thermal energy storage. The heat is used to drive the Rankine cycle engine to generate electricity. The remaining heat from the steam engine is stored in the cold tank of the thermal energy storage and transferred to the HRS. The purpose of the HRS is to reheat the HTF which will be transferred back to the hot tank of the thermal energy storage, starting a new cycle [49,51,52]. Thanks to the reusing and recycling of thermal energy, the inclusion of HRS helps to improve the efficiency of the system. Besides, the dispatchability of concentrating solar technologies is enhanced by increasing their storage capacity.

The CSP is integrated with the steam-forming reactor to generate

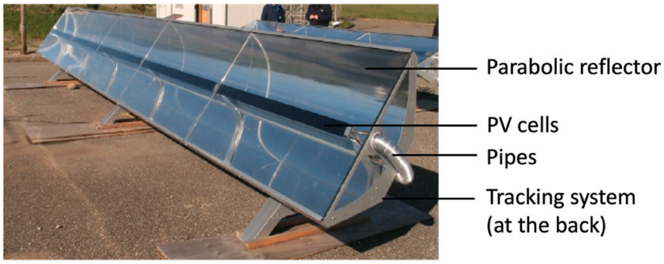


Fig. 3. The CPV system (photo taken at Edificio 9, University of Palermo).

electricity and produce enriched methane for fuel [53]. This hybrid plant consists of a parabolic trough as a receiver, molten salts as HTF and a TES. The heat from hot molten salts is used to run the steam reforming system, while the remaining heat is used to generate electricity. At the end of the process, both enriched methane and electricity can be obtained [53].

4. Life cycle assessment methodological choice

There were 47 LCA case studies on concentrating solar technologies between 2008 and 2024. Most of these studies were conducted in Europe, more specifically 12 papers in Spain, nine papers in Italy and one paper in France. There are several studies being conducted in two or more countries in European such as Belgium, France, Spain and Ireland, and the UK (eight papers). Some other geographical locations being studied include China (four papers), the USA (seven papers) and some African countries such as Lybia, Tunisia and South Africa. These case studies covered three concentrating solar technologies for generating power (CSP), heat (CST) and a combination of concentrating technology and solar PV (CPV), with CSP taking the most advantages (30 papers). CST and CPV were studied in four and 13 papers, respectively. Fig. 4 presents the links between the year of publication, countries, technologies, selected functional units and system boundaries.

With regards to functional units, the most common one is related to power energy, specifically kWh, MWh and GWh, which is selected in 34 papers. This is understandable as most the studies being conducted on CSP. Three case studies even utilized two functional units of kWh (or MWh) and the system at the same time. The impacts were quantified per a system or a plant in five papers. The impacts were also quantified per m^2 and kWp of CPV module in three papers, one of which utilized two functional unit at the same time (m^2 and the system). As mentioned in the previous section, there is a trend of combining concentrating solar technologies with different technologies. For example, the CSP system was combined with a steam reforming system to generate both electricity and enriched methane [53]. Therefore, in this paper, the selected functional units are 0.58 kWhe and 1 Nm3 of enriched methane.

In terms of system boundary, the most common system boundary was cradle to grave, with 31 papers out of 47 papers. Six papers considered the technologies within cradle to gate, and one paper applied several system boundaries, including cradle to grave, cradle to gate (the “ready to install” system), and cradle to use (the “ready to use” system) [54] (which is assigned as ‘cradle to use’ in Fig. 4, because most of the impacts were reported from cradle to use. One paper assessed the technologies within the manufacturing and operation stages and all life cycle stages (cradle to grave) [55] (which is assigned as ‘manufacturing and operation’ in Fig. 4, because these stages decide the difference in the obtained impacts of two comparative technologies), and some papers did not clarify the system boundary.

The assessed impact indicators were diversified in both midpoint and endpoint impact, using various life cycle impact assessment methods. Fig. 5a and b indicate the diversity of selected impact indicators, and impact assessment methods in the reviewed case studies. Seven papers presented the endpoint impacts, either in three endpoints of the ecosystem, resource and human health or in one single endpoint impact of the ecopoint or the total impact. In terms of midpoint impacts, the most common impacts are energy and GHG related impacts, being studied in more than 30 papers. Some energy related impacts are cumulative energy demand, energy payback time, fossil depletion potential, global energy requirement, and primary energy demand. For GHG related impacts, the most common indicator is global warming potential (GWP), and other less common indicators are GHG payback time (GPBT) and CO_2 savings. Other environmental impacts are being studied in less frequency such as water, land, material, eutrophication, acidification, ozone depletion, photochemical oxidization formation, human toxicity and ecotoxicity (around 10 papers).

Regarding life cycle impact assessment methodologies, the most common ones are ReCiPe and methods related to the environmental footprint of the product such as Eco-indicator, Environmental Priority Strategy (in product design) (EDP), Environmental Product Declaration (EPD) and Product Environmental Footprint (PEF), which was applied in 10 and nine papers, respectively (see Fig. 5b). The CML (Centrum voor Milieukunde Leiden) method was utilized in six papers. Methods such as the International Reference Life Cycle Data System (ILCD) and Impact 2000 were less common, being used in two papers each. There are 14

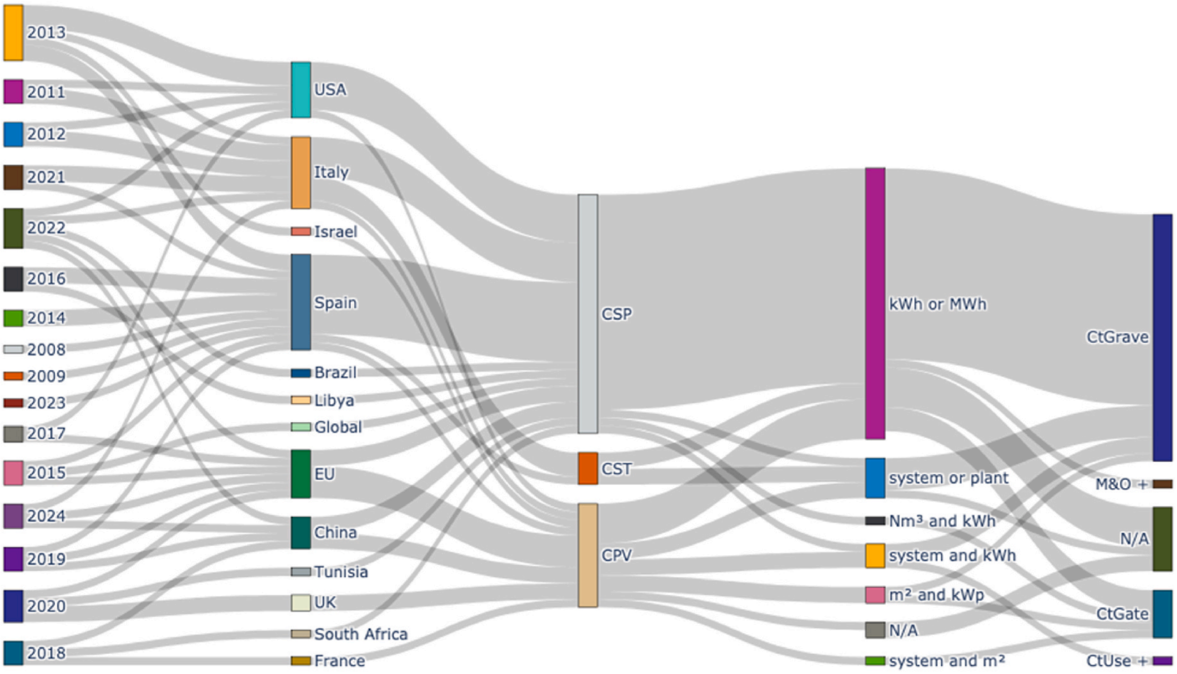


Fig. 4. Distribution of technologies and selected methodological aspects by years.
Notes: UK: the United Kingdom, EU: European, USA: the United States of America, CPV: Concentrating photovoltaics, CST: Concentrating solar thermal, CSP: Concentrating solar power, N/A: not available, CtUse: Cradle to Use, CtGate: Cradle to Gate, M&O: Manufacturing and Operation, CtGrave: Cradle to Grave.

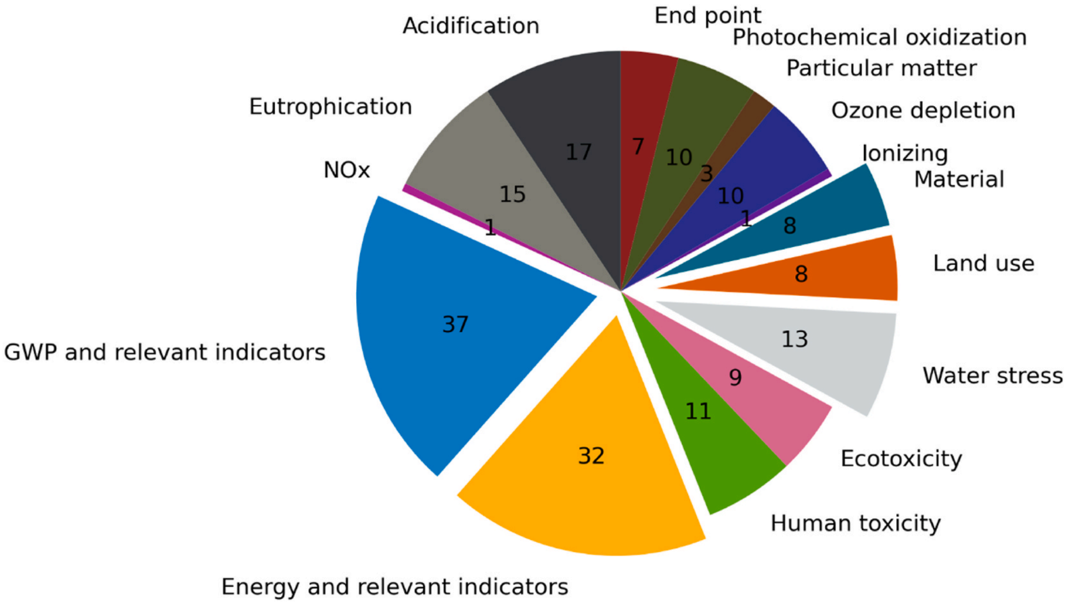


Fig. 5a. Share of impact indicators being studied.

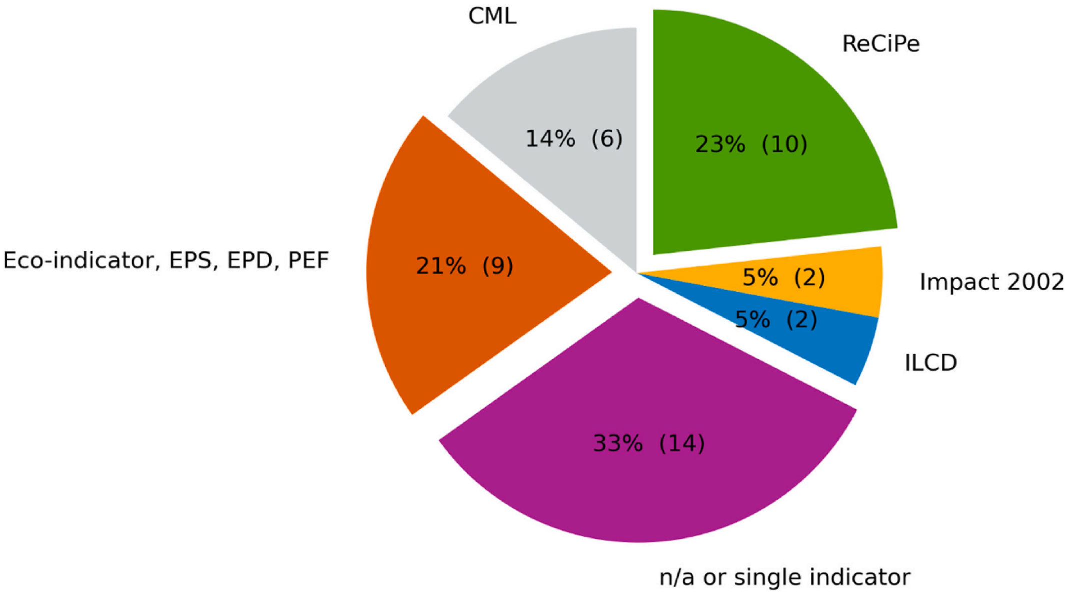


Fig. 5b. Application of impact assessment methods.

papers which did not apply a specific life cycle impact assessment method, but calculated single indicators such as cumulative energy demand, energy payback time, GWP, GPBT, land use, and etc. according to the guidelines of the IEA, International Panel of Climate Change (IPCC) or other guidelines.

Most of the existing studies applied processed-based, attributional LCA approach. The process-based, attributional LCA approach, being used in the reviewed studies complies with the ISO 14040 guidelines, with four fundamental steps of Goal and Scope, Life cycle inventory analysis, Life cycle impact assessment and Interpretation. There is one paper applying both attributional and consequential approaches, and four papers applying hybrid (integrated) approach (combining process-based LCA and environmentally extended input output analysis). Some other methodological choice such as LCA databases and software are not reviewed, as the selection of databases and software does not cause significant impacts in the obtained results. Table 1 summarizes the key characteristics of LCA methodologies reviewed.

5. Life cycle environmental impacts

5.1. Energy related indicators

The life cycle energy consumptions of concentrating solar technologies in the reviewed papers are assessed in terms of Cumulative Energy Demand (CED), Global Energy Requirement (GER), Primary Energy Demand (PED), Fossil Fuel Depletion Potential (FFDP), Energy Payback Time (EPBT), and Energy Return on Investment (EROI). Among these indicators, EPBT and CED are the most common ones, being quantified in 15 and 14 papers, respectively. These two energy indicators are recommended by IEA in conducting LCAs of solar technologies [76,77]. Other indicators such as EROI, FFDP and GER are assessed in one or two papers.

Table 1
Key characteristics of LCA methodologies reviewed.

No	Author	Year	LCA method	Functional Unit	System boundary	LCIA method	Reference
1	Lechon et al.	2008	LCA	kWh	Cradle to grave	CML	[56]
2	Barreiro et al.	2009	LCA	kWh	Cradle to grave	CML and EPBT	[57]
3	Cellura et al.	2011	LCA	the system	Cradle to grave	EPD and EPBT, GPBT	[33]
4	Burkhardt et al.	2011	LCA	kWh	Cradle to grave	N/A	[58]
5	Piemonte et al.	2011	LCA	kWh	Cradle to gate	Eco-Indicator 99, IPCC, CED	[59]
6	Cucumo et al.	2012	LCA	the system	Cradle to grave	Eco-Indicator 99 and EPD 2007	[60]
7	Piemonte et al.	2012	LCA	Nm3 of enriched methane (17 % H2) and 0.58 kWhe	Cradle to gate	Eco-Indicator 99, CML, CED	[53]
8	Fthenakis and Kim	2013	LCA	the system, kWh, MWh, GWh	Cradle to grave	N/A	[43]
9	Whitaker et al.	2013	LCA	kWh	Cradle to gate	N/A	[35]
10	Kuenlin et al.	2013	Hybrid LCA	MWh	Cradle to grave	IMPACT2002+	[61]
11	Desideri et al.	2013	LCA	MWh	Cradle to grave	Eco-Indicator 99 and CML2000	[32]
12	Klein and Rubin	2013	LCA	MWh	Cradle to grave	N/A	[62]
13	Halasah et al.	2013	LCA	the whole system per m2	N/A	N/A	[63]
14	San Miguel and Corona	2014	LCA	MWh	Cradle to grave	Recipe midpoint (and endpoint) EU H	[47]
15	Corona et al.	2014	LCA	kWh	Cradle to grave	Recipe Europe (H and E), CML 2000	[48]
16	Corona and San Miguel	2015	LCA	MWh	Cradle to grave	Recipe, CED, EPBT and 9 environmental categories	[50]
17	Lamnatou et al.	2015	LCA	N/A	N/A	N/A	[40]
18	Gibon et al.	2015	Integrated multiregional LCA	kWh	N/A	N/A	[64]
19	Corona et al.	2016	LCA	MWh	Cradle to grave	Recipe, CED, water stress indexed	[51]
20	Ehtiwesh et al.	2016	LCA	the plant	Cradle to grave	Eco-indicator 99 endpoint and exergetic analysis	[65]
21	Corona et al.	2016	LCA	MWh	Cradle to grave	Recipe midpoint H, CED, water stress index	[52]
22	Corona et al.	2016	Life cycle costing	MWh	Cradle to grave	Monetization of environmental impacts	[66]
23	Lamnatou et al.	2017	LCA	kWh	Cradle to grave	CED, IPCC, Recipe endpoint H Eu, Ecological footprint, USEtox, Eco-Indicator 99 H	[42]
24	Telsnig et al.	2017	LCA	kWh	n/a	n/a	[67]
25	Lamnatou and Chemisana	2017	Review				[17]
26	Ko et al.	2018	LCA	kWh	Cradle to grave	CML 2001	[68]
27	Lamnatou et al.	2018	LCA	N/A	N/A	CED, IPCC, Recipe Ecological footprint and USEtox	[34]
28	Payet and Greffe	2019	LCA	kWh	Cradle to grave	ILCD Midpoint 2011, IPCC 2007	[44]
29	Corona and San Miguel	2019	Integrated hybrid LCA	MWh	Cradle to grave	Recipe European H, CED v9, water stress index	[49]
30	Li et al.	2019	LCA	kWh	N/A	N/A	[69]
31	Kumar et al.	2019	Review				[15]
32	Pelay et al.	2020	LCA	MWh	N/A	IMPACT2002+	[70]
33	Herrera et al.	2020	LCA	MWh	N/A	ILCD 2011 midpoint	[71]
34	Zawadzki et al.	2020	LCA	N/A	N/A	EPBT, EROI	[41]
35	Backes et al.	2021	LCA	the system, MWh	Cradle to use, cradle to gate	CML 2001	[54]
36	Gasa et al.	2021	LCA	kWh	Cradle to grave, manufacturing and operation	Recipe and IPCC2013	[55]
37	Agostini et al.	2021	LCA	kWh	cradle to gate	GWP, ODP, AP, EP, PCOP, ABP, PED non renewable	[72]
38	Rangarajan et al.	2022	LCA	MWh	N/A	N/A	[73]
39	Liao et al.	2022	LCA	MWh of net electricity	Cradle to grave	N/A	[36]
40	Xiao et al.	2022	LCA	N/A	N/A	N/A	[37]
41	Dehghanimadvar et al.	2022	Review				[16]
42	Gamarra et al.	2023	LCA	MWh	Cradle to grave	N/A	[74]
43	Gobio-Thomas et al.	2023	Review				[18]
44	Qi et al.	2024	LCA	kWh	Cradle to grave	N/A	[45]
45	Costa et al.	2024	LCA	N/A	Cradle to grave	N/A	[46]
46	Guiqiang Li et al.	2018	LCA	1 kWp	Cradle to use	CML 2001, PED, EPBT	[75]
47	Zawadzki et al.	2020	LCA	kWh and MJ	N/A	EPBT, EROI	[41]

CED is measured in MJ of oil equivalent of primary energy used by the technology during its life cycle [78]. CED can be quantified according to renewable (including hydro, solar wind, geothermal and biomass) or non-renewable (including fossil and nuclear) energy, which are respectively called CED, renewable and CED, non-renewable. GER or PED denotes the same meaning as CED, indicating the primary energy consumption per functional unit of the technology [33]. These indicators were used in the early version of the EPD LCA method and CML method, respectively. The equation for calculating CED (GER or PED) can be found in Ref. [78].

The CED of concentrating solar technology from cradle to grave ranges from 3.70E-01 to 5.21E+02 MJ per kWh, depending on the specific technologies. The highest CED is 5.21E+02 MJ from dish Stirling CSP using hydrogen as HTF [54]. Because this configuration is not the mainstream among concentrating solar energy technologies, its CED is the highest. The CEDs of concentrating solar technologies per kWh (excluding dish Stirling CSP using hydrogen as HTF [54]) are presented in Fig. 6a. As can be seen from Fig. 6a, most of the CSP plants have the CED below the average value, at 3.00E+00 MJ per kWh. Four CSP plants co-firing with natural gas or biomass have the high CEDs which are 2.69E+01 for CSP plants hybrid with biomass backup burner [59], 5.92E+00, 6.34E+00 and 8.48E+00 MJ per kWh for CSP plant hybridized with natural gas [48,51]. The lower ranges are CEDs of parabolic trough CSP in Ref. [58] and CPV in Ref. [43].

It should be noted that there are several other parameters that can significantly the CED (as well as other environmental indicators) per kWh, such as the location, DNI, technology lifetime, temporal impact. In fact, the correlation between these parameters and CED in the reviewed case studies is not strong. For the location and DNI which are closely related, the correlation is not strong, as most of the reviewed case studies are conducted on CSP plants in high DNI locations (Refer to the life cycle assessment methodological aspects for the location of the reviewed case studies). The technology lifetime is from 20 to 30 years for all case studies, therefore causes no explicit impacts on the CED. The temporal impact may have effect on the LCA database as well as the development of technologies, with the assumptions that the more recent databases are more comprehensive, and the more recent technologies are more efficient. However, the relation between temporal parameter and the CED is not obvious (as can be seen in Figure SI1). This weak correlation can be explained by the small number of datasets, e.g. number of LCA case studies concerning CED per kWh of electricity.

There are studies reporting the CED of concentrating solar technology per less common FUs. For example [53], quantified the CSP combined with steam reforming and reported the CED at 5.97E+01 MJ per one Nm^3 of enriched methane and 0.58 kW h of electricity. In Ref. [33], the CED of a CPV system for both electricity and thermal purposes is 2, 56E+04 MJ per system, and that of a dish Stirling CST plant in Ref. [60] ranges from 7,21E+03 to 2,04E+04 kW h per system, depending on reuse/recycling or landfill waste management scenarios. The absolute CED values of these systems are higher compared to other case studies because they are calculated per system (1 kW electricity and heating water in Ref. [33] and 1 kW electricity and 2 kW thermal in Ref. [60]), while other case studies reported CED per kWh. Besides, both these studies reported global energy requirement (GER), which are very similar to CED. The only difference between GER and CED is that the first is based on higher heating value, while the latter may be based on either lower or higher heating value.

FFDP is similar to CED, non-renewable, which only quantifies the amount of fossil energy needed during the life cycle of the technology. FFDP of concentrating solar technology ranges from 8.08E-03 to 1.23E-01 kg oil eq per kWh from cradle to grave. This range covers from the CSP combined with biomass-based energy systems (the lowest) to CSP combined with NG systems (the highest).

EPBT is the time period needed for a renewable energy system, in this case, a concentrating solar system to generate the same amount of primary energy equivalent which was used to produce the system itself. EPBT is calculated by the following equation [76]:

$$EPBT = E_{LCeM} \Big/ \left(\frac{E_{agen}}{\eta_g} - E_{O\&M} \right) \quad (1)$$

In which:

E_{LCeM} is the primary energy demand during the life cycle of the concentrating solar system, excluding the demand of the operation and maintenance phase (measured in MJ oil eq).

E_{agen} is the annual electricity generation of the concentrating solar system (measured in kWh).

η_g is the grid efficiency, the efficiency of converting the primary energy to electricity at the demand side (kWh electricity per MJ oil eq).

$E_{O\&M}$ is the annual primary energy demand for operation and maintenance (measured in MJ oil eq).

The EPBT of concentrating solar technologies ranges from 0.33 to 10.7 years, depending on the specific systems (as presented in Fig. 6b). The lowest EPBT is at 0.33 years for a solar tower CSP plant using thermochemical storage [70]. Some concentrating solar systems have low EPBT (less than one year), such as hysol CSP biomethane thanks to the inclusion of the heat recovery system and use of renewable energy, and CPV systems thanks to the maximum exploitation of solar radiation with both concentrating solar and solar PV technologies. The EPBTs of hysol biomethane are around 0.5 years [49]. Those of CPV systems are from 0.7 years to nearly one year, with the lower end from CPV systems using parabolic trough as receiver [33,44], and the higher end from CPV systems with Fresnel lens or achromatic lens [44], and flat coated reflectors for concentrating system combined with PV and copper cooling pipe [79]. The EPBT of an asymmetric compound parabolic concentrator combined with PV cells ranges from 2.82 to 4.74 years depending on installation locations in China [75]. There were two exceptional CPV with EPBT longer than six years, which were installed in the UK and Israel [41,63].

Most of CSP and CST technologies have the EPBT between 1 and 6.6 years [32,35,42,48–50,54,56–58,60,69]. There is only one system with EBPT longer than 10 years, which is a dish Stirling CST with landfilling as the end of life treatment [60]. By types of receivers, the EPBT of parabolic trough CSP range from 1 year to 3.43 years per kWh, which are quite similar to that of solar tower CSP, between 0.3 and 3.58 years. The EPBT of solar tower CSP is lower than 1 years for CSP plant with thermochemical energy storage system or with heat recovery system and biomethane backup. Fresnel lens have the EPBT of less than 1 year, for low concentrating PV systems.

EROI considers the relation between the amount of energy produced and the amount of energy consumed during the life cycle of the technology [78]. This indicator was considered in three paper, which range from 3.77 to 6 for the CPV integrated in a building in the UK and EU [40–42].

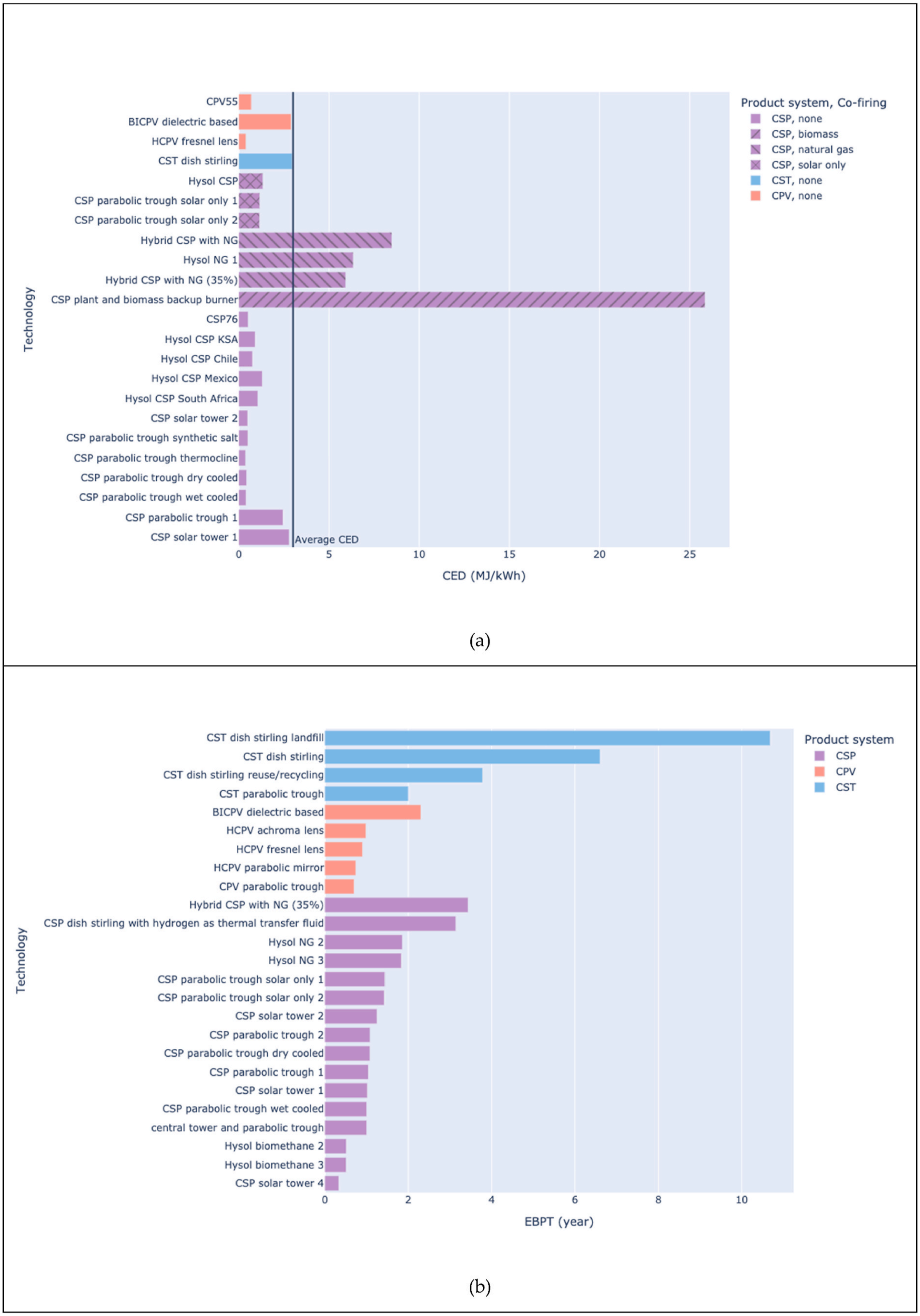
Numeric results related to energy indicators of different concentrating solar technologies are provided in Table SI2.

5.2. *GHG emissions*

The GHG emissions of concentrating solar technologies range from 2.09e+03 to 2.28e+03 kgCO$_2$eq per kW of installed capacity of the system from cradle to grave. The lower end is high CPV which combines the Fresnel lens with GaInP/GaInAs/Ge multijunctional PV cell [43], while the higher end is CPV combining parabolic trough and crystalline silicon PV cell in Ref. [33]. At the same time, the scales of the two systems are different, in which the system in Ref. [33] is small scale, at 1 kW, and that of [43] is 53 kWp. It should be noted that the original functional unit of both studies is "the system" with different installed capacities, therefore the function unit is converted into kW for harmonization, and convenient for comparison.

Cucumo et al. reported the GWP of a dish Stirling system at 3.55e+03 kgCO$_2$eq per system, which has installed capacity of 1 kW electricity and 2 kW thermal energy [60]. Besides, Piemonte et al. reported the GWP of a CSP plant at 4.98e-01 kgCO$_2$eq per functional unit of 1 Nm^3 of enriched methane with 17 % hydrogen and 0.58 kW h of electricity [53].

Per kWh, the GWP of CSP/CST technologies ranges significantly between 9.8e-03 to 3.92e-01 kgCO$_2$eq. This range is dependent on many factors such as installation sites, specific technologies, system boundaries of the LCA studies, etc. The GWPs of concentrating solar technologies, including CSP, CST and CPV are presented in Fig. 7. As can be seen in Fig. 7, CSP technologies with GWP being higher than the median value are those being hybridized with natural gas or biomass), while the CSPs with solar only mode have GWP being lower than the median value. The GHG emissions of CSP are less than 0.4 kgCO$_2$eq per kWh, in which those of parabolic trough CSP vary between 2.56E-02 to 2.11E-01 kgCO$_2$eq. The GHG emissions of solar tower have a slightly larger range, from 8.26E-03 to 3.92E-01 kgCO$_2$eq. The lower range of GHG emissions, which are less than 1.15E-02 kgCO$_2$eq per kWh, are of solar tower CSP



(a)

(b)

Fig. 6. Life cycle energy requirement of concentrating solar technologies.

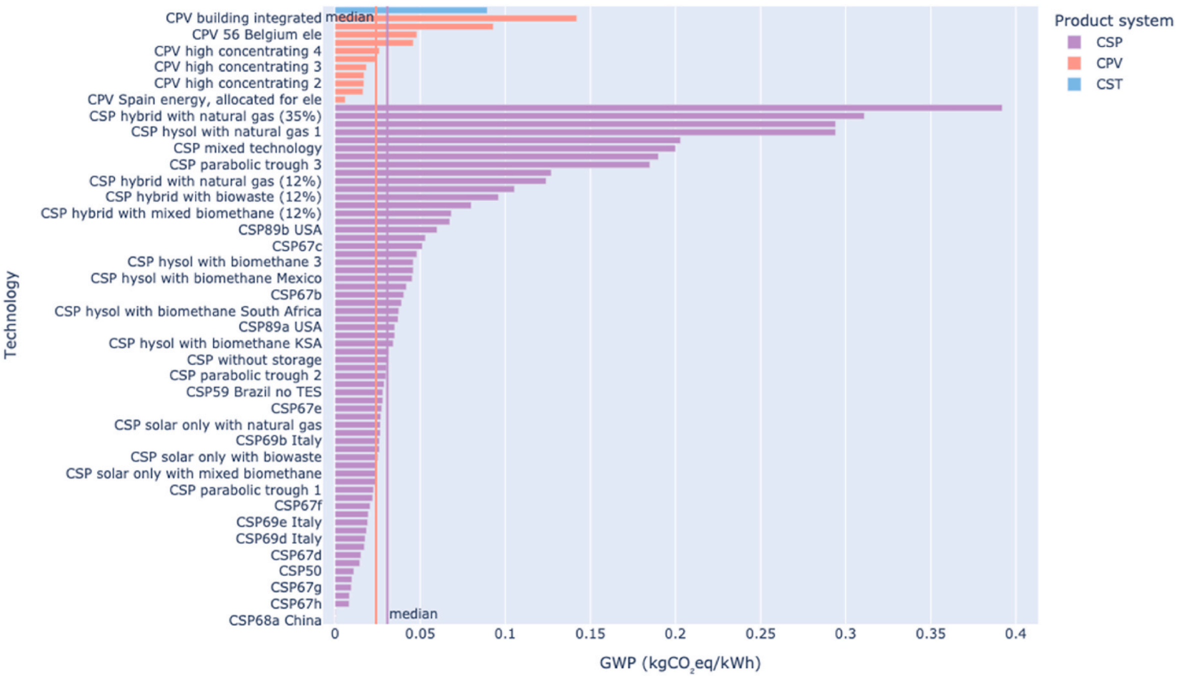


Fig. 7. Carbon footprint of concentrating solar technologies.

plants with SO_2 or CO_2 steam engine. This is further illustrated in Figure SI2 for CSP technologies only. For CPV technologies, the building integrated CPV have the GWPs being higher than the median value, while high concentrating CPV (large scale) cause lower GWPs.

Disregarding CPV or CSP technologies, the lower end of this range is the GWP of CSP considering the manufacturing and operation stage only, 9.8e-03 kgCO$_2$eq [55]. From cradle to gate, the life cycle emissions are 3.02e-02, 3.70e-02, and 1.90e-01 kgCO$_2$eq for different systems [35, 53,54]. From cradle to grave, the range is from 1.64e-02 to 3.92e-01 kgCO$_2$eq per kWh. The lowest GHG emissions are from high concentrating PV technologies which combine multijunction PV cells (GaInP GaAs GaInAs Ge) with different concentrating mirrors or lens. This ranges from 1.64e-02 for parabolic mirrors, 1.69e-02 for Fresnel lens and 1.84e-02 for Achromatic lens kgCO$_2$eq per kWh [44]. The highest GHG emissions are hybrid CSP with fossil fuels. This ranges from 3.11e-01 to 3.92e-01 kgCO$_2$eq per kWh of electricity generated by solar tower CSP hybrid with natural gas (NG) (35 %) using synthetic oil as HTF [48] and by parabolic trough hybrid with NG (54 %) turbine using molten nitrate salts as HTF [51], respectively. The mean value is 9.27e-02 kgCO$_2$eq per kWh and the median value is 3.9e-02 kgCO$_2$eq per kWh.

Similar to EPBT, GPBT denotes the time period a renewable energy system takes to compensate for the GHG emitted during the life cycle of the system. In the reviewed case studies, only CPV technologies were assessed with GPBT, and there was no information on GPBT of CSP and CST. The GPBT of CPV ranges from 0.98 to 2.38 years. The shortest GPBT is 0.98–1.1 years for the high CPV [44]. The report GPBT for the building applied CPV in Italy is 1 year [33]. Other research reported higher GPBT, for example, 1.89 years in Spain and 2.38 years in France for the building integrated CPV [42].

5.3. Land, water and material consumption

Land use of concentrating solar technologies in the reviewed case studies ranges from 4.00E-06 to 1.30E-03 m^2 per kWh. The lower end comes from parabolic trough CSP solar only in Spain, at around 4.00E-06 to 5.00E-06 m^2 per kWh, followed by hybrid CSP with different fuels such as NG and biomass, at around 8.00E-06 to 5.01E-05 m^2 per kWh [47,48,50]. The higher end comes from CSP in the USA, ranging from 2.30E-04 to 1.30E-03 m^2 per kWh [62,73]. The average land use of these technologies is 1.78E-04 m^2 per kWh and the median value is 1.00E-05 m^2 per kWh.

Considering that the technical characteristics of CSP plants in Corona et al.'s studies those in the USA of Klein and Rubin [62] and Rangarajan et al. [73] are very similar in term of electricity generation efficiency, at around 80 GW h per MW of installed capacity over their life cycle, the large difference among the land use of these CSP plants is likely due to the assumptions of LCA calculations. While Corona et al.' studies applied the ReCiPe for LCIA method and Ecoinvent data for the background processes, Klein and Rubin [62] used hybrid LCA combining process based and economic input output methods. For land use, both studies on CSP plants in the USA quantified the direct land use of the plants over their 30-year lifetime.

Water consumption of concentrating solar technologies ranges between 3.87E-04 and 7.10E+00 m^3 per MWh, with average amount at 3.02E+00 m^3 per MWh. There are two factors impacting the amount of consumed water, including the cooling modes and the types of HTF (illustrated in Fig. 8). Concentrating solar technologies which apply the wet cooling mode and use synthetic HTFs such as synthetic oil or synthetic salt require more water over their life cycle than their counterparts which apply dry cooling mode and use the mined HTFs (molten salts, nitrate salts or solar salts). Specifically, the amount of water required for dry cooled CSP ranged from 3.87E-04 to 1.50E+00 m^3 per MWh and that of CSP with mined salts or molten salts as HTF ranged from 1.60E-02 to 1.40E+00 m^3 per MWh, with the lowest water requirements at a dry-cooled hybrid CSP and biomass in Tunisia (3.87E-04 m^3 per MWh) [71] and a hysol CSP plant installed in Mexico (1.60E-02 m^3 per MWh) [52].

Water requirements for wet cooled CSP plants are from 3.69E+00 to 7.10E+00 m^3 per MWh, and those of CSP plants using synthetic HTFs are from 6.24E+00 to 6.41E+00 m^3 per MWh. The highest water requirements are for a wet-cooled parabolic trough CSP in the USA (7.10E+00 m^3 per MWh) [62] and for a hybrid CSP and biomass using synthetic oil as HTF (6.41 E+00 m^3 per MWh) [47].

The water consumption in wet cooling CSP plants is five times higher than that of dry cooling plants, at average. Considering that most of the

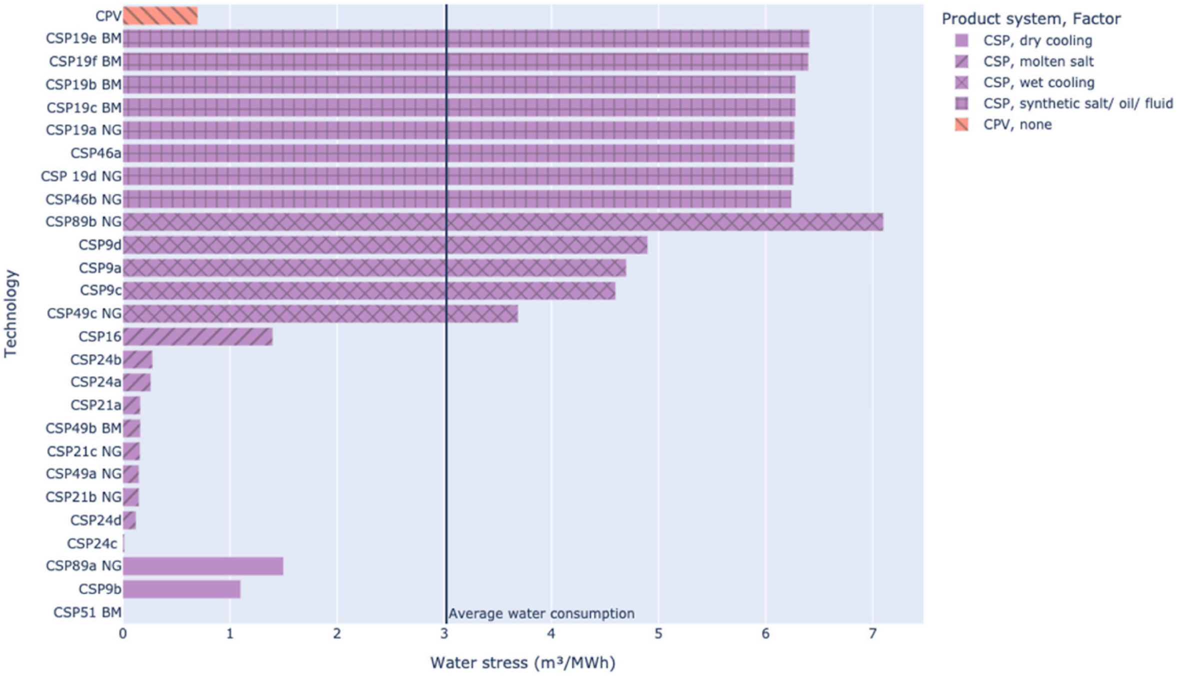


Fig. 8. Water stress of concentrating solar technologies.

water is consumed during the operation stage, for cooling system in the power generation unit and cleaning the mirrors, it is reasonable that the types of cooling system have a considerable influence on the water consumption. Meanwhile, the type of HTF has less impact on water consumption. The average water consumption in CSP plants with synthetic salts as HTFs is from 1.4 to 1.8 times higher than those using mined salts as HTFs, for dry cooling and wet cooling system, respectively. In the same study, the difference is even smaller, at around 4 %, e.g. 4.9 and 4.7 m^3 of water per MWh [58]. This difference must originate from the water consumption for background processes of HTF production.

It is expected that the cofiring of biomass in CSP plant will increase the water requirement over the life cycle, due to the water consumption for both biomass production and water for cooling. In fact, the use of biomass as the co-firing fuels does not always impose the large amount of consumed water. This can be seen from Fig. 8 that the results are contradictory among water requirement of CSPs used biomass for co-firing or auxiliary purposes. Several biomass related CSP plants (with ‘cofiring BM‘ in the technologies’ names, in the ‘y’ coordinate of Fig. 8) have either considerable or insignificant water requirements.

The material requirement of concentrating solar technologies is presented in abiotic depletion potential, which is from 1.93E-05 to 1.60E+00 g Sb eq per kWh. The abiotic depletion is extremely low for hybrid CSP and biomass in Tusinia, at 1.93E-05 g Sb eq per kWh [71], followed by CSP with micro gas turbine in Italy, from 2.85E-04 to 1.28E-03 g Sb eq per kWh [72]. Other technologies such as solar tower cofiring with fossil fuels, solar tower CSP, parabolic CSP and dish Stirling CSP impose a higher material requirement, from 2.02E-02 to 1.60E+00 g Sb eq per kWh [56,57,67,74]. The average material requirement of CSP is 3.56E-01 g Sb eq per kWh and the median value is 2.20E-02 g Sb eq per kWh.

5.4. Other environmental impacts

Other environmental impacts which are discussed in the review paper include acidification, eutrophication, ecotoxicity and human toxicity. These environmental impacts are presented in Fig. 9.

The acidification potential of concentrating solar technologies ranges from 1.40E-01 to 9.80E+00 g SO_2 eq per kWh, disregarding the system boundaries, with the median value at 3.63E-01 g SO_2 eq per kWh. The acidification potential largely depends on the types of fuels used for auxiliary purposes or co-generation. The larger amount of SO_2-intensive fuels such as NG and biomass will increase the acidification potential. CSP with biomass backup burner cause the largest acidification potential impacts, at 9.80E+00 [59] g SO_2 eq per kWh. Other technologies such as solar tower CSP cofiring with 12 % of diesel (CSP47a in Fig. 9a), hybrid CSP with NG (CSP21b), hysol CSP with NG (CSP21c), cause relatively large acidification potential, at 1.34E+00 g SO_2 eq per kWh [67], 6.94E-01, and 8.91E-01 g SO_2 eq per kWh [51], respectively. The lower range of acidification potential comes from solar tower CSP without cofiring (CSP47c in Fig. 9a), at 1.40E-01 g SO_2 eq per kWh [67] and parabolic trough CSP solar only, using NG as auxiliary fuel (CSP46a, CSP19a, CSP20, CSP19c, CSP19b), at around 1.66E-01 and 1.68E-01 g SO_2 eq per kWh [47,48,50]. Considering the cradle to grave system boundary, the acidification potential of concentrating solar technologies narrows down to 1.66E-01 to 8.91E-01 g SO_2 eq per kWh, with the mean value of 4.01E-01 g SO_2 eq and the median value of 3.62E-01 g SO_2 eq per kWh.

The eutrophication potential of concentrating solar technologies is quantified in either g P eq or g PO_4 eq. For the harmonization purpose, the unit of gPO_4 eq will be converted into g P eq based on their atomic weight. The eutrophication potential considerably ranges from 4.33E-09 to 1.79E+01 g P eq per kWh. For all the cases of CSPs in Spain and other countries conducted by Corona et al. [48,50–52,80], the eutrophication potentials are in the high range from 8.09E+00 to 1.79E+01 g P eq per kWh, with the mean value of 1.27E+01 and the median value of 1.18E+01 g P eq per kWh. Four case studies have the lower eutrophication potential from 3.26E-03 to 3.26E-01 g P eq per kWh [56,57,59,67], with the average eutrophication potential at 6.84E-02 g P eq per kWh. The lowest eutrophication potential comes from small scaled CSPs, from 4.33E-09 to 3.62E-05 g P eq per kWh [71,72], with the average eutrophication potential at 6.03E-06 g P eq per kWh. Due to the discrepancy in the eutrophication potential in the existing case studies, no clear conclusion can be drawn, except for that the scales of CSP, may have impacts on their eutrophication potential.

Ecotoxicity includes freshwater ecotoxicity, marine ecotoxicity and

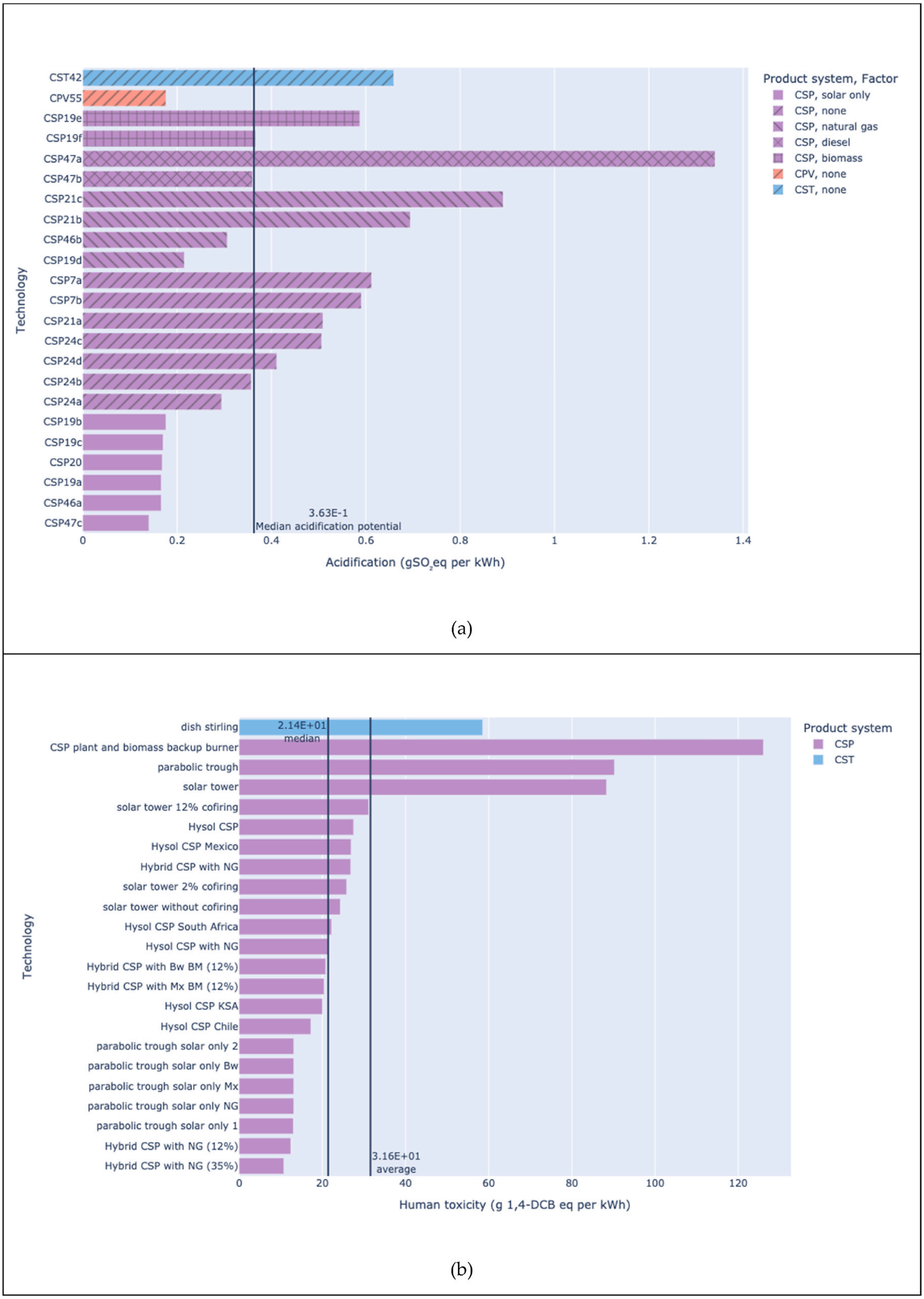


Fig. 9. Other life cycle environmental impacts of concentrating solar technologies.

terrestrial ecotoxicity, which are quantified in grams of 1,4-Dichlorobenzene equivalent (g1,4-DBeq or g1,4-DCBeq). There is a large difference in the quantified ecotoxicity. The freshwater ecotoxicity ranges from 3.29E-01 to 1.36E+01 g1,4-DCBeq per kWh, with the lower range from parabolic trough CSP solar only [50] and hysol CSP [52]. The terrestrial ecotoxicity ranges from 2.66E-01 to 7.90E-01 g1,4-DCBeq per kWh, being calculated for the solar tower, parabolic trough CSP, dish Stirling CST and the solar tower with various percent of cofiring [56,57,67]. The marine ecotoxicity significantly ranges from 2.08E-01 to 1.15E+05 g1,4-DCBeq per kWh. The higher end of marine ecotoxicity compared to freshwater and terrestrial ecotoxicity suggests that most of the ecotoxicity impact of concentrating solar technology is due to the impacts on the marine ecosystem.

Similar to ecotoxicity, human toxicity is quantified in g1,4-DCBeq. The human toxicity of concentrating solar technologies ranges from 1.07E+01 to 1.26E+02 g1,4-DCBeq per kWh (as presented in Fig. 9b), with the lowest from hybrid CSP with biomass from biowaste origin [48]. It is followed by CSP plants without hybridization and being hybridized with different fossil or renewable fuels and hysol CSP plant [47,48,50–52,67]. The higher ranges of human toxicity come from dish Stirling CST in Ref. [57], at 5.85E+01 g1,4DCBeq per kWh and solar tower and parabolic trough CSP in Ref. [56], at 8.83E+01 and 9.02E+01 g1,4DCBeq per kWh, respectively. The highest human toxicity comes from CSP plant hybrid with biomass backup burner, which is 1.26E+02 g1,4DCBeq per kWh [59]. The average human toxicity is 3.16E+01 g1,4DCB per kWh, which is not much different from the median value, of 2.14E+01 g1,4DCB per kWh.

6. Hotspots identification and future development of concentrating solar technologies

The dominant stages/components which contribute the most to the whole life cycle impacts of the technologies are identified for one single endpoint impact and several lifecycle midpoint impacts. The identification will be the foundation for the eco-design of concentrating solar technologies, which not only aims at the technical development (energy efficiency), but also minimizing environmental impacts covering the whole supply chain of solar energy technologies.

In terms of one endpoint impact, the construction stage and solar fields should be prioritized to sustainably develop the CSP in general because they hold large shares of environmental impacts. Construction is the largest contributor among all life cycle stages, accounting for more than 86 % of the total life cycle impact [61]. It is also confirmed by Ref. [68] that construction and use stages hold the largest share of all life cycle impacts, except for renewable primary energy demand. Other authors pointed out the dominant contribution of raw material extraction manufacturing [48] or manufacturing and operation [55] to the total life cycle impact. Considering the contribution of components, most life cycle impacts come from solar fields up to 79.3 % due to the use of steel and synthetic oil, followed by the storage system, at 20.6 % due to the use of molten salt as HTF [65]. Besides, HTF is recognised to be the second largest contributor to the total impacts in Ref. [61].

Considering the energy demand and environmental impacts separately, it is likely that the priority should be put on manufacturing and operation stages and solar concentrator. Some environmental hotspots such as energy, GWP, abiotic depletion, water consumption, and ecotoxicity have been studied. Most of the energy consumption is due to the manufacturing of the system, up to 85 % in CPV [33]. Specifically, solar concentrator requires 38.3 % of the total energy demand, followed by foundations, requiring 25.3 %. Solar concentrator is also identified as the dominant contributor to other environmental impacts such as abiotic depletion [68] and ecotoxicity [57].

In terms of GWP, most of the impact originates from raw material extraction, manufacture, or operation stages. The manufacturing stage contributes up to 46 % of the life cycle impact, followed by the operation stage, at 39 % in wet cooling (water) CSP technology [58]. Similarly, in dry cooling (air) CSP technology, manufacturing accounts for 45 %, while operation accounts for 46 % of total GHG [58]. Other studies agreed with this identification, in which raw material and manufacturing stages are the largest contributors to the GWP of CSP plants [48]. [55] pointed out that the manufacturing stage contributes most to the GWP of CSP with a thermal energy storage, and both manufacturing and operation are the GWP hotspots in CSP without a thermal energy storage. Considering the contribution of various components, the collector system contributes up to 65 % of GWP [67], while the solar field accounts for 30 %, storage and transport 25 % each [68]. In other studies, the components are analysed at a smaller scale, in which steel causes 37 % and electronics causes 16 % of the GWP of the technology [54].

With regards to water consumption, the manufacturing and operation stages consume the largest amount of water, accounting for up to 89 % of the total water demand [58]. Besides, the power conversion unit is a water intensive part of the CSP plant, with 80 % for refrigerating [48].

There are some links between two or more impacts, for example, GHG emissions and resource use, fossils are closely linked. Besides, there are some trade-offs among impacts, in which some design choice may reduce GHG emissions, but increase other impacts such as acidification and eutrophication potential, e.g. the case of bio-based fuels in replacement of natural gas in back-up systems and hybrid CSP plants. One quick and simple way to see the combined effect of two or several impacts are reporting the endpoint result, e.g three endpoint results of human health, resource, ecosystem quality or one endpoint result of eco-point. However, the use of endpoint result will reduce the transparency of LCA results and conceal some important midpoint results. The paper chooses to report the midpoint results, e.g. energy related indicator, GHG emissions, resources use, etc. in order to increase the transparency of the LCA results in the reviewed case studies.

The end-of-life stage contributes to a small part of the life cycle environmental impact, for all impact categories. Regarding energy related indicators, the external energy consumption over the life cycle of CSP plant equals to about 11 % of its net electricity generation, in which the end-of-life stage consumes less than 0.5 % of the total external energy demand [48]. This is the same for other impacts apart from energy use, such as climate change, toxicity, acidification and eutrophication. For an example, the normalized result of all impact categories of CSP plant in San Miguel and Corona's study by life cycle stages indicated that end-of-life phase accounted for less than 8 % of total normalized impact [80].

Though contributing a small part of the total impact, in case a more environmental-friendly end-of-life strategy is applied, some critical impacts reduce. For examples, the reuse and recycling of a decommissioned dish Stirling CST system reduced 65 % of CED [60]. Furthermore, the EPBT reduces from 10 years for landfilling, to 4 years for reuse and recycling for the same system [60].

7. Economic assessment of concentrating solar energy technologies

The economic dimension of LCA of energy technologies are frequently studied with some indicators such as energy return on investment, energy payback time, and levelized cost of energy, and some methods such as cost and benefit analysis and life cycle costing. Levelized cost of energy, which is the most common indicator, is the unit energy cost over the life cycle of a project, including capital cost, operating cost, fuel, interest on loans, repairs and decommissioning. Levelized cost of energy of CSP was studied by Ref. [46], who identified that integrating CSP and PV can lead to cost-effective electricity and heat production with reduced climate change impact. Levelized cost of electricity (LCOE) and levelized cost of heat (LCOH) generated by this plant are studied in two scenarios of considering only generated electricity and considering both electricity and heat. Considering electricity only, LCOE of CPV plants varies between 161 and 304 EUR per MWh, depending on locations of the plants. These LCOEs are higher than the global average LCOE of CSP, at 134 EUR per MWh and of PV, at 71 EUR per MWh. However, the LCOE considerably reduces in case both electricity and heat are considered, making them lower than the global average LCOE of CSP and PV. In this case, the LCOEs are at 41 and 115 EUR per MWh, depending on locations of the plants. Besides, the LCOHs of this case are at 63 and 103 EUR per MWh, slightly lower than the LCOH in the literature at 107 EUR per MWh. The LCOE and LCOH dissimilarity between locations originates from the different energy outputs, meanwhile the distribution of costs is similar among scenarios and location. The CSP system accounts for 64 % of the total cost, including 18 % from solar field, 8 % from heat transfer system, 10 % from power block, 11 % from thermal storage system and 17 % from other costs [46].

The LCOE of hybrid CSP and PV is very similar to that of supercritical CO_2 central tower CSP plant, which is at $116 per MWh [81]. The study of Liang et al. also pointed out that 77 % of the total cost is for capital investment, in which 81 % of the capital investment is for the solar concentrator. Operating and maintenance costs account for 15.86 % of the total cost, in which the cost operation activities only account for 0.04 %. The labour cost holds about 7 % of the total cost [81].

Besides, the results of Costa et al.'s study [46] confirmed the conclusions of Freeman et al. [82], on the larger benefit of CSP systems if both electricity and heat are considered. Freeman et al. studied the combined solar heat and power (solar CHP) system with organic Rankine cycle for domestic use [82]. In this system, the concentrating parabolic trough or non-concentrating evacuated tube is applied to provide heat for organic Rankine system (ORC), to generate both electricity and hot water. The best case (optimized system) is the average electricity output of 89W with 776 kW h per year and hot water provision capacity of 80 % of total demand. The capital cost for this system is £2700 to £3,900, and LCOE is £0.44 per kWh (around 0.52 EUR per MWh). The comparisons with PV alone system of similar size, or side by side system (electricity and hot water in the same roof area) or hybrid PVT system, indicate that the best case is ORC system with heat provided by parabolic trough or evacuated tube [82].

The LCOE and LCOH of the CHP system in Freeman et al.'s study [82] is quite similar to those obtained by Norwook and Kammen [83], for distributed solar CHP in the USA. Specifically, a dish collector system with peak capacity of 1 kW electricity and 5 kW heat would produce electricity at LCOE of $0.25 per kWh, and heat at LCOH of $0.03 per kWh [83].

Table 2 summarizes the LCOE and LCOH of CSP. As indicated in the table, the LCOE of CSP is gradually decreasing, disregarding the particular systems. It is likely thanks to the reduction of capital investment, especially for the solar concentrator. The result agrees with the highlight of progress in solar concentrator cost, in which the cost significantly reduced from around \$150–200 per m^2 in 2013 to \$75-\$100 per m^2 in 2017 [84].

In the context of climate change, the weather condition certainly has some certain impacts on the LCOE of power from CSP plants. For an example, over the lifetime of 35 years from now, the climate change causes an increase in the electricity generation cost at a solar tower plant in Chile by 1.1 %; however, reduces the cost at the Spanish plant by 2.5 % [85]. This variance in LCOE is caused by the difference in water cost, due to the limited access to water resource, therefore depending on water transportation or desalination process in Chile. Meanwhile the situation is contrary in Spain, with less water stress.

Table 2
Economic analysis of CSP.

System	LCOE per kWh	LCOH per kWh	Scale (installed capacity)	Reference
Hybrid CSP and PV system in Spain and Belgium	€0.04 - €0.12	€0.06 -€0.1	Commercial plant	[46]
Supercritical CO2 CSP plant	$0.12		Commercial plant (50 MW)	[81]
ORC with PT or evacuated tube in UK (providing 80 % of hot water demand)	£0.44- £0.94		Residential (0.37–0.52 kWp)	[82]
Solar CHP system in USA	$0.25	$0.03	Distributed (1 kW)	[83]

Limited study applies life cycle costing (LCC), taking into account the external cost of concentrating solar energy technologies. Corona et al. found out that the life cycle internal costs of the plant operating with solar energy only represent 82.8 €/MWh, while revenues from electricity sales amount to 85.7 €/MWh, resulting in a net present value of 2.95 €/MWh [66]. Internal costs are primarily spent on materials and equipment during the extraction and manufacturing stages. External costs account less than 2.6 % of the internal costs. When the natural gas is hybridized with the solar only system, the electricity output increases, however the operating and maintenance costs also increase, causing a reduction on revenue and net present value. At the same time, the external cost increases due to the GHG emissions from the natural gas system [66]. As a result, hybridizing CSP and natural is not economic attractive, considering both financial economics and environmental economics.

8. Conclusion

The paper reviewed the life cycle environmental impacts of concentrating solar technologies, by their technical characteristics and by life cycle methodological aspects. Various life cycle environmental impacts have been analysed, such as energy, GHG, land, water and material use, acidification, eutrophication, ecotoxicity and human toxicity, with some statistical discussion. Besides, the environmental hotspots during the life cycle of concentrating solar technologies have been identified.

Energy related impacts are assessed in two indicators: CED and EPBT. The cradle to grave CED of the technologies are between 3.70E-01 to 5.21E+02 MJ per kWh. CSP plants and high CPV plants in high solar radiation area have the lowest CED, while CSP plants hybridized with fossil fuels require the higher CED. The EPBTs of the concentrating solar technologies are from 0.33 to 10.7 years, and most concentrating solar technologies have the EPBT between 1 and 6.6 years. Several systems having the EPBT less than one year are CSP plants with the inclusion of heat recovery systems and use of renewable energy as auxiliary fuel and CPV plants thanks to the maximum exploitation of solar energy. The only concentrating solar system with the EPBT longer than 10 years is dish Stirling CST with landfilling as the end-of-life treatment.

Similar to energy, the impacts related to GHG emissions are assessed in GWP and GPBT. The GWPs of concentrating solar technology range from 2.65E-04 to 3.92E-01 $kgCO_2eq$ per kWh. The high CPV plants have a lower GWP, while the hybrid CSP plants cause a higher GWP. The GPBT is only available for CPV technologies, which is within the range of 0.98–2.38 years.

Regarding the resource consumption of concentrating solar technologies, the consumption of three types of resources is analysed, including land, water and material. Land transformation of the technology ranges from 4.00E-06 to 1.30E-03 m^2 per kWh, with the average value at 1.78E-04 m^2 per kWh and the median value is 1.00E-05 m^2 per kWh. In contrast with land transformation, the ranges of water consumption and material requirement of concentrating solar technologies are significant. Water consumption is between 3.87E-04 and 7.10E+00 m^3 per MWh, depending on the types of working fluids and HTFs. Moreover, these technologies require the amount of materials ranging from 1.93E-05 to 1.60E+00 g Sb eq per kWh. The material requirement is extremely low for one case study, while other studies report the material requirement of between 1.00E-01 to 1.60E+00 g Sb eq per kWh.

Disregarding the system boundary, the acidification potentials of these technologies range from 1.40E-01 to 9.80E+00 g SO_2 eq per kWh, depending on the types of auxiliary fuels. The cradle to grave eutrophication potential is between 4.33E-9 to 1.79E+01 g P eq per kWh. The freshwater ecotoxicity ranges from 3.29E-01 to 1.36E+01 g1,4-DCBeq per kWh and terrestrial ecotoxicity is between 2.66E-01 to 7.90E-01 g1,4-DCBeq per kWh. The marine ecotoxicity is much larger than the other two ecotoxicity impact categories, from 2.08E-01 to 1.15E+05 g1,4-DCBeq per kWh. Human toxicity of the technologies is between 1.07E+01 to 1.26E+02 g1,4-DCBeq per kWh.

In terms of environmental hotspots, the three stages of construction, material extraction and manufacturing are the largest contributors to the whole life cycle impacts in general. For specific environmental impacts, the hotspot stages are either manufacturing (energy demand, material depletion and ecotoxicity) operation (GWP) or both (water consumption). Interestingly, the operation is a large source of GWP, as concentrating solar technology is a renewable energy technology, which is deemed to emit no GHG during its operation. The large share of GWP during the operation of these technologies points out the need for further research and development on some components that directly affect the GHG emissions of this stage such as auxiliary boiler (with the use of fossil fuels), cooling system (with the use of water) and thermal energy storage (with the use of HTF).

Among the components of concentrating solar systems, solar concentrator contributes the most to several life cycle impacts such as energy demand, GWP, material depletion and ecotoxicity. Most of the water demand originates from the power conversion unit, for refrigerating the system.

LCA considers the environmental impacts of the technologies over their whole life cycle, therefore it helps to avoid transferring the impacts from one stage to another stage and avoid neglecting some ‘less important’ impacts. The application of LCA on renewable energy technologies supports the technical development of technologies, while improving their environmental profile over the life cycle, e.g. eco-design of the technologies. The environmental profiles of the technologies are not only better in term of common environmental impacts such as GHG emissions, but also other impacts such as resource use (land, water and materials), and ecosystem quality (acidification, eutrophication, toxicity, etc.).

For concentrating solar energy technologies, the LCA results of CSP technologies indicated that the use of natural gas for auxiliary purposes should be minimized, and it should not be used as a co-fuel at CSP plants. The reduction and no-use of nature gas significantly reduce GHG emissions, energy demand and other life cycle environmental impacts per kWh of electricity from CSP. For the solar-to-power system, the improvement in some ‘hotspot’ components will further reduce the environmental impacts of solar-only CSP plant, such as solar concentrators, power generation unit, thermal storage system. The improvement of these components may help to reduce their direct environmental impacts, but also increase the efficiency of the plant, consequently reducing environmental impacts per energy (electricity and heat) generated.

CRediT authorship contribution statement

Maurizio Cellura: Writing – review & editing, Writing – original draft, Supervision, Resources. **Le Quyen Luu:** Writing – review & editing, Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **Francesco Guarino:** Writing – review & editing, Writing – original draft, Resources. **Sonia Longo:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Institutional review board statement

Not applicable.

Funding

This work has been developed in the framework of the project ’’Network 4 Energy Sustainable Transition – NEST″, code PE0000021, CUP B73C22001280006, Spoke 1, funded under the National Recovery and Resilience Plan (NRRP), Mission 4, by the European Union – NextGenerationEU.

The views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maurizio Cellura and Le Quyen Luu reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

CED	Cumulative Energy Demand
CML	Centrum voor Milieukunde Leiden
CPV	Concentrating photovoltaics
CSP	concentrating solar power
CST	concentrating solar thermal
EDP	Environmental Priority Strategy (in product design)
EPBT	Energy Payback Time
EPD	Environmental Product Declaration
EROI	Energy Return on Investment
FFDP	Fossil Fuel Depletion Potential
GER	Global Energy Requirement
GHG	Greenhouse gas
GPBT	Greenhouse gas payback time
GWP	Global warming potential
HRS	Heat recovery system
HTF	Heat transfer fluid
IEA	International Energy Age

(*continued on next page*)

(*continued*)

ILCD	International Reference Life Cycle Data System
IPCC	International Panel of Climate Change
kWh	Kilowatt hour
LCA	Life Cycle Assessment
MJ	Megajoule
MWh	Megawatt hour
NG	Natural gas
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaics
TES	Thermal energy storage
USD	the United States dollar

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2025.123203.

Data availability

The authors confirm that the data supporting the finding of this study are available within the article and the supplementary data.

References

[1] IRENA, “world energy transitions outlook 2023: 1.5°C pathway, Int. Renew. Energy Agency 1 (2023). Abu Dhabi, www.irena.org/publications.

[2] IEA, Trends in photovoltaics applications 2024 [Online]. Available: https://iea-pvps.org/trends_reports/trends-in-pv-applications-2024/#:~:text=Operational%20Capacity%3A%20By%20early%202024,8.3%25%20of%20global%20electricity%20demand, 2024.

[3] S. Rodat, R. Thonig, Status of concentrated solar power plants installed worldwide: past and present data, Cleanroom Technol. 6 (1) (Mar. 2024) 365–378, https://doi.org/10.3390/cleantechnol6010018.

[4] IEA, Net Zero by 2050 A Roadmap for the Global Energy Sector, International Energy Agency, 2021 [Online]. Available: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

[5] R. Horne, Life cycle assessment: origins, principles and context, in: R.E. Horne, T. Grant, K. Verghese (Eds.), Life Cycle Assessment - Principles, Practice and Prospects, CSIRO Publishing, Collingwood, 2009, pp. 1–8.

[6] R. Araya, F. Bustos, J. Contreras, A. Fuentes, Life-cycle savings for a flat-plate solar water collector plant in Chile, Renew. Energy 112 (Nov. 2017) 365–377, https://doi.org/10.1016/j.renene.2017.05.036.

[7] A. Famiglietti, A. Lecuona, Energetic and economic analysis of a novel concentrating solar air heater using linear fresnel collector for industrial process heat, Renew. Energy 236 (Dec. 2024) 121362, https://doi.org/10.1016/j.renene.2024.121362.

[8] S.F. Moosavian, D. Borzuei, A. Ahmadi, Energy, exergy, environmental and economic analysis of the parabolic solar collector with life cycle assessment for different climate conditions, Renew. Energy 165 (Mar. 2021) 301–320, https://doi.org/10.1016/j.renene.2020.11.036.

[9] G. Manente, S. Rech, A. Lazzaretto, Optimum choice and placement of concentrating solar power technologies in integrated solar combined cycle systems, Renew. Energy 96 (Oct. 2016) 172–189, https://doi.org/10.1016/j.renene.2016.04.066.

[10] H. Chen, et al., Comparative study on a solar-assisted ground source heat pump with CPC solar collector and phase change heat storage, Renew. Energy 239 (Feb. 2025) 122065, https://doi.org/10.1016/j.renene.2024.122065.

[11] M. Souliotis, N. Arnaoutakis, G. Panaras, A. Kavga, S. Papaefthimiou, Experimental study and life cycle assessment (LCA) of hybrid photovoltaic/thermal (PV/T) solar systems for domestic applications, Renew. Energy 126 (Oct. 2018) 708–723, https://doi.org/10.1016/j.renene.2018.04.011.

[12] F. Magrassi, E. Rocco, S. Barberis, M. Gallo, A. Del Borghi, Hybrid solar power system versus photovoltaic plant: a comparative analysis through a life cycle approach, Renew. Energy 130 (Jan. 2019) 290–304, https://doi.org/10.1016/j.renene.2018.06.072.

[13] T.C. Roumpedakis, G. Kallis, D. Magiri-Skouloudi, D. Grimekis, S. Karellas, Life cycle analysis of ZEOSOL solar cooling and heating system, Renew. Energy 154 (Jul. 2020) 82–98, https://doi.org/10.1016/j.renene.2020.02.114.

[14] M. Jahami, P. Singh, B. Khandelwal, Life cycle assessment of SMR and Electrified-SMR with renewable energy systems: projecting emissions and optimizing hydrogen production for California’s 2035 goals, Renew. Energy 243 (Apr. 2025) 122501, https://doi.org/10.1016/j.renene.2025.122501.

[15] L. Kumar, M. Hasanuzzaman, N.A. Rahim, Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: a review, Energy Convers. Manag. 195 (Sep. 2019) 885–908, https://doi.org/10.1016/j.enconman.2019.05.081.

[16] M. Dehghanimadvar, R. Shirmohammadi, F. Ahmadi, A. Aslani, K.R. Khalilpour, Mapping the development of various solar thermal technologies with hype cycle analysis, Sustain. Energy Technol. Assessments 53 (Oct. 2022) 102615, https://doi.org/10.1016/j.seta.2022.102615.

[17] Chr Lamnatou, D. Chemisana, Concentrating solar systems: life cycle assessment (LCA) and environmental issues, Renew. Sustain. Energy Rev. 78 (Oct. 2017) 916–932, https://doi.org/10.1016/j.rser.2017.04.065.

[18] L.B. Gobio-Thomas, M. Darwish, V. Stojceska, Environmental impacts of solar thermal power plants used in industrial supply chains, Therm. Sci. Eng. Prog. 38 (Feb. 2023) 101670, https://doi.org/10.1016/j.tsep.2023.101670.

[19] P. Glasziou, Chapter 14 how to write a review, in: G.M. Hall (Ed.), How to Write a Paper, John Wiley and Sons Publishing, 2013.

[20] M.J. Page, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ (Mar. 2021) n71, https://doi.org/10.1136/bmj.n71.

[21] M.J. Page, et al., PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews, BMJ (Mar. 2021) n160, https://doi.org/10.1136/bmj.n160.

[22] T.M. Gulotta, R. Salomone, G. Mondello, B. Ricca, FLAVIA-LCT - framework for systematic literature review to analyse vast InformAtion in life cycle thinking studies, Heliyon 9 (5) (May 2023) e15547, https://doi.org/10.1016/j.heliyon.2023.e15547.

[23] M. Gusenbauer, N.R. Haddaway, Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of google scholar, PubMed, and 26 other resources, Res. Synth. Methods 11 (2) (Mar. 2020) 181–217, https://doi.org/10.1002/jrsm.1378.

[24] Elsevier, “ScienceDirect: elsevier’s premier platform of peer-reviewed scholarly literature.” [Online]. Available: https://www.elsevier.com/products/sciencedirect.

[25] Elsevier, “Scopus: comprehensive, multidisciplinary, trusted abstract and citation database.” [Online]. Available: https://www.elsevier.com/products/scopus.

[26] C. Golonis, A. Skiadopoulos, D. Manolakos, G. Kosmadakis, Assessment of the performance of a low-temperature organic rankine cycle engine coupled with a concentrating PV-Thermal system, Renew. Energy 179 (Dec. 2021) 1085–1097, https://doi.org/10.1016/j.renene.2021.07.103.

[27] L. Zhu, et al., Comprehensive analysis of heat transfer of double-skin facades integrated high concentration photovoltaic (CPV-DSF), Renew. Energy 161 (Dec. 2020) 635–649, https://doi.org/10.1016/j.renene.2020.07.045.

[28] A. Hu, et al., Assessment of the carbon footprint, social benefit of carbon reduction, and energy payback time of a high-concentration photovoltaic system, Sustainability 9 (1) (Dec. 2016) 27, https://doi.org/10.3390/su9010027.

[29] A. Lekbir, S. Hassani, S. Mekhilef, Techno-economic and life cycle assessment of a nanofluid-based concentrated Photovoltaic/thermal-thermoelectric hybrid system, J. Power Sources 595 (Mar. 2024) 234066, https://doi.org/10.1016/j.jpowsour.2024.234066.

[30] NREL, SolarPACES - concentrating solar power (CSP) projects [Online]. Available: https://solarpaces.nrel.gov/by-technology, 2024.

[31] NREL, SolarPACES - concentrating solar power (CSP) projects [Online]. Available: https://zenodo.org/records/7112761#.YzSaeezMIUR, 2022.

[32] U. Desideri, F. Zepparelli, V. Morettini, E. Garroni, Comparative analysis of concentrating solar power and photovoltaic technologies: technical and environmental evaluations, Appl. Energy 102 (Feb. 2013) 765–784, https://doi.org/10.1016/j.apenergy.2012.08.033.

[33] M. Cellura, V. Grippaldi, V.L. Brano, M. Mistretta, Life cycle assessment of a solar PV/T concentrator system [Online]. Available: https://www.lcm2011.org/3_Cellura-Life_cycle_assessment_of_a_solar_PVT_concentrator_system-642_b56a3.pdf?file=tl_files/pdf/paper/23_Session_LCM_in_the_Energy_Sector_II/3_Cellura-Life_cycle_assessment_of_a_solar_PVT_concentrator_system-642_b.pdf, 2011.

[34] Chr Lamnatou, B. Lecoeuvre, D. Chemisana, C. Cristofari, J.L. Canaletti, Concentrating photovoltaic/thermal system with thermal and electricity storage: CO2.eq emissions and multiple environmental indicators, J. Clean. Prod. 192 (Aug. 2018) 376–389, https://doi.org/10.1016/j.jclepro.2018.04.205.

[35] M.B. Whitaker, G.A. Heath, J.J. Burkhardt, C.S. Turchi, Life cycle assessment of a power tower concentrating solar plant and the impacts of key design alternatives, Environ. Sci. Technol. 47 (11) (Jun. 2013) 5896–5903, https://doi.org/10.1021/es400821x.

[36] X. Liao, et al., Life cycle assessment of innovative concentrated solar power plants using supercritical carbon dioxide mixtures, in: Supercritical CO2, vol. 9, American Society of Mechanical Engineers, Rotterdam, Netherlands, Jun. 2022, https://doi.org/10.1115/GT2022-83576. V009T28A033.

[37] T. Xiao, et al., Life cycle assessment of the solar thermal power plant integrated with air-cooled supercritical CO2 brayton cycle, Renew. Energy 182 (2022) 119–133, https://doi.org/10.1016/j.renene.2021.10.001.

[38] A. Vossier, S. Verne, A. Soum-Glaude, A. Dollet, From ideal to realistic compact hybrid PV-CSP systems: a technoeconomic evaluation, Renew. Energy 236 (Dec. 2024) 121380, https://doi.org/10.1016/j.renene.2024.121380.

[39] D. Ziyati, A. Dollet, G. Flamant, Y. Volut, E. Guillot, A. Vossier, A multiphysics model of large-scale compact PV–CSP hybrid plants, Appl. Energy 288 (Apr. 2021) 116644, https://doi.org/10.1016/j.apenergy.2021.116644.

[40] Chr Lamnatou, H. Baig, D. Chemisana, T.K. Mallick, Life cycle energy analysis and embodied carbon of a linear dielectric-based concentrating photovoltaic appropriate for building-integrated applications, Energy Build. 107 (Nov. 2015) 366–375, https://doi.org/10.1016/j.enbuild.2015.08.030.

[41] P. Zawadzki, et al., Life cycle assessment of a rotationally asymmetrical compound parabolic concentrator (RACPC), Sustainability 12 (11) (Jun. 2020) 4750, https://doi.org/10.3390/su12114750.

[42] Chr Lamnatou, H. Baig, D. Chemisana, T.K. Mallick, Dielectric-based 3D building-integrated concentrating photovoltaic modules: an environmental life-cycle assessment, Energy Build. 138 (Mar. 2017) 514–525, https://doi.org/10.1016/j.enbuild.2016.12.038.

[43] V.M. Fthenakis, H.C. Kim, Life cycle assessment of high-concentration photovoltaic systems, Prog. Photovoltaics Res. Appl. 21 (3) (May 2013) 379–388, https://doi.org/10.1002/pip.1186.

[44] J. Payet, T. Greffe, Life cycle assessment of new high concentration photovoltaic (HCPV) modules and multi-junction cells, Energies 12 (15) (Jul. 2019) 2916, https://doi.org/10.3390/en12152916.

[45] X. Qi, X. Yao, P. Guo, Y. Han, L. Liu, Applying life cycle assessment to investigate the environmental impacts of a PV–CSP hybrid system, Renew. Energy 227 (Jun. 2024) 120575, https://doi.org/10.1016/j.renene.2024.120575.

[46] D. Costa, et al., Environmental and economic impacts of photovoltaic integration in concentrated solar power plants, Sol. Energy 274 (May 2024) 112550, https://doi.org/10.1016/j.solener.2024.112550.

[47] G. San Miguel, B. Corona, Hybridizing concentrated solar power (CSP) with biogas and biomethane as an alternative to natural gas: analysis of environmental performance using LCA, Renew. Energy 66 (Jun. 2014) 580–587, https://doi.org/10.1016/j.renene.2013.12.023.

[48] B. Corona, G.S. Miguel, E. Cerrajero, Life cycle assessment of concentrated solar power (CSP) and the influence of hybridising with natural gas, Int. J. Life Cycle Assess. 19 (6) (Jun. 2014) 1264–1275, https://doi.org/10.1007/s11367-014-0728-z.

[49] B. Corona, G. San Miguel, Life cycle sustainability analysis applied to an innovative configuration of concentrated solar power, Int. J. Life Cycle Assess. 24 (8) (Aug. 2019) 1444–1460, https://doi.org/10.1007/s11367-018-1568-z.

[50] B. Corona, G. San Miguel, Environmental analysis of a concentrated solar power (CSP) plant hybridised with different fossil and renewable fuels, Fuel 145 (Apr. 2015) 63–69, https://doi.org/10.1016/j.fuel.2014.12.068.

[51] B. Corona, D. Ruiz, G.S. Miguel, Environmental assessment of a HYSOL CSP plant compared to a conventional tower CSP plant, Procedia Comput. Sci. 83 (2016) 1110–1117, https://doi.org/10.1016/j.procs.2016.04.231.

[52] B. Corona, D. Ruiz, G. San Miguel, Life cycle assessment of a HYSOL concentrated solar power plant: analyzing the effect of geographic location, Energies 9 (6) (May 2016) 413, https://doi.org/10.3390/en9060413.

[53] V. Piemonte, M. De Falco, A. Giaconia, A. Basile, G. Iaquaniello, Production of enriched methane by a molten-salt concentrated solar power plant coupled with a steam reforming process: an LCA study, Int. J. Hydrogen Energy 37 (15) (Aug. 2012) 11556–11561, https://doi.org/10.1016/j.ijhydene.2012.03.064.

[54] J.G. Backes, A. D'Amico, N. Pauliks, S. Guarino, M. Traverso, V. Lo Brano, Life cycle sustainability assessment of a dish-stirling concentrating solar power plant in the mediterranean area, Sustain. Energy Technol. Assessments 47 (Oct. 2021) 101444, https://doi.org/10.1016/j.seta.2021.101444.

[55] G. Gasa, A. Lopez-Roman, C. Prieto, L.F. Cabeza, Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with and without thermal energy storage (TES), Sustainability 13 (7) (Mar. 2021) 3672, https://doi.org/10.3390/su13073672.

[56] Y. Lechón, C. De La Rúa, R. Sáez, Life cycle environmental impacts of electricity production by solarthermal power plants in Spain, J. Sol. Energy Eng. 130 (2) (May 2008) 021012, https://doi.org/10.1115/1.2888754.

[57] I.O. Barreiro, N.J. Tirado, M.A.S. Pérez, Life Cycle Environmental Impacts of Electricity Production by Dish/Stirling Systems in Spain, 2009.

[58] J.J. Burkhardt, G.A. Heath, C.S. Turchi, Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives, Environ. Sci. Technol. 45 (6) (Mar. 2011) 2457–2464, https://doi.org/10.1021/es1033266.

[59] V. Piemonte, M.D. Falco, P. Tarquini, A. Giaconia, Life cycle assessment of a high temperature molten salt concentrated solar power plant, Sol. Energy 85 (5) (May 2011) 1101–1108, https://doi.org/10.1016/j.solener.2011.03.002.

[60] M. Cucumo, V. Ferraro, V. Marinelli, S. Cucumo, D. Cucumo, Lca analysis of a solar concentration system for the micro-chp and comparison with a pv plant, Int. J. Heat Technol. 30 (10) (2012) 62–68.

[61] A. Kuenlin, G. Augsburger, L. Gerber, F. Maréchal, Life Cycle Assessment and Environomic Optimization of Concentrating Solar Thermal Power Plants, 2013.

[62] S.J.W. Klein, E.S. Rubin, Life cycle assessment of greenhouse gas emissions, water and land use for concentrated solar power plants with different energy backup systems, Energy Policy 63 (2013) 935–950, https://doi.org/10.1016/j.enpol.2013.08.057.

[63] S.A. Halasah, D. Pearlmutter, D. Feuermann, Field installation versus local integration of photovoltaic systems and their effect on energy evaluation metrics, Energy Policy 52 (Jan. 2013) 462–471, https://doi.org/10.1016/j.enpol.2012.09.063.

[64] T. Gibon, R. Wood, A. Arvesen, J.D. Bergesen, S. Suh, E.G. Hertwich, A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change, Environ. Sci. Technol. 49 (18) (Sep. 2015) 11218–11226, https://doi.org/10.1021/acs.est.5b01558.

[65] I.A.S. Ehtiwesh, M.C. Coelho, A.C.M. Sousa, Exergetic and environmental life cycle assessment analysis of concentrated solar power plants, Renew. Sustain. Energy Rev. 56 (Apr. 2016) 145–155, https://doi.org/10.1016/j.rser.2015.11.066.

[66] B. Corona, E. Cerrajero, D. López, G. San Miguel, Full environmental life cycle cost analysis of concentrating solar power technology: contribution of externalities to overall energy costs, Sol. Energy 135 (Oct. 2016) 758–768, https://doi.org/10.1016/j.solener.2016.06.059.

[67] T. Telsnig, G. Weinrebe, J. Finkbeiner, L. Eltrop, Life cycle assessment of a future central receiver solar power plant and autonomous operated heliostat concepts, Sol. Energy 157 (Nov. 2017) 187–200, https://doi.org/10.1016/j.solener.2017.08.018.

[68] N. Ko, M. Lorenz, R. Horn, H. Krieg, M. Baumann, Sustainability assessment of concentrated solar power (CSP) tower plants – integrating LCA, LCC and LCWE in one framework, 25th CIRP Life Cycle Eng. LCE Conf. 30 April – 2 May 2018 Cph. Den 69 (2018) 395–400, https://doi.org/10.1016/j.procir.2017.11.049.

[69] R. Li, H. Zhang, H. Wang, Q. Tu, X. Wang, Integrated hybrid life cycle assessment and contribution analysis for CO2 emission and energy consumption of a concentrated solar power plant in China, Energy 174 (May 2019) 310–322, https://doi.org/10.1016/j.energy.2019.02.066.

[70] U. Pelay, C. Azzaro-Pantel, Y. Fan, L. Luo, Life cycle assessment of thermochemical energy storage integration concepts for a concentrating solar power plant, Environ. Prog. Sustain. Energy 39 (4) (Jul. 2020) e13388, https://doi.org/10.1002/ep.13388.

[71] I. Herrera, I. Rodríguez-Serrano, Y. Lechón, A. Oliveira, D. Krüger, C. Bouden, Sustainability assessment of a hybrid CSP/biomass. Results of a prototype plant in Tunisia, Sustain. Energy Technol. Assessments 42 (2020) 100862, https://doi.org/10.1016/j.seta.2020.100862.

[72] A. Agostini, C. Carbone, M. Lanchi, A. Miliozzi, M. Misceo, V. Russo, Environmental impacts of a solar dish coupled with a micro-gas turbine for power generation, Front. Energy Res. 9 (Nov. 2021) 776821, https://doi.org/10.3389/fenrg.2021.776821.

[73] S. Rangarajan, R.R. Hernandez, S.M. Jordaan, Life cycle impacts of concentrated solar power generation on land resources and soil carbon losses in the United States, Front. Sustain. 3 (2022) 1021971, https://doi.org/10.3389/frsus.2022.1021971. Oct.

[74] A.R. Gamarra, Y. Lechón, S. Banacloche, B. Corona, J.M. de Andrés, A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: a case study for renewable energies, Sci. Total Environ. 867 (2023) 161502, https://doi.org/10.1016/j.scitotenv.2023.161502.

[75] G. Li, Q. Xuan, G. Pei, Y. Su, Y. Lu, J. Ji, Life-cycle assessment of a low-concentration PV module for building south wall integration in China, Appl. Energy 215 (Apr. 2018) 174–185, https://doi.org/10.1016/j.apenergy.2018.02.005.

[76] R. Frischknecht, G. Heath, M. Raugei, P. Sinha, M. de Wild-Scholten, Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, International Energy Agency, 2016. IEA-PVPS T12-08:2016.

[77] M. Raugei, R. Frischknecht, C. Olson, P. Sinha, G. Heath, Methodological Guidelines on Net Energy Analysis of Photovoltaic Electricity, vol. 12, International Energy Agency, 2016. IEA-PVPS Task.

[78] M. Cellura, L.Q. Luu, F. Guarino, S. Longo, A review on life cycle environmental impacts of emerging solar cells, Sci. Total Environ. 908 (Jan. 2024) 168019, https://doi.org/10.1016/j.scitotenv.2023.168019.

[79] K. Menoufi, D. Chemisana, J.I. Rosell, Life cycle assessment of a building added concentrating photovoltaic system (BACPV), Energy Proc. 128 (Sep. 2017) 194–201, https://doi.org/10.1016/j.egypro.2017.09.041.

[80] G. San Miguel, B. Corona, Hybridizing concentrated solar power (CSP) with biogas and biomethane as an alternative to natural gas: analysis of environmental performance using LCA, Renew. Energy 66 (Jun. 2014) 580–587, https://doi.org/10.1016/j.renene.2013.12.023.

[81] Y. Liang, J. Chen, Z. Yang, J. Chen, X. Luo, Y. Chen, Economic-environmental evaluation and multi-objective optimization of supercritical CO2 based-central tower concentrated solar power system with thermal storage, Energy Convers. Manag. 238 (2021) 114140, https://doi.org/10.1016/j.enconman.2021.114140.

[82] J. Freeman, K. Hellgardt, C.N. Markides, An assessment of solar-powered organic rankine cycle systems for combined heating and power in UK domestic applications, Appl. Energy 138 (Jan. 2015) 605–620, https://doi.org/10.1016/j.apenergy.2014.10.035.

[83] Z. Norwood, D. Kammen, Life cycle analysis of distributed concentrating solar combined heat and power: economics, global warming potential and water,

Environ. Res. Lett. 7 (4) (Dec. 2012) 044016, https://doi.org/10.1088/1748-9326/7/4/044016.

[84] A. Pfahl, et al., Progress in heliostat development, Sol. Energy 152 (Aug. 2017) 3–37, https://doi.org/10.1016/j.solener.2017.03.029.

[85] C. Marugán-Cruz, M. Fernández-Torrijos, C. Sobrino, D. Santana, Assessment of climate change impacts and water restrictions on solar tower plants, Int. J. Energy Res. 2023 (Nov. 2023) 1–20, https://doi.org/10.1155/2023/4830467.