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

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

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

Chr. Lamnatou*, D. Chemisana

Applied Physics Section of the Environmental Science Department, University of Lleida, c/Pere Cabrera s/n, 25001 Lleida, Spain

ARTICLE INFO

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

ABSTRACT

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

1. Introduction

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

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

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

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

* Corresponding author.
E-mail address: lamnatou@macs.udl.cat (C. Lamnatou).

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

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

CPV or CPVT) [1,2].

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

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

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

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

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

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

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

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

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