Chapter 5 A systematic review on life cycle assessment of solar water heaters

Capítulo 5 Una revisión sistemática sobre la evaluación del ciclo de vida de los calentadores solares de agua

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DOI: 10.35429/H.2022.8.56.75

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Abstract

The aim of this study is to provide an up-to-date literature review of Life Cycle Assessment (LCA) of solar water heaters, published in 2000-2021. A systematic review was chosen as the research method to achieve a comprehensive overview of existing studies in solar thermal systems, identifying the variability of the reported results due to the methodological choices such as functional units (FU), location, system boundaries, life cycle inventory, and impact methods. We conducted a quantitative analysis of the environmental impact of solar water heaters. The results show that there is a significant variability in studies for lack of data inventory, presentation of results in absolute or percentage terms, lack of normalization, and sensitivity studies. The major challenges in solar water heater LCA were identified as the lack of LCA studies in the American, Asian and Australian continents, lack of comparative studies of LCA with similar goals and scopes, lack of studies of evacuated-tube solar collectors, integral collector storage systems, and new solar water heaters.

Assessment, Systematic, Environmental issues, Solar water heater

Resumen

El objetivo de este estudio es proporcionar una revisión bibliográfica actualizada de la evaluación del ciclo de vida (LCA) de los calentadores de agua solares, publicado en 2000-2021. Se eligió una revisión sistemática como método de investigación para lograr una visión general completa de los estudios existentes en sistemas solares térmicos, identificando la variabilidad de los resultados informados debido a las opciones metodológicas, como unidades funcionales (FU), ubicación, límites del sistema, inventario del ciclo de vida. y métodos de impacto. Realizamos un análisis cuantitativo del impacto ambiental de los calentadores solares de agua. Los resultados muestran que existe una importante variabilidad en los estudios por falta de inventario de datos, presentación de resultados en términos absolutos o porcentuales, falta de normalización y estudios de sensibilidad. Los principales desafíos en el ACV de calentadores solares de agua se identificaron como la falta de estudios de ACV en los continentes americano, asiático y australiano, la falta de estudios comparativos de ACV con objetivos y alcances similares, la falta de estudios de colectores solares de tubo de vacío, almacenamiento de colector integral y nuevos calentadores solares de agua.

Evaluación, Sistemática, Cuestiones ambientales, Calentador de agua solar

1. Introduction

With the rapid population growth and industrial development, the energy demand has increased substantially. According to the International Energy Agency (IEA), world energy demand for this year is projected to increase by 4.6%, where energy consumption is centred on natural gas (3.2%) and electric energy (4.5%) (IEA, 2020). As energy plays a crucial role in the daily activities of humans, many efforts have been led to the use of conventional and no conventional energy sources to cover it. Under this context, the use of solar energy has become one of the most promising alternative energy options to cover part of energy demands at a low cost and without damaging the environment.

One of the solar technologies that has emerged is solar water heater (SWH) system, which is used to heat water for domestic and industrial applications. It offers significant advantages to their user such as cost reduction in gas and electricity bills and the carbon footprint, return on investment in a short time and reduced greenhouse gas emissions (Wang et al., 2015). It is a technology available today in both commercial and industrial scale. Despite the fact that energy technology is considered as a cleanest source, significant interaction with the environment take place throughout the life cycle of this technology. These interactions may result in an important environmental impact, especially during the manufacturing process and end-of-life phase.

As an answer to the growing interest for reducing the greenhouse gas emissions, the methodology LCA has been applied in solar technology projects. Life cycle assessment (LCA) is a valuable tool for quantifying the environmental and potential impacts of a product, process, or service. It is based on the extraction and processing of raw materials; manufacturing, transportation, and distribution; use, reuse, maintenance; recycling and final disposal (Horne et al. 2009, Kikuchi and Kanematsu, 2020).

The LCA methodology is standardised by two international standards, named ISO 14040:2006 and ISO 14044:2006 (ISO, 2006; Toniolo et al., 2020,). As described in ISO 14040/44, an LCA analysis consists of four phases: goal and scope definition; inventory analysis; lifecycle impact assessment (LCIA); and interpretation. The goal and scope definition phase determines the appropriate limits of the analysis. It establishes the functional unit, system boundaries, and quality criteria for inventory data. The life cycle inventory (LCI) analysis is the heart of the LCA process since it is involved with data collection, synthesis, validation, and calculation procedures. Life cycle impact assessment examines the process or product system from an environmental perspective, using several impact categories and indicators connected with LCA results. Different environmental impact categories are evaluated such as climate change, ozone depletion, ecotoxicity, human toxicity, photochemical ozone formation, acidification, eutrophication, resource depletion, and land use. Finally, the life cycle interpretation deals with the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment (ISO, 1997, Haque, 2020).

A number of life cycle assessment studies have been carried out with the aim to cover the environmental impacts of SWH systems in the last decade. However, very few review studies have been published. An example of this is the study carried out Tsilingiridis and Martinopoulos (Tsilingiridis et al., 2010) which demonstrated the growing interest in the energy and environmental benefits of SWH of thirty years in Greece. Their analysis showed that CO_2 reduction exceeded by 44.7% the objectives of the Greek program of ‘Climatic Change’. In 2015, Lamnatou et al. (Lamnatou et al. 2015) carried out a review on Life Cycle Analysis of solar technologies with emphasis on building-integrated (BI) solar thermal systems. Their paper revealed that is a need for solar thermal system LCA studies, especially for BI active configurations. In 2016, they studied in detail, the building-integrated solar thermal system based on vacuum-tube technology. The paper compiled all manuscripts related to this topic. The focus of this study was to analyse critical aspects of vacuum-tube technology through a case study. They showed that there are few LCA studies about this solar technology and most of them are based on embodied energy and CO_2 emissions (Lamnatou et al., 2015).

Therefore, the main objective of our research is to systematically organize and summarise published literature of solar water heating system LCAs. Our primary goal is to present an overview of the environmental impact and energy assessment of SWH. A striking feature of the solar water heating system LCAs is the variability of the reported results due to the methodological choices. These choices include functional unit (FU), location, system boundaries, life cycle inventory, and impact method. Our secondary goal is to analyse these methodological choices through qualitative analysis. It helps the research community to identify challenges and research gaps that need further exploration.

2. Research Method

We conducted a systematic review to gain an understanding of LCA on solar thermal systems. This review was done following the guidelines proposed by Kitchenham et al. (Kitchenham et al., 2007, Kitchenham et al., 2009) and Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019). The research includes several stages: i) development of a review protocol; ii) the search process for relevant publication; iii) identification of inclusion and exclusion criteria; iv) quality assessment; and v) data extraction and synthesis.

2.1 Review Protocol

Two research questions were formulated to discuss the aim of this review. The first question is directed at environmental concerns, ‘In the analysis of solar water heater, what the environmental impacts are the most analysed and topics more researched?'. The second question is directed at the research community, ‘In the analysis of the environmental impact assessment of solar water heaters, which methodological steps in the LCA can be sources of variation of results?'. A review protocol was developed to gather information on the specific question addressed by this study. As shown in Table 2.1, the review protocol consisted of two sections: bibliographic data and publication content. The bibliographic data include title, year, type of publications, and location. In the content of the publication, goal and scope definition, type of solar collector, FU, system boundaries, methodology, life cycle inventory, and impact categories were considered.

Table 2.1 Review protocol

Bibliographic data	
Author(s)	Who is/are the author(s) of the publication
Year	In which year was the work published?
Title	What is the title of the publication?
Type of publication	What kind of publication (journal/proceeding/book)?
Location	Where was the study carried out?
Focus and content of the publication	
Goal	What was the purpose/aims of the study?
Solar collector	Which is the solar thermal system studied?
Functional Unit (FU)	Which is FU used in this study?
System boundaries	Which life cycle phases were studied?
Methodology	What was the methodology used in this study?
Life cycle inventory	What were life cycle inventory used in the study?
Results	What were the environmental impacts reported?

Source: (Self Elaboration)

2.2 Data sources and search strategy

The literature search was carried out by searching for relevant articles published in Elsevier (www.sciencedirect.com), Springer (www.springerlink.com), Wiley (www.wiley.com), IEEE Xplore (http://www.ieee.org), and Google Scholar (scholar.google.com). The keywords used were related to synonyms and their acronym of LCA (‘Life Cycle Analysis', ‘Life Cycle Assessment', ‘LCA', ‘environmental performance/impact', ‘life cycle energy analysis' ‘energy assessment', and ‘LCEA'), and solar water heater (‘solar thermal collector/system', ‘heating systems', ‘domestic solar system', and ‘SWH'). The search words were connected by Boolean operators and applied to the title, abstract, and keywords.

In the first search, 2 685 studies were identified considering the diverse keywords for our systematic review. After removing duplicated publications, a second screening was based on information derived from titles and abstracts, in this stage, 325 relevant studies were identified. At the last count, a total of 38 articles were identified as primary studies.

2.3 Inclusion and exclusion criteria

In this review, journal papers, conference proceedings, and book chapters published in 2000 or later were considered in this analysis. We concentrate on English literature to make this review replicable for readers. Studies were eligible for inclusion if the focus of the study was based on the environmental and energy impact assessment of domestic solar water heaters.

Gray literature was excluded to ensure the quality of the selected articles such as research reports, thesis, presentations, and comments. These publications are usually not peer-reviewed and may represent preliminary research findings, reflecting in high variability of its quality (Costa et al., 2019). We also excluded studies on solar thermal plants, photovoltaic systems, studies presented in languages other than English, studies whose findings are unclear and ambiguous, studies that do not provide answers to the research questions, and duplicated paper of a study exist in different versions that appear as books, journal papers, conference and workshop papers.

2.4 Quality assessment

After using the inclusion and exclusion criteria, each research paper was based on four quality assessment criteria, shown in Table 2.2. Using the quality assessment, all the included papers contain high quality on Life Cycle Assessment (LCA) and Life Cycle Energy Assessment (LCEA) of solar thermal systems used in heating water.

Table 2.2 Quality assessment

Bibliographic data	
Study ID	Who is/are the author(s) of the publication
Author(s)	In which year was the work published?
Year	What is the title of the publication?
Title	What kind of publication (journal/proceeding/book)?
Type of publication	Where are they?
Country	What is the name of journal/proceeding/report?
Information about numerical simulator of thin film solar cells	
Name of the tool	What is the numerical simulation tool used in the analysis?
Features	What are the main features of the numerical simulation tools? Is the software free or licenced?
Name URL	What is the URL from which it can be downloaded?
Focus and content of the publication	
Goal	What is the purpose/aims of the study?
Topic of case study	What are the topics addressed with numerical simulation tools?
Dimensionality	What was the dimensionality addressed in the study?
Solar cell structure	What was type of structure simulated?
Type of study	What is the type of study address? (Optimisation, modelling, validation or comparison)
Date used	What were type of data introduced in the software? (Experimental/ Literature)
Simulated parameters	What were the parameters used in the simulation?

Source: (Self Elaboration)

2.5 Data extraction and synthesis

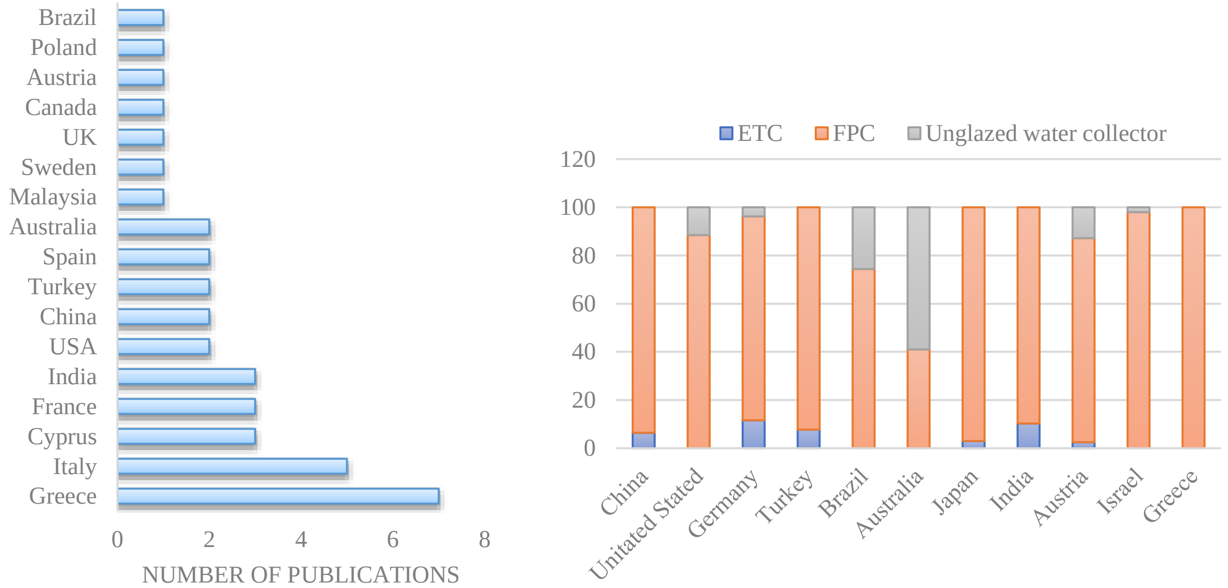
According to the review protocol, data extraction was conducted qualitatively for each of the 38 primary studies included in this review. This form enabled us to gather details of primary studies, such as aim, research methods description, findings, and conclusions. All the selected articles were analyzed in line with the research questions set for this review.

3 Results

3.1 Overview of selected studies

In general, we found that most LCAs of solar water heaters have been prepared in a European context, as shown in Graphic 3.1a. The country with the highest number of articles in LCA is Greece (7/38), evidencing the interest in developing and assessing environmental emissions of domestic solar water heaters. Italy (5/38) and Cyprus (3/38) also presented the largest number of case studies of the life cycle assessment methodology. From its part, North America is well represented with 2/38 studies of environmental impact analysis. As shown in detail in Graphic 3.1b (Qiu et al., 2015), Greece, Israel, India, Japan, Turkey and Germany are world leaders in the use of FPC systems, while China is world leader in ETC systems and United States is in unglazed water collectors. It can be seen that Israel, Brazil, Japan and Germany only report the installation of SWH and show few interests to develop and assess environmentally solar water heater systems.

Graphic 3.1 Solar water heaters in the world

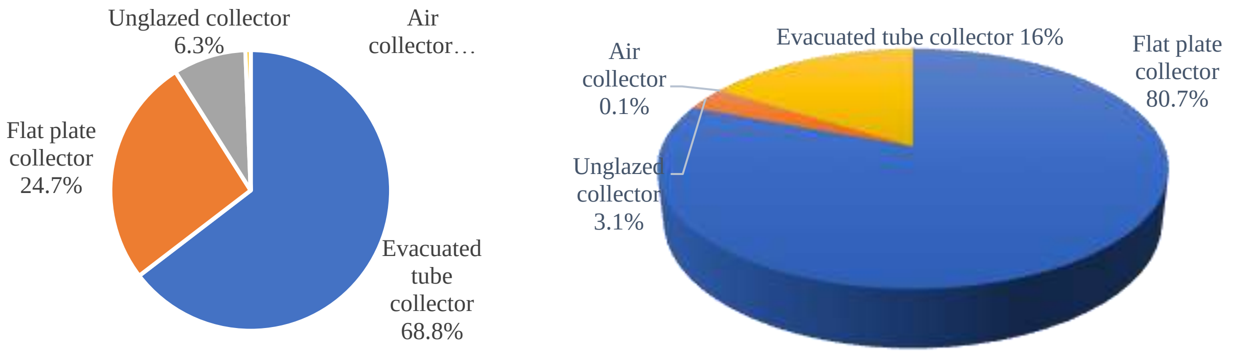


a) Geographical distribution of LCA solar water heaters
Source: (Self elaboration)

b) Ten leading countries in solar water heaters
Source: (Qiu et al., 2015)

If we consider the type of solar technology, LCA methodology has been mainly applied in flat plate solar collectors (FPC), evacuated-tube solar collectors (ETC), integral collector storage systems (ICS), and new designs of solar water heaters. The emphasis is given to the life cycle impact assessment of the flat plate solar collectors (36/38), followed by ETC systems (5/38) and ICS systems (3/38). Few studies examine the environmental performance of new designs of solar water heaters (Lamnatou et al., 2014, Kicker et al., 2018). Our results are coherent with previous findings that also indicated that in the European continent FPC are most commonly used for water heating (84.9%) than ETC (9%) or unglazed water collectors (4.5%) (Graphic 3.2b) (Giama et al., 2018). However, the situation is different at the global level, ETC are the predominant solar thermal systems in the world (64.6%), followed by FPC collectors (26.4%) and then the unglazed ones (8.4%) (Giama et al., 2018), as shown in Graphic 3.2a, which indicates a lack of LCA analysis in ETC systems.

Graphic 3.2 Solar water heater distribution



a) Distribution of SWH in the World

b) Distribution of SWH in Europe

Source: (Solar Heat Worldwide, 2020)

Analysing the topics addressed in solar water heater LCAs, we identified three subjects: a) identification of the most polluting environmental impacts during some of the life cycle scenarios in solar water heaters, b) Comparison overall or in each stage of their life cycle of products or process and c) propositions of improvement across the product life cycle (eco-design alternatives). Among the 38 studies evaluated in this review, 11 manuscripts focused on the environmental impacts overall or in some stage of the life cycle of the SWH systems. 24/38 studies compared SWH with traditional heater systems or other different solar water heater design, and 4/38 papers gave eco-design alternatives.

This study reveals that one of the three most outstanding articles analysing the environmental impacts of solar water heaters was carried out by Kalogirou et al. (Kalogirou, 2009), which evaluated the thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. The authors focused on the pollution created for the manufacture process and installation of SWH systems. The analysis showed that the total energy used in the manufacture and installation of the system can be recouped in about 13 months. The annual solar contribution is 79% with a payback time of 2.7 years and the life cycle savings of 2240 € for electricity backup and 4.5 years and 1056 € for diesel backup. Similarly, Faizal et al. (Faizal et al., 2013) presented an energy, economic and environmental analysis of a flat-plate solar collector. According to this study, more than 70% of the embodied energy of the SWH system comes from the manufacturing of the collector. Both glass and copper influence the overall weight and embodied energy of the system. The use of a nanofluid based solar collector reduces 170 kg CO_2 emissions and 0.09 years of the payback period than a conventional solar collector. In (Koroneos et al., 2012), the researchers examined the manufacturing stages of an FPC and recorded resource consumption and waste streams to the environment. The study showed that the highest environmental effect is the acidification followed by the winter smog potential.

In the topic of comparison of their life cycle of products, Hang et al. (Hang et al., 2012) evaluated FPC and ETC collectors and compared them with natural gas or electricity boilers. The results showed that the FPC and ETC have the best energetic, economic, and environmental performance. Tsilingiridis et al. (Tsilingiridis et al., 2010) applied the LCA methodology to a hybrid-solar electrical system used in Greece and compared it with electricity and natural gas boilers. It was noted that the natural gas heater has a lower environmental impact than the hybrid-solar electrical system. Moore et al. (Moore et al., 2017) investigated the global warming potential (GWP) and primary energy demand (PED) of five standard hot water systems (gas, electric and solar systems). The results indicated that the carbon footprint was reduced in domestic hot water.

For the topic of eco-design alternatives, four manuscripts explored weak points of the SWH design and proposed different eco-design proposals related to the change of materials or design. Ardente et al. (Ardente et al., 2005) studied the energy balance between the employed energy during the collector life cycle and the energy saved. The main focus of this study was eco-profile of input materials, eco-profile of electricity and transport of raw materials, installation, maintenance, and disposal steps. The results showed that the production process affects the eco-profile about 5% of impacts. It was estimated that the energy consumption of raw material eco-profiles achieved from 8 to 15 GJ, CO_2 emission from 500 to 900 kg, and the energy and emission payback times could be lower than 4 years in the worst scenario. Battisti and Corrado (Battisti et al., 2005) evaluated the environmental impact of solar thermal collectors with integrated water storage.

They reported the environmental impacts of the production, operation and disposal phase. In Eco-design, the authors chose different materials and components, in order to improve the performance of solar collector. Thanks to the optimization of the collector, the impacts were reduced 40%, with an environmental pay back times from 5 to 19 months. Albertí et al. (Albertí et al., 2019) compared a solar thermal system used in conjunction with a traditional natural gas heating system, and the natural gas heating system and evaluated different eco-design scenarios for achieving a more circular economy. It was found that the water tank, the collector and the copper tubes are the components with the largest environmental impacts. The authors proposed the change of material in the tubes from cooper to galvanized steel, the use of recycled aluminium in the collector frame and replacing the cover glass with a polycarbonate cover to reduce the environmental impacts.

Also, we identified other studies that analyse the life cycle energy assessment (10/38). Within this category, the initial embodied energy and recurrent energy incorporate were examined. In the first case, it was analysed energy required for the manufacture of material together with the energy required for transportation of a material used for solar water heaters. In the second case, it was studied the energy embodied in the material use due to maintenance, repair during the service life of the solar water heater system (Kalogirou, 2009). A case study was presented by Menzies et al. (Menzies et al., 2010), in which demonstrated how the energy embody can be reduced the through increased use of recycled materials. Leckner et al. (Leckner and Zmeureanu, 2011) found that the incorporation of SWH in buildings gives significant energy savings with relatively quick energy payback times of 8–11 years. Michael et al. (Michael and Selvarasan, 2017) compared PV/T, PV, and FPC systems.

They found that the choice of material-of-construction plays a vital role in reducing the mass, cost, embodied energy, and embodied CO_2 emissions. In addition to this, it was found that 4/38 studies based their investigation on energy carbon methodology for knowing how ‘clean’ is the solar water heater system. The rest of the studies considered both analyses.

3.2 Functional Unit (FU)

According to the review process, we found three types of Functional Unit used in LCA solar water heaters:

a) Entire equipment: the results of the assessment are reported as global quantities concerning the whole collector. It can consider the solar collector, water tank, structure, and other components.
b) Impacts per unit of area: this type of functional unit is usually selected from studies that study the environmental impacts based on the collector surface.
c) Impacts per unit of energy output: this functional unit is generally the most common alternative to energy systems, due to the environmental impacts is based on solar collectors' energy performance.

As shown in Anexo, the great majority of solar water heater LCAs used the functional unit per unit of energy output, which was selected from around 14/38 of the references. In this category, it was found several types of FU, which is related to daily (Hang et al., 2012; Marimuthu et al., 2014; Zambrana et al., 2015) and annual (Moore et al., 2017) heating energy for a specific number of people at a temperature of 60°C the production of 1 kWh (Mahmud et al. 2018; Milousi et al. 2019; Alberti et al. 2019) and 1MW (Koroneos et al., 2012) of thermal energy; 1TJ of natural gas when the solar collectors cannot provide enough hot water (Rey et al., 2008), and production in litres of heated water (Piroozfar et al., 2016). However, three publications did not detail the functional unit in this category (Vechi et al., 2018; Uctug et al., 2018; Liu et al., 2019.) On the other hand, 10/38 publications used the functional unit of the entire equipment, from which 6 articles included the solar collector, water tank, and support (Ardente et al., 2005, Menzies et al., 2007; Martinopoulos et al., 2013; Comodi et al., 2014; Comodi et al., 2016; Arnaoutakis et al., 2017). Other authors such as Lamnatou et al. (Lamnatou et al., 2015; Lamnatou et al,. 2016) considered as FU the solar collector and additional components of the systems (storage tank, pump, external tubes with their installation, and glycol), while Giama et al. (Giama et al, 2018) considered gas low-temperature boiler, solar collector pipelines, circulating pump, and radiators in this FU. Battisti et al. and Souliotis et al. (Battisti and Corrado, 2005; Souliotis et al., 2018) did not provide a detailed list of the items studied.

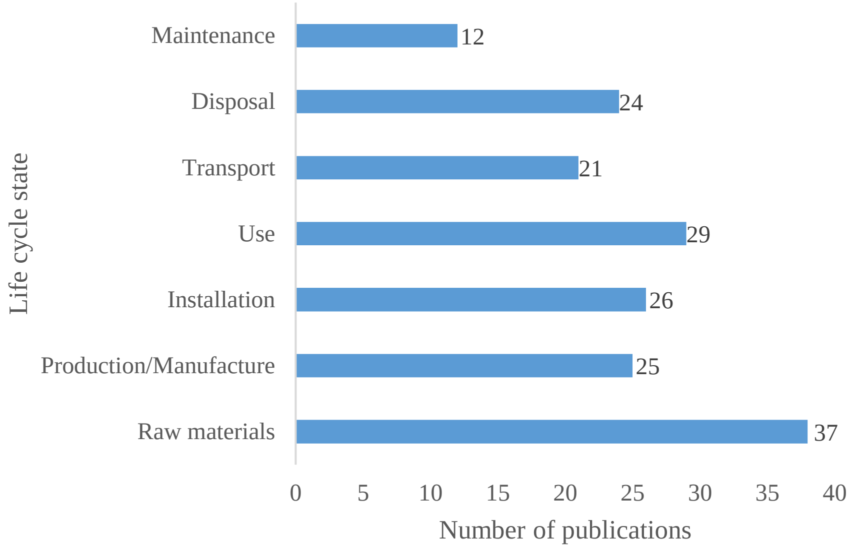
Concerning the functional unit of impacts per unit of the area, it was found that it was the least used in the LCA studies (3/38). For this functional unit, the authors (Carnevale et al., 2014; Anastaselos et al., 2016, Michael et al., 2017) defined m^2 of surface and m^2 of absorber area of a solar collector. The remaining studies provided an unclear description of the FU. It can only be implied, e.g., figure legends or tables of results, therefore, an ambiguous description of the FU can generate biased results from the LCA study.

3.3 System boundaries

In solar water heater systems, there is significant heterogeneity in the selection of system boundaries. Considering the system boundaries approached in the reviewed studies, it was found that the central focus of these publications was to examine the system boundary from cradle-to-grave (19/38), 2/38 publications specified the used of cradle to gate system boundaries (Michael et al., 2017; Mahmud et al., 2018), 1/38 conducted the LCA of a solar thermal system used cradle-to-use analysis (Kylili et al., 2018), and the remaining studies omitted one or several life cycles stages.

The consideration of all stages of the life-cycle is difficult due to the complexity to obtain data. As shown in Graphic 3.3, raw materials (37/38), installation (26/38), production (35/38), and use (28/38) phases are the most studied life cycle phases in the life cycle assessment of solar water heaters. A challenge commonly noticed in the production phase of SWH is related to the use of different materials or techniques without increasing the cost and reducing the efficiency. Moreover, it was noted that the maintenance phase was considered less frequently (12/38). Transportation is generally included in solar water heaters LCAs.

Graphic 3.3 Life cycle states



Source: (Self Elaboration)

Regarding the end-of-life phase, 24/38 articles included life cycle phase; however, a higher degree of heterogeneity can be observed in this stage. For example, some studies assumed that no recycling takes effects and the systems are put in landfill is made (Hang et al., 2012; Faizal et al., 2013; Lamnatou et al., 2016; Giama et al., 2018; Uctug et al., 2018). On the other hand, other studies such as Battirsti et al. (Battisti and Corrado, 2005) compared two different scenarios of the disposal phase: uncontrolled and controlled disposal. The controlled stage showed lower environmental impacts. Their research work did not show a detailed process of the environmental impact in eh end-of-life. For example, Carnevale et al. (Carnevale et al., 2014) considered two end-of-life scenarios for i) dismantling phase and ii) recycling treatments and disposal of residues. However, the authors focused on end-of-life of PV systems due to lacking data in SWH. On the other hand, Carlsson et al. (Carlsson et al., 2014) estimated the end-of-life-cost of a flat plate solar collector based on its expected value, considering its mental content and associated scrap metal prices. The results showed that its end-of-life valued could reduce the total cost of the system by roughly 5-10%.

3.4 Life Cycle Inventory (LCI)

The phase in which the input and output data of the system under investigation are gathered and/or calculated is known as the life cycle inventory (LCI). For the majority of the solar water heater LCAs, the inventory analysis adopted a national-level database. Some databases used in the literature were ELCD/PE International, ECODOM eco-sustainability report, PE international measured, Australian National Greenhouse Accounts, and others.

According to the review papers, the Ecoinvent database is the most used commercial database for environmental data. Fourteen articles adopted it. Other databases referred to the environmental data is the SimaPro database used in 6/38 studies (Battisti and Corrado, 2005, Hang et al., 2012, Comodi et al., 2014; Martinopoulos et al., 2013; Anastaselos et al., 2016; Souliotis et al., 2018) and the Gabi database used in the research of Comodi et al. (Comodi et al., 2016) and Moore et al. (Moore et al., 2017). From the total reviewed articles, 8/38 articles did not specify the sources of information used in their analysis.

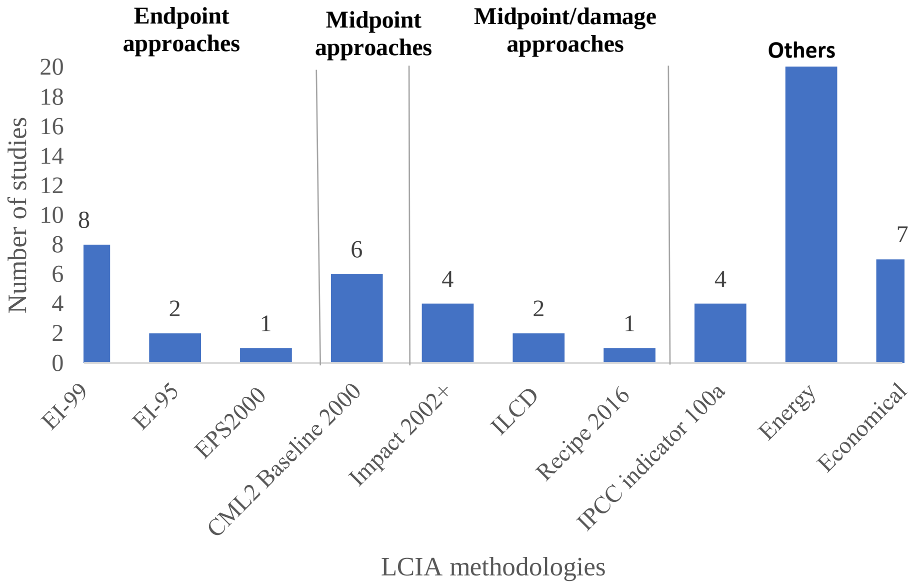
Moreover, by examining the 38 papers included in this study, it was found that 25/38 articles opted for the use of secondary sources for inventory data, which could not be reliable enough to describe the particular scenarios being modelled in solar water heater LCAs. 4/38 manuscripts used primary data such as laboratory analysis (Rey et al., 2008), lead take from collected in the field directly from the producers and verified jointly with the manager of process chains (Battisti and Corrado, 2005), information taken from manufactures' data-sheet (Martinopoulos et al., 2013; Kylili et al., 2018).

The remaining studies did not specify the collection of data inventory. Finally, it was found that out of reviewing studies of solar water heaters, only one study included an allocation scenario. It is based on the quantification of the benefits due to material recycling in system disposal (Battisti and Corrado, 2005).

3.5 Life cycle impact assessment

Life cycle impact assessment (LCIA) is used to establish a linkage between the inventory of elementary flows of a product and its potential environmental impacts. In practice, the selection of impacts categories is obtained into predefined methods, often referred to as life cycle impact assessment methods or LCIA methods (Hauschild et al., 2018). In the reviewed articles, 36 manuscripts applied LCIA methods, which are well known in the scientific literature. From these, the most used were Eco-indicator 99 in different versions with 10/38 studies, CML2 baseline 2000 method with 6/38 studies, IPCC indicator GWP 100a with 4/38 studies and Impact 2002+ method with 4/38 studies. Some manuscripts used the ILCD method (2/38), 2000 method (1/38) and ReCiPe (1/38) to evaluate the environmental impacts of SWH systems, as shown in Graphic 3.4. From the remaining articles, 23/38 studies focused on energy analysis, 7/38 studies included economic evaluations, and 3/38 did not explicitly state the characterisation method applied but reported impact categories.

Graphic 3.4 Life cycle assessment methodologies



Source: (Self Elaboration)

Considering the LCIA diverse impact categories in the studies, three main significant types of environmental impacts were found in LCA of solar water heater: i) human health, ii) ecosystem quality, and iii) resources. Based on these three categories, the ecosystem category was the most frequently studied in the SWH literature. This category was the topic of 19 publications of solar water heater LCAs. The second most commonly reviewed category, human health was included in 18 of the studies. Finally, the least frequently studied was resources. Only 13/38 studies examined this category, as shown in Anexo

Regarding the reported environmental impacts, it can be noted that 23 impacts categories were considered in the studies assessed in this review. From those, only eight impacts categories are common to at least 18 studies; acidification (17/38), ozone depletion (14/38), eutrophication (14/38), cancerogenic (10/38), fossil fuels (9/38), GWP (8/38), land use (8/38) and ecotoxicity (8/38). On the other hand, the least reviewed categories were energy resources, pesticides, and particle matter. Table 3.1 shows the results of the impact categories studied most frequent.

Table 3.1 Environmental impact categories

Author/ environment impact	Human Health										Ecosystem									Resources			
	OD	AD	SM	CA	RO	RI	RA	HT	EP	AP	GWP	GE	AC	CC	EC	LU	PE	PO	SW	MI	FF	ER	FW
Tsilingiridis et al. [16]										x													
Battisti et al. [17]	x		x						x			x	x						x				
Koroneaos et al. [26]	x		x	x					x		x		x										
Martinopoulos et al. [29]				x	x	x			x				x	x	x	x				x	x		
Comodi et al. [32]	x			x	x	x	x						x	x	x	x				x	x		
Carnevale et al. [34]	x		x	x					x				x				x		x			x	
Zambrana et al. [36]	x	x							x		x	x	x					x					
Anastaselos et al. [37]		x						x	x		x		x		x			x					x
Comodi et al. [38]	x			x	x	x	x						x	x	x	x				x	x		
Lamnatou et al. [39]	x			x	x	x	x		x				x	x	x	x				x	x		
Arnaoutakis et al. [42]	x			x	x	x	x		x				x	x	x	x				x	x		
Kylili et al. [44]	x							x	x		x		x					x			x		x
Mahmud et al [47]	x			x			x		x				x	x		x		x		x	x		x
Giama et al. [49]								x	x		x		x		x			x			x		x
Uctug et al [50]	x							x	x				x					x					
Souliotisa et al. [51]	x			x	x	x	x		x				x	x	x	x				x			
Liu et al. [52]								x			x												
Milousi et al [53]	x			x			x	x			x		x			x				x	x		x
Alberti et al. [54]	x								x		x		x					x					

OD= Ozone depletion, AD= Abiotic depletion, SM= Smog, CA=Cancerogenic, RO= Respiratory Organics, RI= Respiratory Inorganics, RA= Radiation, HT= Human toxicity, EP= Eutrophication, AP= Atmospheric pollution, GWP= Global warming potential, GE= Greenhouse effect, AC= Acidification, CC= Climate change, EC= Ecotoxicity, LU=Land use, PE= Pesticides, PO= Photochemical oxidation, SW= Solid waste, MI= Minerals, FF= Fossil fuels, ER= Energy resources, FW= Fresh water

Source: (Self Elaboration)

Results are presented according to the type of solar collector and unit. Also, 6/38 studies carried out sensitivity analysis (Ardente et al., 2005; Menzies et al., 2010; Hang et al., 2012; Moore et al., 2017; Uctug et al., 2018; Liu et al,. 2019) and 2/38 studies normalized their results (Koroneos et al., 2012; Hang et al., 2012). Therefore, in this review, it is not possible to fully compare the environmental impact of the selected studies. The range of impact categories covered is widespread, however, the assessed results for the various categories differ due to they are presented in absolute or percentage terms and with different units (Table 3.2), which hamper comparisons with other studies.

Table 3.2 Environmental impact categories

Author/ environment impact	Solar Collector	Acidification	Ozone Depletion	Eutrophication	GWP	Cancerogenic	Land use	Fossil fuels	Ecotoxicity
Battisti et al. [17]	ICS	4.045 kg SO_2	5.65E-05 kg CFC11	0.0627 kg PO_4					
Koroneaos et al. [26]	FPC	123.42	0	0.060		1.75E-04			
Martinopoulos et al. [29]	FPC	29.6 PDF*m^2 year		29.6 PDF*m^2 year		1.04E-04 DALY	34.2 PDF*m^2 year	727 MJ	8.13 PDF*m^2 year
Comodi et al. [32]	FPC	13.56 PDF*m^2 year	0 DALY			2.6E-01 DALY	0 PDF*m^2 year	25.71 MJ	2.34 PDF*m^2 year
Carnevale et al. [34]	FPC	-1.42E+01 kg SO_2	-4.89E-04 kg CFC11	-2.51 kg PO_4		-9.33E-05 kg B(a)P			
Zambrana et al. [36]	FPC	36.10 kg SO_2	5.93E-04 kg CFC11	10.50 kg PO_4	1.01E+04 kg CO_2				
Anastaselos et al. [37]	FPC/ ETC	0.233/ 0.2232 10kg SO_2	0.0356/ 0.0344 g CFC11	0.2796/ 0.2738 kg PO_4	0.3691/ 0.3597 Tn CO_2				0.0656/ 0.0610 100 kg 1,4DCB-eq
Comodi et al. [38]	FPC	1.1 PDF*m^2 year	0 DALY			0.3 DALY	0 PDF*m^2 year	25.7 MJ	2.3 PDF*m^2 year
Lamnatou et al. [39]	ICE	0.5 Pts/m^2	0 Pts/m^2	0.5 Pts/m^2		0.4 Pts/m^2	0.4 Pts/m^2	2.2 Pts/m^2	0.4 Pts/m^2
Arnaoutakis et al. [42]	FPC/ ICS	3 Pts	0 Pts	3 Pts		2.35 Pts	5 Pts	0 Pts	2.5 Pts
Kylili et al. [44]	FPC	1.77 E+01 kg SO_2	8.35E-07 kg CFC11	1.94 kg PO_4	7.07E+03 kg CO_2			9.72E+04 MJ	
Mahmud et al [47]	FPC	50%	55%	52%		53%	71%	30%	
Giama et al. [49]	FPC/ ETC	978/ 1.38E+03 kg SO_2		46.9/ 54.3 kg phosphate-eq	1.97E+05/ 2.04E+05 kg CO_2			2.37E+06/ 2.44E+06 MJ	525/676
Uctug et al [50]	FPC	5.82 kg SO_2	0.01 g CFC11	1 kg PO_4					
Souliotis et al. [51]	ICS	1 Pts/m^2	0 Pts/m^2	0 Pts/m^2		3 Pts/m^2	0.72 Pts/m^2		1 Pts/m^2
Milousi et al [53]	FPC/ ETC	2.07E-04/ 2.01E-04 kg SO_2	1.29E-08/ 1.6E-08 kg CFC11		2.38E-02/ 2.22E-02 kg CO_2	6.56E-03/ 6.53E-03 Kg 1,4DCB-eq	1.25E-03/ 1.52E-03 m^{2}a crop-eq		
Alberti et al. [54]	FPC	2.5E-04 kg SO_2	1.25E-08 kg CFC11	4.00E-05 kg PO_4	9.24E-02 kg CO_2				

Source: (Self elaboration)

Apart from environmental impacts, most of the studies carried out energy analysis in terms of embodied energy, embodied carbon cumulative energy demand (CED), greenhouse gas emission, and others. The embodied energy was calculated during the manufacturing, installation, maintenance phase of the solar water heater, and the transportation of material (Kalogirou et al., 2009; Menzies et al., 2010; Leckner et al., 2011; Arif et al., 2012). Of the 38 case studies reviewed, 4 studies only estimated the total embodied energy (Kalogirou, 2009; Faizal et al., 2013; Lamnatou et al., 2016; Michael et al., 2017), leading to significant differences in results. Also, the Energy Payback Time (EPT) and CO_2 Payback Time have been assessed within of LCA analysis. As shown in Table 3.3, they varied from 0.7 to 12 years and from 2 to 5 years, respectively. It will depend on different used materials, components, types and number of solar collectors analysed. Besides embodied energy, some studies included cumulative energy demand (CED) (Hang et al., 2012; Altun et al., 2016), CO_2 emission (Ardente et al., 2005; Menzies et al., 2007; Arif et al., 2012; Ozturk et al., 2012; Faizal et al., 2013; Carlsson et al., 2014; Comodi1 et al., 2016; Lamnatou et al., 2016; Altun et al., 2016; Michael et al., 2017, Kicker et al., 2018; Milousi et al., 2019) and carbon footprint (Hang et al., 2012; Kicker et al., 2018). The energy use for the dismantling of solar systems was not considered. Additionally, some authors included economic indicators that involved the solar water heater's initial and annual cost, pay-back period, net present value, internal rate of return, etc. (Leckner et al., 2011; Hang et al., 2012; Arif et al., 2012; Carlsson et al., 2014; Kylili et al., 2018). It was identified, that they have not been compared with other LCAs studies.

Table 3.3 LCA studies based on Embodied Energy (EE) and Payback Time

Reference	Results: Energy Payback Time	Results: Embodied Energy (EE)	Results: CO_2 Payback time	Others
Ardente et al. [18]	Less than 2 years		Less than 4 years	CO_2 emission= 500-900 kg Energy consumption= 8-15GJ CO_2 emission saving=407 kg-$_{eq}$ CO_2 yearly
Kalogirou et al. [20]	Less than 3.2 years	EE in production =2663MJ Total EE=6946MJ		
Menzies et al. [21]	6 months-2.5 years	EE in manufacture = 653.95MJ EE from transport= 227.8MJ EE in installation= 584.44 MJ EE in maintenance=888.13MJ	3.7-4.9 years	EC in Manufacture = 32.05 kg CO_2 EC from transport= 5.03 kg CO_2 EC in installation=36.94 kg CO_2 EC in maintenance=55.41 kg CO_2
Leckner et al. [22]	8-11 years	EE in manufacture=760kWh/m^2 EE in installation=7.9KWH/m^2 EE from transport= 0.0875kwh/ton km		EPR=36-4.8years
Hang et al. [23]				CED=600kwh-5000kwh per person CED payback time=1-2 months Personal carbon footprint=150-1100kg Carbon footprint payback time=1-4 months
Laborderie et al. [24]	1-1.5 years			
Arif et al. [25]	3.2-7.9 years	EE in manufacture=2924MJ		CO_2 emission reduction=2.5 tons
Ozturk et al. [27]	2 years		1.6 years	CO_2 emission=390kg
Faizal et a. [28]	2.4 years	EE=1183MJ		CO_2 emission=718.08kg
Carlsson et al. [30]	1.6-2.3 years			
Marimuthu et al. [31]	2.3 years		2.21 years	CO_2 emission=2643.34kg
Comodi et al. [32]	5-12 years		2-12 years	
Carnevale et al. [34]	1.2 years		1 year	
Yan et al. [35]	6.5 years			
Comodi et al. [38]	2-12 years		2-30 months	CO_2 emission=1213-1739kg
Lamnatou et al. [39]	Less tan 2 years	EE=7.2-46.66GJ		CO_2 saving=3.3-29.8 kg Embodied carbon=0.16t CO_2/m
Altun et al. [40]	3-4 years			CO_2 selective surface production= 0.3245kg CED=2.36E+04MJ
Michel et al. [43]	0.8 years	EE=6324.4MJ	0.13 years	CO_2 emission=424.1kg
Kicker et al. [46]	0.7-1.7 years			CO_2 footprint=101-250kg
Milousi et al. [53]				CO_2 emission=2.2-2.8E-02

Source: (Self Elaboration)

4. Summarised findings from previous studies and challenges

The results of this review indicate that there are still considerable divergences in the LCA analysis of solar water heaters. First of all, there is a notable difference between European, Asian, and Latin-American LCAs in regard to the SWH systems. We observed that most studies were developed in the European context, and a small portion of the reviewed studies belong to North America. Specifically, countries such as China, Turkey, India, Brazil and Germany that are leading the world in the installation and use of SWH are required the assessment the environmental impacts of SWH systems (Qiu et al., 2015; Gautam et al., 2017). Moreover, the results reveal that most of the LCA studies are focused on FPC systems, which is consistent with the usage popularity of the solar water heater collectors in Europe, but it is not coherent with worldwide solar water heater distribution. This distribution indicates that the most widely used solar water heater in the world is ETC systems. Therefore, it should be considered the increase of LCA studies in ETC systems and new solar water heaters.

Also, the topic of eco-design alternatives has received little attention in LCA of the solar water heater, which limits the option of identifying improvement opportunities in solar technologies in order to reduce environmental impacts along the production chain, increase the marketability of SWH through product innovation and reduce the cost of raw materials. The topic of comparison overall or in each stage of the life cycle of SWH systems is often limited to the comparison between SWH with traditional heater systems (PV, PV-T, electrical or gas boilers). The focus of the reviewed studies does not consider the comparison of a specific SWH in other locations with similar or different climatic conditions, or in different stages.

In the functional unit, we identified variations in each one of the three categories (impacts per unit of area, impacts per unit of energy output and whole system). For example, variations in the units, some authors considered MW of thermal energy, others TJ of natural gas, some others kWh; variations in the components of the SWH systems, in this point it was considered the solar collector with and without storage systems or with auxiliary systems, and variations in the surface area of SWH collector. All these variations can lead to difficulties in comparing the results of other studies with similar scopes. Given the diversity of products on the market in terms of size, components and design are impossible to establish a single functional unit to be used in all environmental assessments. However, it can be defined as a standardized set of characteristics that describes the SWH structure and its material properties, performance, and meteorological parameters helping to determine under which set to scenarios are applicable each of the functional units. Another inconsistency important in the FU was that some studies did not express their final results in terms of any specific unit, which could lead to ambiguous reference units. Under this context, it is recommendable to define this parameter to avoid misinterpretation of the results.

In the system boundaries, the majority of the studies addressed cradle-to-grave analysis. However, not all studies cover all stages of the life-cycle and exclude the end-of-life stage for a lack of data inventory and the complexity to obtain data. Also, most LCA studies do not consider financial feasibility or life cycle cost in their analysis, which can help the users to select the appropriate technology for their hot water needs. Therefore, the life cycle cost of SWH systems can be a research opportunity area.

Part of the accuracy of the LCA comes from the LCI. In this aspect, we identified that secondary data has been considered the first option in the LCA studies, which could not be reliable enough to describe the particular scenarios. In this sense, it is prudent to report the manufacturing process and materials information or collect the information in some international database or commercial software package, in order to reduce the variations in the LCA studies. Finally, in life cycle impact assessment, it was possible to identify the application of different LCIA methods, such as Eco-indicator 99, CML2 baseline 2000, IPCC indicator GWP 100a, Impact 2002+ method, and others. It allows the know the application and the differences between the methodologies. However, if we considered the LCIA diverse impact categories in the studies, studies show different categories resulting in a difficult to compare methods and results among similar studies of solar water heaters. Therefore, it is suggested use some normalization, grouping and weighting, and sensitivity studies for comparing the environmental impact.

5. Annexes

Key points of analysis of reviewed papers

Author	Year	Country	SWH	Scope	Type	FU	Methodology	R	P	I	U	T	D	M
Tsilingiridis et al. [16]	2004	Greece	FPC	To compare of environmental impact of SHW system vs electric boiler	LCA		EI-99	x	-	x	-	x	-	-
Battisti et el. [17]	2005	Italy	ICS	To calculate the energy and environmental pay back times of ICS, and providing hints for collector optimization, especially in the production step	LCA	Solar collector	EI-95	x	x	x	x	-	x	-
Ardente et al. [18]	2005	Italy	FPC	To synthesise the main energy and environmental impacts	LCA/ LCEA	Solar collector	EPT, EMPT	x	x	x	-	x	x	x
Rey-Martínez et al. [19]	2008	Spain	FPC	To evaluate the environmental impacts and quantify the financial cost of such emissions.	LCA	1TJ of natural gas when the solar collectors cannot provide enough hot water	EPS2000	x	-	x	-	-	-	-
Kalogirou [20]	2009	Cyprus	FPC	The environmental benefits of SWH	LCEA		EE	x	x	x	-	-	-	-
Menzies et al. [21]	2010	UK	FPC	To evaluate the lifecycle energy and carbon intensity	LCEA	Solar collector	EE, LCCA	x	x	x	-	x	-	x
Leckner et al. [22]	2011	Canada	FPC	To compare the life-cycle energetic, economic and environmental impacts	LCEA/ LCC		EE, LCC	x	x	x	x	x	-	-
Hang et al. [23]	2012	USA	FPC, ETC	To compare the energetic, economic and environmental impacts	LCEA/ LCC	The daily heating energy for a family of 2.53 persons (236 l of hot water at 60°C).	IPCC GWP100a	x	x	x	x	x	x	-
Laborderie et al. [24]	2012	France	FPC	To characterise the environmental performances	LCA	Production of DHW for a four-person household, for template climate (assessed to be 140 litres of 60°C) and tropical (assessed to be 200 litres of 50°C)	Impact 2002+	x	x	-	x	-	x	-
Arif [25]	2012	India	FPC	To estimate the primary energy and costs required in manufacturing process and in maintaining	LCEA/ LCC		EPF, EE	x	x	x	-	-	-	-
Koroneos et al. [26]	2012	Greece	FPC	To quantify the environmental and financial benefits of the installation of a SWH with electricity as auxiliary	LCA	1 MW of produced hot water	IRR, NPV, PBP	x	x	x	x	x	x	-
Ozturk et al. [27]	2012	Turkey	FPC, PV, PVT	To evaluate energy, exergy and LCA Analysis of a FPC, PV and PV-T collector	LCEA	The energy used by all the processes associated with the production of the materials	EE	x	x	-	-	-	-	-
Faizal et a. [28]	2013	Malaysia	FPC	To quantify the emissions from the manufacturing of the collectors and damage cost reduction	LCEA		EE, CS	x	x	-	-	-	-	-
Martinopoulos et al [29]	2013	Greece	FPC	To investigate of how different materials/techniques used in the manufacturing of DSHWS influence environmental performance	LCA	Solar collector	EI-99	x	x	x	x	x	x	-
Carlsson et al. [30]	2014	Sweden	FPC	To assess the suitability of solar collector systems	LCA/ LCEA/ LCC		IPCC GWP100a, CED	x	x	-	x	-	x	x
Marimuthu et al. [31]	2014	India	FPC	To compare FPC with electric water to quantify the environmental and energy benefit	LCEA	100 l per day solar water heater available	EPT, CPBP	x	x	-	x	-	x	x
Comodi et al. [32]	2014	Italy	FPC	To present both An LCA and a payback time analysis for a SWH	LCA	Solar collector	EI-99-EE	x	x	x	x	-	x	x
Lamnatou et al. [33]	2014	France	FPC	To study a patented solar thermal collector based on EE and EC methodologies	LCEA	Solar collector	EE, EPT, EC	x	x	x	x	x	x	x
Carnevale et al. [34]	2014	Italy	FPC	To compare the energy and environ- mental performances of PV and FPC	LCA/ LCEA	1 m^2 of roof surface.	EI-95, EPT, EMPT	x	x	x	x	x	x	x
Yan et al. [35]	2015	Hong Kong	FPC	To present a simplified method for optimizing the key parameters of solar water heating systems based on LCAE	LCEA		EPT	x	-	-	x	-	-	-
Zambrana et al. [36]	2015	Spain	FPC	To analyse the environmental implications of SHWS	LCA/ LCEA	Daily heating energy for HWD in each target building considered	CML 2 baseline 2000, EPT	x	x	x	x	x	x	-

Anastaselos et al. [37]	2015	Greece	FPC	To evaluate of the environmental performance of SWH	LCA	1 m^2 of FPC area	CML 2 baseline 2000	x	x	x	x	-	-	-
Comodi et al. [38]	2015	Italy	FPC	To evaluate energy, CO_2 and economic payback times	LCA/ LCEA	Solar collector	EI-99-EE, EPT, EMPT, ECPT	x	x	x	x	x	x	-
Lamnatou et al. [39]	2015	France	ICE	To examine three alternative configurations with EI99, IMPACT 2002+, embodied energy and embodied carbon	LCA	Solar collector	EI-99 IMPACT 2002+ EE EC	x	x	x	x	x	x	x
Altun et al. [40]	2016	USA	FPC	To show the effect of the production method on the manufacturing process of FPC	LCA	Area of 250,000 m^2	CED Greenhouse Gas Protocol EI-99	x	x	x	x	x	x	-
Piroozfar et al. [41]	2017	Cyprus	FPC	To gauge the environmental impacts of different types of residential water heating systems	LCA/ LCEA	The production of 392,448,000 litres of heated water with a temperature of at least 37° C	CML 2001	x	x	x	x	x	x	-
Arnaoutakis et al. [42]	2017	Greece	FPC, ICS	To present a detailed comparative experimental study of SWHs	LCA/ LCEA	Solar collector	EI-95	x	x	x	x	-	-	-
Michel et al. [43]	2017	India	FPC, PVT	To compare a solar PV/T, a PV system and a FPC based on economic evaluation and environmental assessment	LCA/ LCEA		EE EC	x	x	-	-	-	-	-
Kylili et al. [44]	2017	Cyprus	FPC	To quantify this unexploited potential and assess the environmental impact	LCA/ LCEA/ LCC	Aperture area [m²] Number of solar collectors Number of water storage tanks	CER	x	x	x	x	x	-	x
Moore et al. [45]	2017	Australia	FPC	To investigate the GWP and PED	LCEA	Annual hot water load of 34.4 MJ/d	IMPACT 2002+ ILCD, PED	x	x	-	x	x	x	-
Mahmud et al. [47]	2018	Australia	FPC	To present an LCA of a PV system and a solar-thermal system	LCA	1 kWh of energy	ILCD Impact 2002+ RMF CED IPCC	x	x	x	x	-	-	-
Vechi et al. [48]	2018	Brazil	FPC	To assess the environmental impact of electric, natural gas and SWH	LCA	2,803,200 litres of hot water at a temperature greater than or equal 37°	IPCC GWP 100a	x	x	-	x	x	x	-
Giama et al. [49]	2018	Greece	FPC, ETC	To compare and present an environmental evaluation of SWH	LCA	Solar collector	CML 2001, GPW	x	x	x	x	x	x	x
Uctug et al. [50]	2018	Turkey	FPC	To estimate and compare life cycle environmental impacts of supplying domestic hot water to households	LCA	100 l per day at a temperature of 60 °C	CML 2001	x	x	-	-	-	x	x
Souliotis et al. [51]	2018	Cyprus	ICS, PVT	To present am LCA study of two innovative solar water heating systems, integrated on the facades and the roof of a social house building	LCA	Solar collector	EI-99	x	x	-	x	-	x	-
Liu et al. [52]	2019	China	ETC, FPC	To estimate the life-cycle environmental impacts and costs of a SWH	LCA/ LCEA	Energy requirements for using DHW per person, per year, supplied by the DHW system in a typical three person Chinese household	PED	x	x	x	x	x	x	x
Milousi et al. [53]	2019	Greece	PV, FPC/ ETC	To present a holistic evaluation of the energy and environmental profile of PV and FPC	LCA	The saving of 1 kWh electricity for hot water production	ReCiPe 2016	x	x	x	x	x	x	-
Albeti et al. [54]	2019	China	FPC	To compare a SWH and a natural gas heating system	LCA/ LCEA	1 kW h of thermal energy to cover the DHW demand of a 6 persons house	CML 2001	-	x	-	x	x	x	-

LCCA=Life Cycle Carbon Analysis, LCC= Life Cycle Costs, EC= Embody Carbon, EE= Embody Energy, EPF=Energy Production Factor, CED= Cumulative Energy Demand, GWP= Global Warming Potential, Uncost= Annualized Uniform Cost, PED= Primary Energy Demand, ILCD=International Reference Life Cycle Data System, IE=Eco-Indicator, IRR= Internal Rate-of-Return, NPV=Net Present Value, CS=Cost savings, CER= Consumed Energy Ratio, EPT= Energy payback time, CPBT= Carbon Payback Time, ECPT= Economic payback time, RMF=Raw Material Flows, IPCC= Intergovernmental Panel on Climate Change, E= Raw materials, P= Production/Manufacture, I= Installation, M= Maintenance, D= Disposal, T= Transport,

Source: (Self Elaboration)

6. Acknowledgment

All authors acknowledge financial support from Conacyt (Mexico), and PRODEP. The author Álvarez-Macías is thankful to TecNM for the financial support.

7. Conclusions

This study presents a systematic review of environmental and energy assessment of solar water heaters, focusing on the variability of reported results due to methodological choices. The methodological choices include functional unit (FU), location, system boundaries, life cycle inventory, and impact method. Significant variations in the results were identified in terms of methodological choices (e.g., system boundaries, allocation procedures, or data quality). The most important aspects were related to the lack of studies in America, Asia, and the Australian continents. From a technological aspect, there is a need for LCA in evacuated-tube solar collectors (ETC), integral collector storage systems (ICS), and new designs of solar water heaters. From an LCA methodological perspective, there are limitations in studies on comparison overall or in each stage of their life cycle of products and the identification of possible opportunities for improving the solar water heaters through eco-design alternatives. Another critical aspect is that some studies provide an unclear description of the FU, which leads to discrepancies in the results. Moreover, it was observed that the significant discrepancies are in system boundaries and life cycle impact assessment, due to the authors excluding life cycle phases in the system boundaries. There is a lack of uniformity in the results unit (some studies presented in absolute or percentage terms), and a need for normalization, grouping, weighting and sensitivity studies.

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