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Title: A systematic review on life cycle assessment of solar water heaters

Authors: SALGADO-CONRADO, Lizbeth, ÁLVAREZ-MACÍAS, Carlos, ESMERALDA-GÓMEZ, Alma Graciela and PÉREZ-GARCÍA, Laura Andrea

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ECORFAN-México, S.C.
143 – 50 Itzopan Street
La Florida, Ecatepec Municipality
Mexico State, 55120 Zipcode
Phone: +52 1 55 6159 2296
Skype: ecorfan-mexico.s.c.
E-mail: contacto@ecorfan.org
Facebook: ECORFAN-México S. C.
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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).

One of the solar technologies that has emerged is the solar water heater (SWH) system, which is used to heat water for domestic and industrial applications

Introduction

Tsilingiridis et al., 2010

studied the energy and environmental benefits of SWH systems

Lamnatou et al., 2015

analysed critical aspects of vacuum-tube technology through a case study

Lamnatou et al. 2015

carried out a review on Life Cycle Analysis of solar technologies with emphasis on building-integrated (BI) solar thermal systems.

LCA Methodology

It is a tool for quantifying the environmental and potential impacts of a product, process, or service.

*ISO 14040:2006
*ISO 14044:2006

Four phases

1. Goal and scope definition
2. Inventory analysis
3. Lifecycle impact assessment (LCIA)
4. Interpretation.

Objetive

OBJETIVE

The aim of this study is to provide an up-to-date literature review of the Life Cycle Assessment (LCA) of solar water heaters, published in 2000-2021.

QUESTIONS

‘In the analysis of solar water heater, what the environmental impacts are the most analysed and topics more researched?'

‘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?

Methodology

This review was based on Kitchenham et al. (Kitchenham et al., 2007, Kitchenham et al., 2009) and Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019).

Stage1

Development of a review protocol

Stage 2

Search process for relevant publication

Stage3

Identification of inclusion and exclusion criteria

Concept 3

Quality assessment

Concept 4

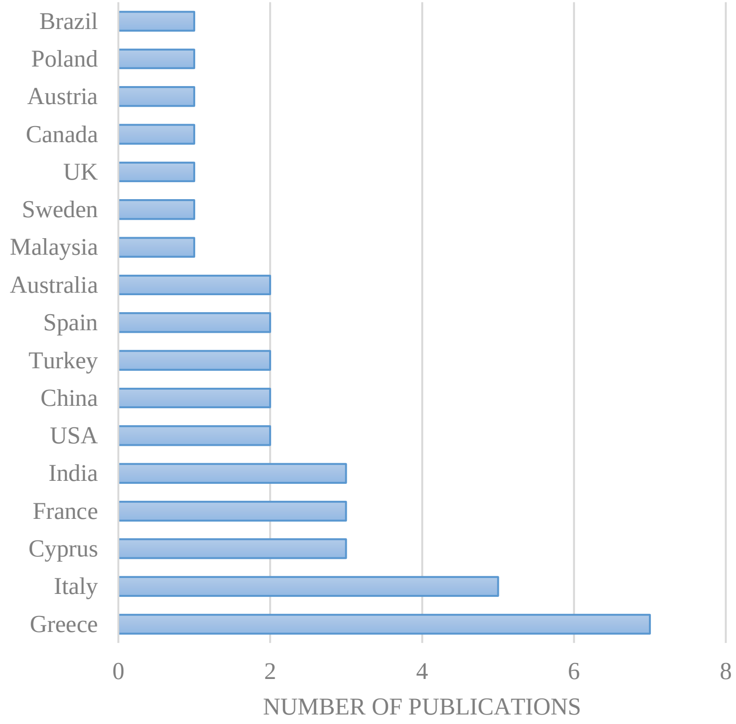
Data extraction and synthesis

Results

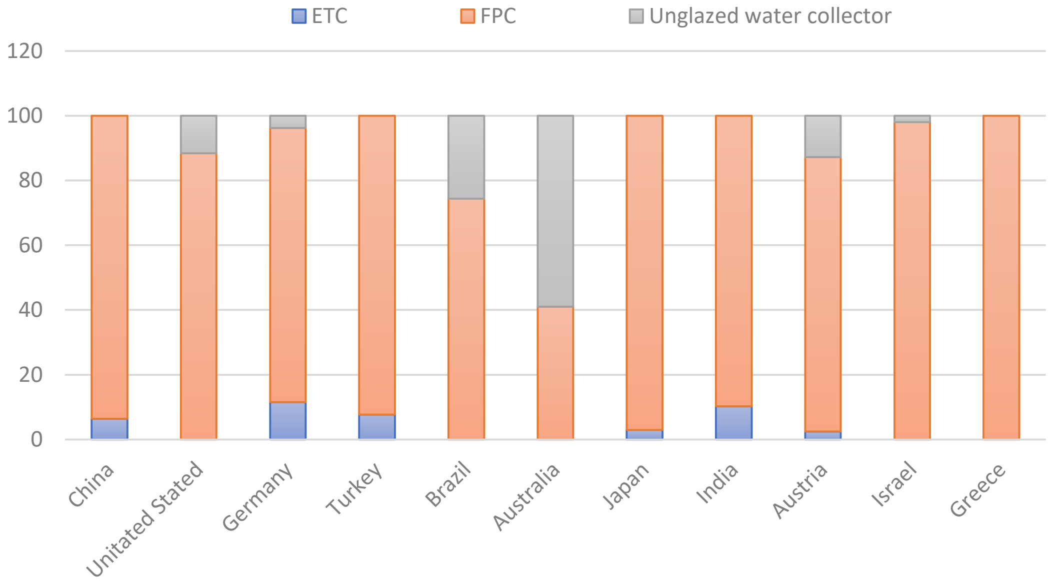
The country with the highest number of articles in LCA is Greece (7/38), evidencing the interest in developing and assessing environmental emissions of domestic solar water heaters.

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.

Graphic 3.1 Solar water heaters in the world

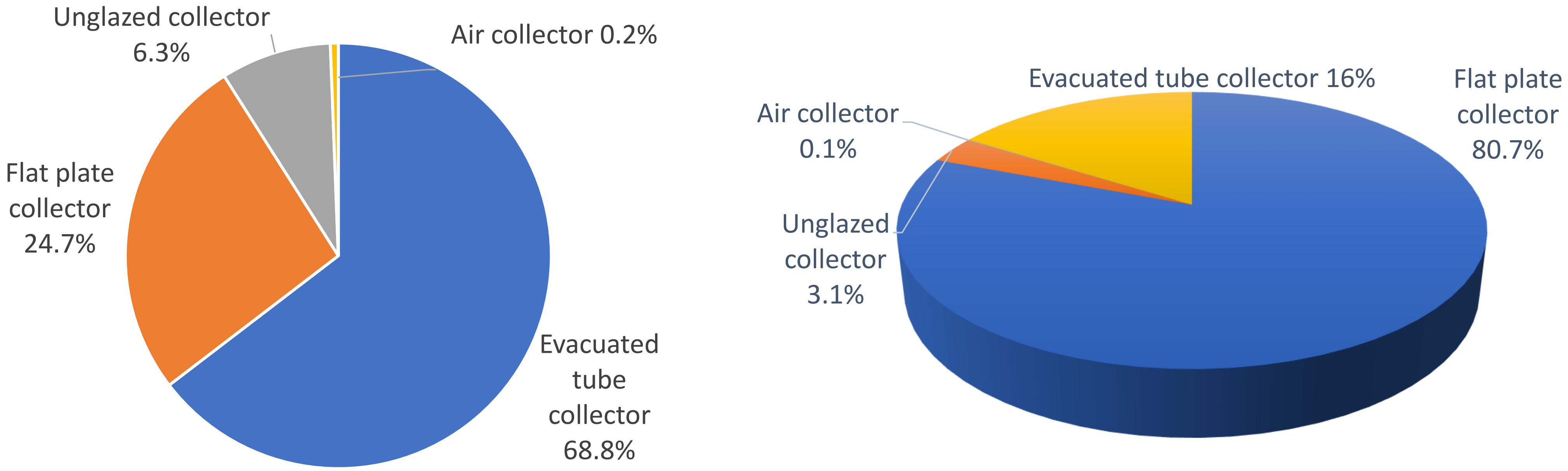


Geographical distribution of LCA solar water heaters Source: (Self elaboration)



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

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)

Topics addressed in solar water heater LCAs

Topics LCA

- Identification of the most polluting environmental impacts
- Comparison overall or in each stage of their life cycle
- Propositions of improvement across the product life cycle (eco-design alternatives)

Functional Units

01

*Entire equipment

*Impacts per unit of area

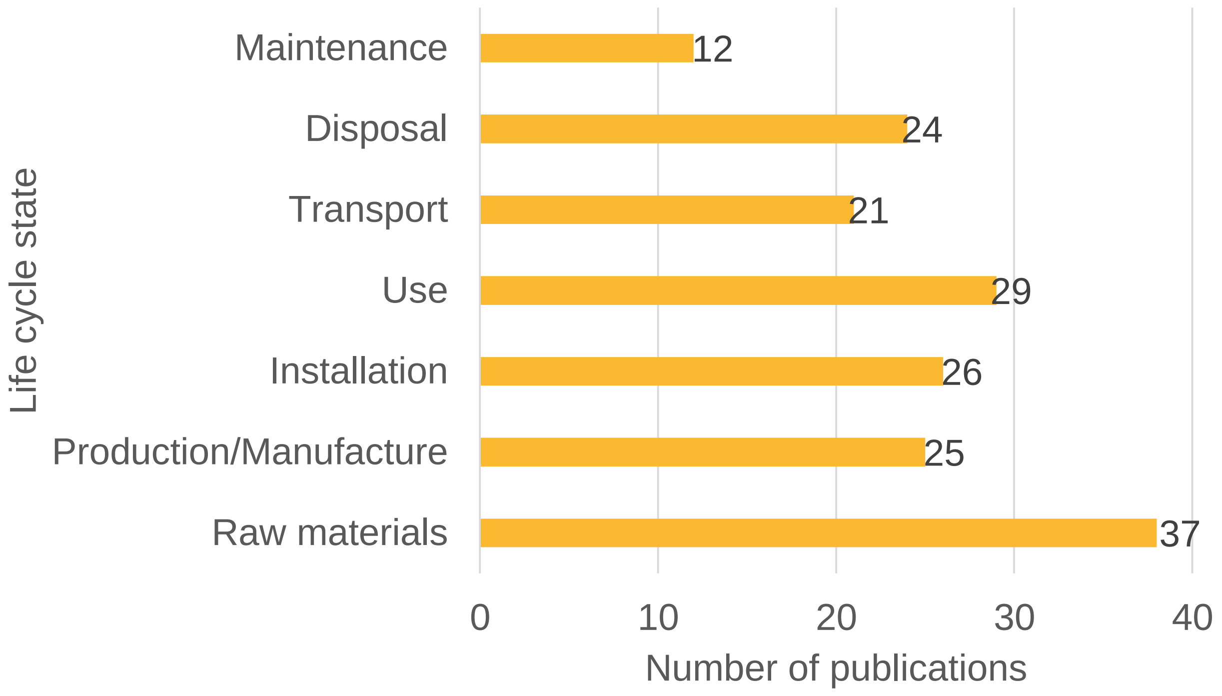
*Impacts per unit of energy output

System boundary

In solar water heater systems, there is significant heterogeneity in the selection of system boundaries.

The central focus in reviewed 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.

Graphic 3.3 Life cycle states



Source: (Self elaboration)

Life Cycle Inventory (LCI)

National-level database

ELCD/PE International, ECODOM eco-sustainability report, PE international measured, Australian National Greenhouse Accounts, and others.

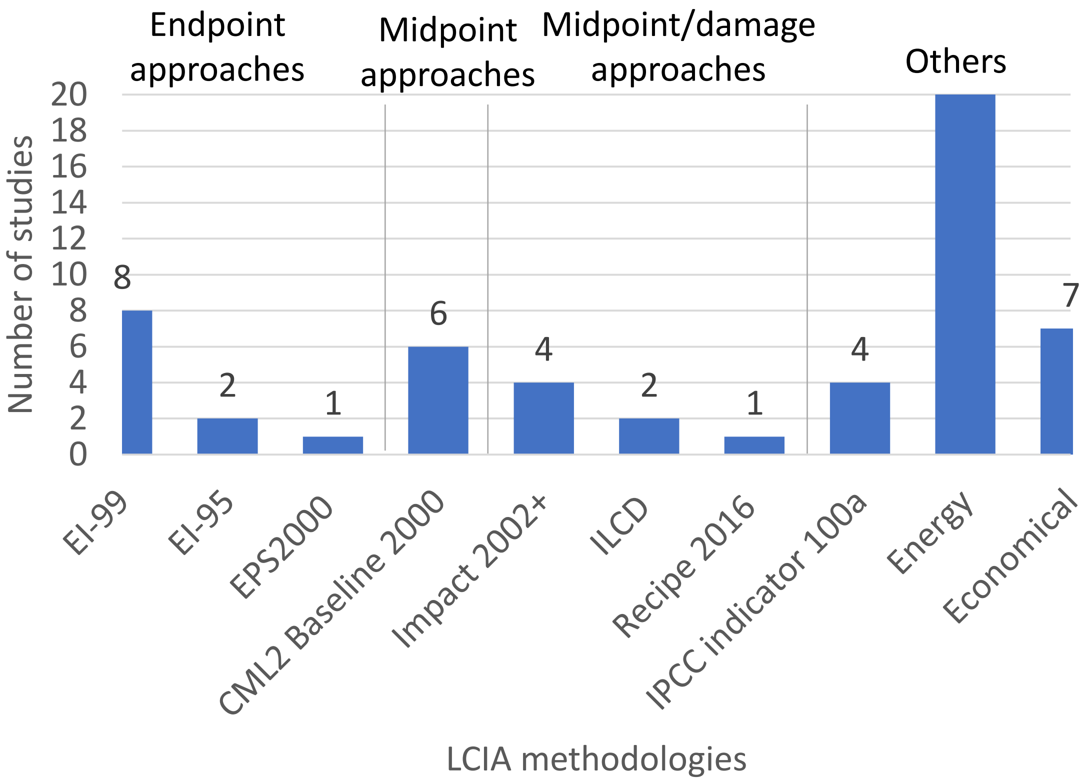
Software

Ecoinvent database
SimaPro database
Gabi database

No specified

Life cycle impact assessment

Graphic 3.4 Life cycle assessment methodologies



Source: (Self elaboration)

Life cycle impact assessment

Table 3.1 Environmental impact categories

Source: (Self elaboration)

Author/ environment impact	Human Health								Ecosystem										Resources				
	OD	AD	SM	CA	RO	RI	RA	HT	EP	AP	GW	P 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

Life cycle impact assessment

Table 3.2 Environmental impact categories

Source: (Self elaboration)

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

Conclusions

*It was identified a lack of LCA studies in solar water heaters 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.

*It was identified that some studies provide an unclear description of the FU, which leads to discrepancies in the results.

*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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