Thermal Science and Engineering Progress 38 (2023) 101670

Contents lists available at ScienceDirect

Thermal Science and Engineering Progress

journal homepage: www.sciencedirect.com/journal/thermal-science-and-engineering-progress

Environmental impacts of solar thermal power plants used in industrial supply chains

Lisa Baindu Gobio-Thomas [a], Muhamed Darwish [a], Valentina Stojceska [a,b,*]

[a] Brunel University London, College of Engineering, Design and Physical Sciences, Uxbridge UB8 3PH, UK
[b] Brunel University London, Institute of Energy Futures, Centre for Sustainable Energy Use in Food Chains, Uxbridge UB8 3PH, UK

ARTICLE INFO

Keywords:
Life Cycle Assessment (LCA)
Environmental assessment
Solar thermal plants
Environmental impact
Sustainability assessment
CSP plants

ABSTRACT

A systematic literature review was conducted to investigate the environmental impact of solar thermal power plants in the industrial supply chains. A number of different solar thermal power collectors like parabolic trough (PT), linear Fresnel (LFR), solar dish (SD) and solar towers (ST) were considered and analysed. The first observation was that PT collectors generate the lowest level of Green House Gas (GHG) emissions, followed by LFR, DT and SD plants. There was a lack of studies dealing with the GHG emissions of LFR and SD plants, which demonstrated a need of conducting more studies to gain better understanding of their environmental performances. The second observation was that different environmental assessment software tools used for analysing the environmental impact showed conflicting results because of the different approaches used in the characterization factors management in each software. Those software tools include: SimaPro, Gabi, System Advisor Model (SAM), Umberto and Thermoflex + PEACE. The standardization of environmental software tools and life cycle impact assessment methods is required to prevent discrepancies in life cycle assessment results. The third observation was the need for integrated environmental and economic assessments to provide a comprehensive evaluation of the solar thermal plants as it will enable investors, policy-makers and researchers to make informed decisions about the environmental and economic impacts of those plants.

1. Introduction

Demand for energy has increased significantly due to population growth and socio-economic development in different sectors [1]. The world’s energy needs are mainly provided by fossil fuels that generate higher levels of greenhouse gas (GHG) emissions in the atmosphere. There is a pressure from the governments across the world to reduce GHG emissions in order to limit global warming to approximately 1.5 °C, as documented in United Nations Framework Convention on Climate Change (UNFCCC) and 2015 Paris Agreement [2]. In line with those agreements, the EU Parliament and its member states have agreed to reduce greenhouse gas (GHG) emissions by at least 55 % by 2030, compared to 1990 levels and be carbon neutral by by 2050 [3]. As a result, a number of incentives have been provided to the member states like “Just Transition Mechanism, “Innovation Fund” and “Horizon Europe” to encourage the reduction of GHG emissions in various sectors [5]. The EU’s Just Transition Mechanism provides financial support for the transition of carbon-intensive industries to low carbon technologies [4,5]. The Innovation Fund provides funding for technologies that can achieve significant GHG emission reductions through low carbon technologies, renewable energy generation, and carbon capture [4]. Horizon Europe funds research and innovation projects that tackle climate

---

Abbreviations: CSP, Concentrated Solar Power; LFR, Linear Fresnel Reflector; TES, Thermal Energy Storage; HTF, Heat Thermal Fluid; GHG, Greenhouse Gas Emissions; SAM, System Advisor Model; LCA, Life Cycle Assessment; LCIA, Life Cycle Impact Assessment; CO_2, Carbon-dioxide; g CO_2 eq/kWh, Grams of carbon-dioxide equivalent per kilo-watt hour; ST, Solar tower plant; PT, Parabolic trough plant; GWP, Global Warming Potential; PCM, Phase Change Materials; IPCC, Intergovernmental Panel on Climate Change; EIPPCB, European Integrated Pollution Prevention & Control Bureau; ReCiPe, The ReCiPe method combines both approaches of midpoint and endpoint modelling and can be used globally for LCIA. It enables the life cycle inventory results to be translated into a limited number of indicator scores which shows the relative severity in a category of environmental impact; IMPACT 2002+, IMPACT 2002+ is a life cycle impact assessment method that combines both midpoint and damage techniques. It connects the life cycle inventory results (inputs & outputs) with the four damage categories of human health, ecosystem quality, resources and climate change.

* Corresponding author at: Brunel University London, College of Engineering, Design and Physical Sciences, Uxbridge UB8 3PH, UK.
E-mail address: Valentina.Stojceska@brunel.ac.uk (V. Stojceska).

https://doi.org/10.1016/j.tsep.2023.101670
Received 9 October 2022; Received in revised form 11 January 2023; Accepted 12 January 2023

change, while improving the EU's economic growth [5]. Most of the European countries also have feed-in-tariffs that pay renewable energy producers for the electricity exported to the national grid encouraging more generation of renewable energy. Currently, the renewable energy contributes to approximately 22 % of the total energy demand that is mainly used for heating and cooling processes while the rest is provided by the fossil fuels, particularly for the industrial processes that require temperature of above 400 °C [7,6,3–5]. This accounts 47 % of the EU's total heat demand in EU industry whilst overall heating and cooling accounts 73 % [8]. The solar thermal power technologies seem promising to provide heating and cooling for industrial processes that will contribute to their decarbonisation.

One of the techniques that has been widely used to assess the environmental performances of solar thermal plants is life cycle assessment (LCA). It quantifies and evaluates the environmental impact of entire product or service over and considers the environmental impact of all the activities from the extraction of raw materials, manufacturing, transportation, usage, to the final disposal or recycling of the products [30]. A various method such as ReCiPe indicator, IMPACT 2002+, Eco-indicator 99, IPCC Global Warming Potential (GWP) could be used to evaluate the environmental impacts through LCA. LCA enables the environmental performance of solar thermal plants to be assessed and compared with the other technologies of different energy sources. It also enables investors, policy-makers and researchers to have a better understanding and make informed decisions about the sustainability of solar thermal plants.

The aim of this review is to investigate the environmental impact of solar thermal power technologies and identify knowledge gaps in the environmental impact of the solar thermal plants that are used in different industrial processes. The use of different types of solar thermal technologies, their maximum thermal temperatures, plant capacities and the LCA tools are considered.

2. Systematic literature review

The systematic literature review was conducted using several web sites: Web of Science, Science Direct and Scopus databases. The five central key words used in the searches were: Environmental assessment, LCA, CSP plants, solar thermal plants and environmental impact. The terms like "life cycle assessment" OR "environmental assessment" OR "environmental impact" and CSP plants or solar thermal plants were used to retrieve papers. The inclusion criteria were: articles, proceeding papers, book chapters and publication dates between 2010 and 2022. The retrieved papers were then carefully reviewed on a case-by-case basis considering their titles and abstracts. It was observed that thirty-five papers were relevant to meet the inclusion criteria while twenty-two papers were based solely on the environmental LCA of solar thermal plants and thirteen papers evaluated both the environmental and economic performance of the plants.

3. Investigation of the environmental impact of solar thermal plants

In this section, the environmental impact of different solar thermal technologies with their thermal output temperatures and capacities are investigated. Fig. 1 shows the frequency of the solar thermal technologies used in thirty-five studies. It can be seen that the parabolic trough technology was the most popular, used in twenty studies, which can be attributed to it being the most established and developed solar thermal technology. The next popular technology was solar tower plants, used in thirteen studies. This is probably because it is a well-established technology and can achieve higher temperatures compared to parabolic trough plants. The linear Fresnel technology as a fairly new technology was used only in six studies, however, it gained a lot of interest due to its cheaper cost and high land use efficiency [52]. The solar dish technology was used in only three studies, that could be attributed to its higher capital costs, which resulted in the lack of its deployment on a commercial scale [19].

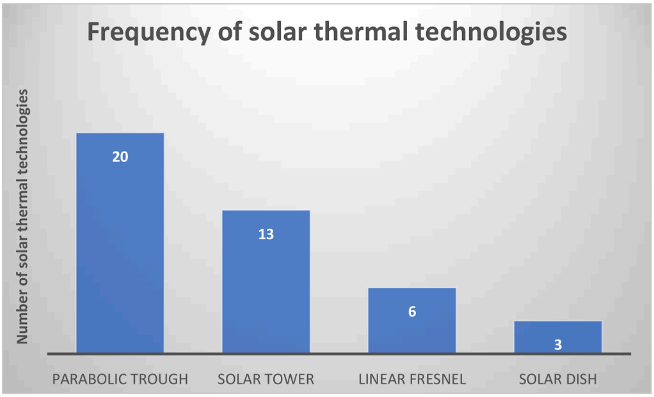

Fig. 1. Frequency of solar thermal technologies used in the studies.

Parabolic trough, solar tower, linear Fresnel and solar dish are solar thermal technologies discussed in this paper, with their diagrams presented in Figs. 2–5. The least popular solar thermal technologies are solar dish, linear Fresnel and solar tower as shown in Fig. 1. Fig. 2 presents a diagram of a solar dish system. A solar dish also known as a parabolic dish, uses mirrors that are mounted over a parabolic-shaped dish to focus the sun's rays onto a receiver. The dish and the receiver follow the sun together using a two-axis solar tracking system. The receiver is mounted at the focal point of the dish along with a heat engine such as a stirling engine. The heat transfer fluid in the receiver absorbs the collected thermal energy from the sun and can be transferred to a thermal storage unit, to supply heat directly for industrial applications, or to operate a turbine to generate electricity [21,20].

Fig. 3 presents a linear Fresnel reflector (LFR) technology. A linear Fresnel reflector's design is similar to a parabolic trough system but it has a fixed receiver pipe while the mirrors track the sun to reflect light onto the receiver tube. This simpler design results in its cheaper cost compared to parabolic trough. In linear Fresnel technology, the trough shape is split into multiple mirror facets which can be either flat or curved reflective mirrors [23]. The concentrating mirrors are set either on the ground or very close to the ground with a single-axis or double-axis sun-tracking system [24]. Each mirror can be individually controlled and rotates around an axis at a certain angle to reflect solar beam radiation toward the fixed receiver system. The fixed receiver system consists of a receiver tube which contains a heat transfer fluid that absorbs the collected thermal energy and can be used for heat or electricity generation [13]. The main advantages of LFR are its simplicity, robustness, low wind load, low capital cost, and flexibility of design [24].

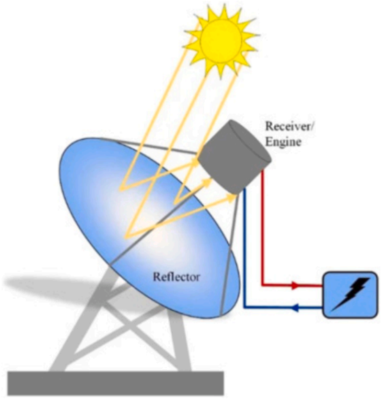

Fig. 2. Diagram of a solar dish system [22].

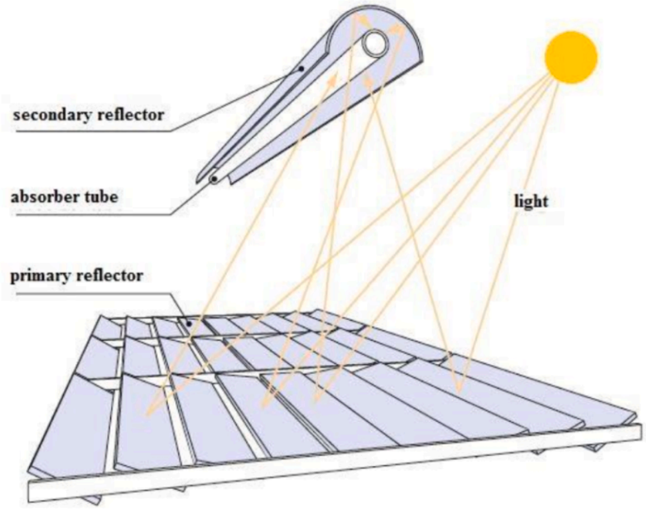

Fig. 3. Diagram of a linear Fresnel reflector [25].

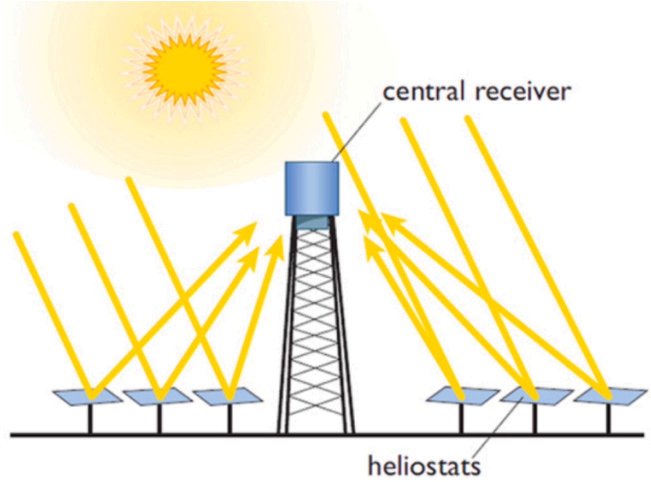

Fig. 4. Diagram of a solar tower system [26].

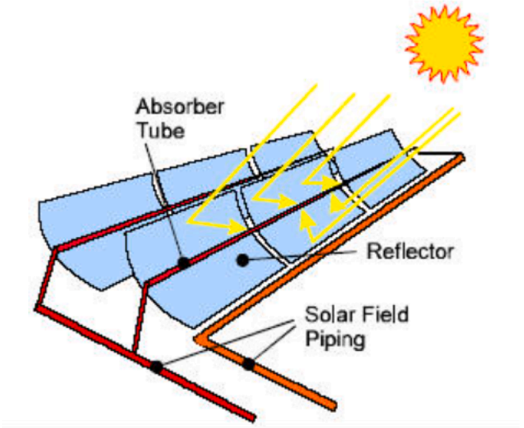

Fig. 5. Diagram of a parabolic trough (PT) solar collector (SolarPaces, 2023).

Fig. 4 presents a solar tower technology. A solar tower plant also known as a central receiver system, consists of a tall tower supporting a receiver surrounded by an array of flat or slightly curved mirrors known as heliostats. The heliostats are fitted with a solar tracking system which tracks the sun and focuses sunlight onto a receiver at the top of a tower. The receiver contains a heat transfer fluid such as water or molten salt which absorbs the thermal energy and can be used to generate steam, heat or electricity [53].

Parabolic trough (PT) is the most mature and dominant solar thermal technology, implemented in 80 % of operational plants [1]. PT are parabolic-shaped collectors (troughs) made of reflecting materials with the collectors focusing the solar radiation to a receiver/absorber tube along its focal line, absorbing the concentrated solar energy through the heat transfer fluid (HTF) inside it [27]. As a result of the parabolic shape of the troughs, it can focus the sun at 30–100 times its normal intensity. The reflector as well as the absorber tube follows the movement of the sun to collect the maximum solar radiation. The heat transfer fluid flowing through the absorber tube is heated by the absorbed sunlight which is then used to generate steam that turns a conventional steam turbine/generator to produce electricity. Alternatively, the thermal energy from the HTF can be transferred to a thermal energy storage tank to the store the heat and release it when needed. Parabolic trough systems can produce high temperatures up to 550 °C when heat transfer fluids such as molten salts or direct steam is used [23].

Fig. 6 depicts the range of thermal output temperatures used in the solar thermal plants. It can be seen that the thermal output temperature with a range of 500–600 °C was the most studied in the literature, followed by the thermal output temperature with ranges of 300–400 °C and 400–500 °C then 200–300 °C. The thermal output temperature range of >600 °C was the least studied in the literature resulting with only one study that involves a solar dish plant generating higher thermal temperatures of up to 1000 °C [53]. The reasons for lack of research may be due to their high capital costs resulting in their lack of use on a commercial scale. In terms of the temperatures rate there are three temperature rates observed in the literature, as follows: low temperature below 100 °C, medium temperature at the range of 100–400 °C and high temperature of above 400 °C [8]. About 25.5 % of the industrial sector have a heat demand below 100 °C, 27.2 % of 100–400 °C and 47.4 % of above 400 °C [8]. Fig. 6 shows that thirteen studies used solar thermal plants with temperatures above 400 °C while eight studies had thermal output temperatures of 200–400 °C. A higher proportion of the studies had thermal output temperatures above 400 °C and this could be attributed to it being the most required temperature range for industry. The solar thermal technology with the lowest thermal output temperature was the parabolic-trough at 212.7 °C while the solar dish plant had the highest thermal output temperature of 720 °C [39,43]. This might be due to the solar dish technology having a higher thermal efficiency resulting in higher output temperatures than parabolic trough.

The capacities of the solar thermal plants are presented in Tables 1 to 4, of which Table 1 shows the capacities of 1KW-500KW, Table 2 1 MW – 50 MW, Table 3 100 MW – 440 MW while Table 4 shows the solar thermal plants with no plant capacities provided.

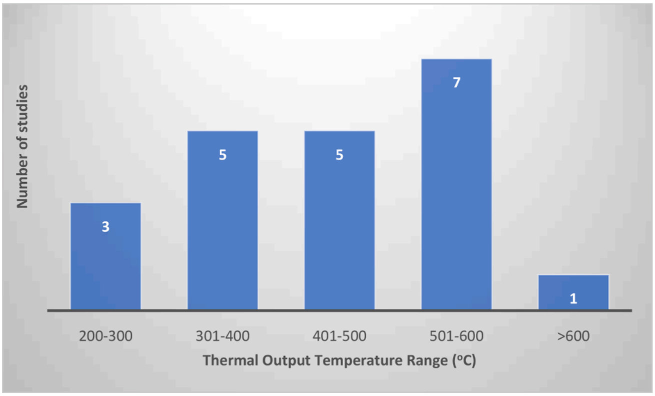

Fig. 6. Number of studies within the various temperatures from solar thermal plants.

Table 1
Studies with solar thermal plants of 1 kW-500 kW.

References	[9]	[10]	[39]
Type of solar thermal system	Parabolic trough (PT) plant	Parabolic trough (PT) plant with a biomass back-up burner	Parabolic trough
Thermal output temp. (°C)	550 °C	550 °C	212.7 °C
Plant capacity (KW)	400 KW	400 kW	55.19 KW
Environmental assessment Software	SimaPro 7 Software	SimaPro 7 software	Thermodynamics analysis
Environmental Impact Assessment Method & System Boundary	Eco-indicator 99 (Endpoint), CML 2001 (Midpoint) Method, Global Warming Cradle to Gate	Eco-indicator 99 (Damage Oriented Approach), IPCC Global Warming Potential (GWP) 100a, Cumulative Energy Demand Cradle to Gate	N/A
Environmental Impact (g CO2eq/kWh)	Emissions of 0.405 kg CO_2 eq per 1 Nm3 of hydrogen concentration in natural gas (HCNG-17) equivalent to 0.115 kg CO_2eq/kWh.	The parabolic trough plant had CO_2 emissions of 0.19 kg CO_2eq/kWh. The MSP-solar thermal had a global warming impact of 18 %.	98.56 % of daily energy savings achieved using the PTSC system, compared to electrically heated boiler.

3.1. *Solar thermal plants with capacities of 1KW-500KW*

This section presents the studies of solar thermal plants with capacities of 1 KW – 500 KW and all used parabolic trough (PT) plants, as depicted in Table 1. Piemonte et al. [9] assessed the environmental impact of a hybrid PT and steam reformer plant that produced hydrogen and electricity whilst Piemonte et al. [10] compared the environmental performance of a PT plant with a biomass back-up burner of the conventional oil and gas power plants [10]. Kizilkan et al. [39] used a PT system to provide thermal energy for the heating and cooling stages of an ice cream production. SimaPro software was used in two studies, whilst one study used thermodynamics analysis to assess the environmental performance of the plant.

Piemonte et al. [9] conducted a life cycle assessment (LCA) of a hybrid PT and steam reformer plant and the results showed that the plant produced 0.405 kg CO_2eq per 1 Nm3 of HCNG-17, equivalent to emissions of 0.115 kg CO_2eq/kWh. Studies have compared the environmental performance of solar thermal plants with fossil-fuel plants [10,1]. The GHG emissions of a PT plant with a biomass back-up burner was compared with the emissions of an oil-power plant and a gas-power plant [10]. The authors found that the PT plant with a biomass back-up burner had the lowest emissions at 0.19 kg CO_2eq/kWh, followed by the gas-powered plant at 0.934 kg CO_2eq/kWh and then the oil-powered plant at 1.13 kg CO_2eq/kWh. The GHG emissions produced by the PT plant was significantly lower than that of the oil and gas-powered plants. The authors reported that the PT plant had a global warming impact of 18 %, compared to an equivalent gas-powered plant which has a global warming impact of 80 % [10]. Achkari and El Fadar [1] also reported that the average GHG emissions of solar thermal plants were 22 g CO_2-eq/kWh compared to 130–900 g CO_2-eq/kWh for advanced fossil-fuel based systems. This demonstrates that solar thermal plants produce significantly less GHG emissions than fossil-fuel plants. Kizilkan et al. [39] reported the energy savings achieved by replacing a 60KW electrically heated boiler with a hybrid PT- solar energy system in an ice cream factory. The authors conducted thermodynamics analysis of the PT system and the results showed that the proposed PT system used only 1.235 kWh per day, generating an energy savings of 98.56 % compared to the old system which used 85.81 kWh per day. It can be deduced that a system with lower energy consumption results in less environmental impacts.

3.2. *Solar thermal plants of 1 MW–50 MW*

This section discusses the environmental impact of solar thermal plants with capacities of 1 MW-50 MW which are displayed in Table 2. Five of the studies were based on parabolic trough (PT) technology and two on solar tower (ST) plants. One study conducted an environmental assessment of both a PT and a ST plant. Parabolic trough was the most popular technology used in the studies, followed by solar tower technology.

The environmental impacts of solar thermal plants were assessed using different software and tools like: SimaPro software (PRé Sustainability), a mathematical embodied energy model, an integrated hybrid input–output LCA and thermodynamic analysis. The use of different environment assessment software & tools can lead to discrepancies in the comparison of the environmental impact of the solar thermal plants. This hypothesis was confirmed by Herrmann & Moltesen [11] who performed an LCA study using GaBi and SimaPro software. Although, the same LCA study was conducted using both software tools, there were discrepancies in the results. Speck et al. [12] conducted a study to compare GaBi 5, SimaPro 7.2.4, COMPASS 2.0 and Package Modeling 3.0 for the LCA of packaging containers. The authors found significant discrepancies in the LCA results for GHG emissions, fossil fuel energy, eutrophication, and water depletion impact categories. The results from the four LCA software disagreed on which container had the greatest environmental impact. Speck et al. [12] found that the differences in the LCA results were caused by the different approaches used in the characterization factors management in each software.

The GHG emissions savings and the auxiliary fuels used by the solar thermal plants were also considered in their environmental assessment. Arabkoohsar & Sadi [14] compared the environmental impact of a hybrid PT – waste incineration power plant and a natural gas-fired power plant. The authors reported that compared to a natural gas power plant, the hybrid PT plant saved 74.5 thousand tonnes of carbon emissions annually. Solar thermal plants used auxiliary fuels such as natural gas to enable the start-up operation of the plant, avoid freezing of the heat transfer fluid and increase power output [15]. The environmental performance of a 50 MW PT plant operating with different levels of natural gas (NG) inputs, ranging from 0 % to 35 % NG were evaluated by Corona et al. [15]. The results showed that the plant produced 26.6 kg CO_2eq/MWh when no natural gas was used but produced 311 kgCO_2 eq/MWh when the plant was fuelled on 35 % natural gas. The use of biofuels as auxiliary fuels in solar thermal plants can affect their environmental performance and increase their GHG emissions by about 10 % [31]. San Miguel & Corona [16] found that replacing natural gas with biogas reduced the GHG emissions of the plant from 26.6 kg CO_2eq/MWh to 25.1 kg CO2eq/MWh and was further reduced to 24.2 kg CO_2 eq/MWh when mixed manure biogas was used. Corona et al. [36] also observed that when the auxiliary fuel of a solar thermal plant was replaced with biomethane, the GHG emissions of the plant was reduced from 45.9 kg CO_2 eq/MWh to 27.9 kg CO_2 eq/MWh. This highlights the environmental benefit of using biofuels as auxiliary fuels in solar thermal plants instead of fossil-fuels. The environmental performance of

Table 2
Studies of solar thermal plants of 1 MW-50 MW.

Reference	[17]	[18]	[28]	[14]
Type of solar thermal system	Parabolic trough	Solar Tower plant	Parabolic Trough	Parabolic trough
Thermal output temp (°C)	500 °C	390 °C.	N/A	227 °C
Plant Capacity (MW)	2 MW	1.5 MW	50 MW	15 MW
Environmental assessment Software	SimaPro 7.1	Mathematical model of the embodied energy.	SimaPro 7	Thermodynamics & Emissions model
Environmental impact assessment methods & System Boundary	Eco-indicator 99, IPCC GWP 100a Cradle to Grave	Cradle to Gate	ReCiPe Midpoint & Endpoint Europe (H), Cumulative Energy Demand	N/A
Environmental Impact (gCO_2eq/kWh)	GHG emission of the PT plant was 29.9 g CO_2 eq/kWh.	The plant produced 36.3 g CO_2eq/kWh.	PT plant produced 26.9 g CO_2eq/kWh (solar only mode).	Hybrid PT system reduces annual CO_2 emissions by 74.5 thousand tonnes compared to a natural gas-fired plant.

References	[15]	[29]	[16]
Type of solar thermal system	Parabolic trough plant	Solar Tower plant	Parabolic Trough
Thermal output temp. (°C) & Size of Plant (MW)	50MW	10MW	50 MW
Environmental assessment Software	Sima Pro 7.3	Integrated hybrid input–output LCA used based on matrix computations.	SimaPro 7.3
Environmental Impact Assessment Method & System Boundary	ReCiPe Europe (H), CML 2 baseline 2000 World, ReCiPe Europe E, Cumulative Energy Demand Cradle to Grave	Cradle to Grave	ReCiPe Midpoint & Endpoint Europe (H) Cradle to Grave
Environmental Impact (g CO2 eq/kWh)	PT plant produced 26.6g CO_2 eq/kWh using only solar energy compared to 311g CO_2 eq/kWh when the plant is fuelled on 35% natural gas.	Plant produced 35 g/kWh of CO_2 emissions. In the construction phase, the solar field construction has the highest emissions. The thermal energy storage using molten salt, and solar collection demanding lots of steel are the two most significant contributors to CO_2 emission and energy consumption.	26.6 g CO_2 eq/kWh (with natural gas) 25.1g CO_2 eq/kWh (with biowaste biogas) 24.2g CO_2 eq/kWh (with mixed manure biogas).

solar thermal plants has also been compared to other renewable energy technologies such as PV plants. Desideri et al. [17] compared the environmental impact of a PT and a PV plant and found that the PT plant when compared to the PV system, achieved GHG emissions savings of 2,262 tonnes of CO_2. The PT plant produced lower carbon emissions of 29.9 g CO_2eq/kWh compared to 47.9 g CO_2eq/kWh generated by the PV plant. These studies demonstrate the significant contribution of solar thermal technologies in reducing GHG emissions compared to fossil-fuel plants and PV plants.

3.3. *Solar thermal plants of 100 MW–440 MW*

This section presents the eight peer-reviewed papers dealing with environmental assessment of solar thermal plants of 100 MW–440 MW. Five of those papers were based only on solar tower (ST) plants, two papers on parabolic trough (PT) plants and one on linear Fresnel (LFR) plants. Table 3 presents summary of the solar thermal plants with capacity of 100 MW–440 MW. It can be seen that the ST plant had the highest capacity of 440 MW as well as the highest thermal output temperature of 565 °C. The environmental LCA of the plants was mainly conducted using SimaPro and System Advisor Model (SAM) software. SimaPro software was used in five of the eight studies while SAM software was used in only one study.

The factors that impact the environmental performance of solar thermal plants were assessed. These include the solar thermal plant components, life cycle phases and the life cycle impact assessment (LCIA) method used. Studies have reported that the solar field (solar collectors & receivers) and the thermal energy storage have the most environmental impact of a solar thermal plant. This is due to the large amount of steel used to support the mirrors, the significant amount of steel, aluminium and concrete used to build the thermal storage tanks as well as the manufacturing of the molten salt [40,19,32,29,31,30]. Burkhardt et al. [34] found that the manufacturing phase contributed the largest at 46 % of the GHG emissions of a PT plant with TES, followed by the operational & maintenance (O&M) phase at 39 %, then the dismantling & disposal at 8.5 % and finally the construction phase at 6.5 %. San Miguel & Corona [16] reported that the extraction & manufacturing (E&M) phase generated the largest proportion at 78 % of the GHG emissions of a PT plant with a 7.5hrs TES, while the O&M phase only produced 19 % of the GHG emissions of the plant. However, Klein & Rubin [33] and Whitaker et al. [35] reported conflicting results with the O&M phase contributing the largest to the GHG emissions of the PT plants at 52–68 % and 45 % respectively. The manufacturing phase was the next largest contributor of the GHG emissions of both plants, followed by the dismantle & disposal phase and then the construction phase. The discrepancies in the phase with the largest GHG emissions could be attributed to the amount of natural gas and electricity used in the operational phase of the plants and whether the GHG emissions from the extraction of the raw materials were included in the manufacturing phase of the materials. The greater the amount of electricity or natural

Table 3
Studies of solar thermal plants of 100 MW – 440 MW.

Reference	[33]	[31]	[34]	[35]	[36]	[30]
Type of solar thermal system	Parabolic Trough	Solar Tower Plant	Parabolic Trough	Solar Tower plant	Solar Tower plant	Solar Tower plant
Thermal output temp. (°C)	393 °C	500 °C	N/A	565 °C	N/A	565 °C
Plant Capacity (MW)	110 MW	100 MW	103 MW	106 MW	100 MW	110 MW
Environmental assessment Software Tool	SimaPro 7.1 & EIO -LCA datasets	SimaPro 7.3	SimaPro 7.1 & EIO-LCA datasets	SimaPro 7.2	SimaPro 8.0.3	SAM software
Environmental Impact Assessment Method & System Boundary	IPCC GWP100a Cradle to Grave	IMPACT 2002+ Cradle to Gate	IPCC GWP 100a, Cumulative Energy Demand Cradle to Grave	IPCC GWP 100a, Cumulative Energy Demand, water consumption Cradle to Grave	ReCiPe Midpoint World (H perspective), Cumulative Energy Demand, water stress index Cradle to Grave	ReCiPe indicators, IPCC method with GWP 20a indicator
Environmental Impact (gCO_2eq/kWh)	PT plant with minimum natural gas backup produced 35 g CO_2eq/kWh.	The solar field group was the most impacting factor (≈75 %) on Global Warming Potential (GWP), followed by the thermochemical energy storage (TCES).	Wet cooled system emitted 26 g CO_2eq/kWh & water consumed was 4.7L/kWh. Dry cooled system emitted 28 g CO_2eq/kWh & water consumed was 1.1L/kWh.	The plant produced CO_2 emissions of 37 g CO_2eq/kWh. Using synthetic salts is estimated to increase GHG emissions by 12 %, CED by 7 %, and water consumption by 4 % compared to mined salts.	The CO_2 emissions of the HYSOL plant is 27.9gCO_2eq/kWh compared to 45.9gCO_2eq/kWh when the digestate obtained in the production of the bio-methane fuel is used.	The climate change impact of the plant was 67 % higher without storage (31 gCO_2eq/kWh) than with storage (9.8 gCO_2eq/kWh). The solar field, TES & HTF had the most impact on the environment.

Reference	[37]	[38]
Type of solar thermal system	Linear Fresnel power plant	Solar Tower Plant
Thermal output temp. (°C)	N/A	565 °C
Plant Capacity (MW)	125 MW	440 MW
Environmental assessment Software	N/A	N/A
Environmental impact assessment method & System Boundary	Cumulative Energy Demand, IPCC 2007 GWP 100a Cradle to Grave	IPCC GWP 100a, CML Baseline Cradle to Grave
Environmental Impact (g CO_2eq/kwh)	The AREVA linear Fresnel plant produced 31g CO_2/kWh.	The ST with 12% fossil co-firing produced 105.4g CO_2eq/kwh. The ST with 2% fossil co-firing produced 31.4g CO_2eq/kwh. With no co-firing, the GHG emissions is 14.5 CO_2eq/kwh, with a dominant share of 65% stemming from the collector system, followed by the electric power generation system at 17% and the receiver system at 12%.

gas used in the O&M phase, the greater the GHG emissions it generates. Studies have shown that the auxiliary electricity & natural gas consumption generates the largest GHG emissions within the O&M phase [35,33]. Studies have reported that the manufacturing of the solar field components such as the mirrors/heliostats, heat collection elements and the frames contributes the largest GHG emissions of the manufacturing phase of a solar thermal plant [33,35,31]. The heliostats comprise mainly of mirrors and metals and most of their emissions are attributed to the extraction, transformation and shaping of the materials [31].

The life cycle impact assessment (LCIA) method used in a study can impact its LCA results. Gasa et al. [30] conducted an LCA of a ST plant and found that when the ReCiPe indicators were used for the plant with TES, the TES & heat transfer fluid (HTF) systems had the highest environmental impact of 48 %, followed by the solar field with an environmental impact of 29 %. However, when the authors used the IPCC indicator at 20 years, the results showed that the solar field had the highest environmental impact of 46 % of the plant, followed by the TES & HTF systems at 33 % environmental impact. Pelay et al. [31] used the IMPACT 2002+ in SimaPro software to assess the environmental impact a ST plant with thermochemical energy storage (TCES). The study found that the solar field generated the largest climate change impact of around 75 %, followed by the thermochemical energy storage which contributed around 30 % to the climate change impact of the plant. Corona et al. [15] used the ReCiPe (E & H perspectives) and CML Baseline 2000 to assess the environmental impact of a PT plant. The authors found that CML Baseline 2000 produced significantly higher impact values than the ReCiPe methods mainly in the marine ecotoxicity and fresh water eutrophication categories. This was attributed to the difference in the LCIA methods used in the study. This demonstrates that the use of different LCIA methods affects the environmental impact results of solar thermal plants. The use of TES can also affect the environmental performance of a plant. Gasa et al. [30] reported that the

Table 4
Studies of solar thermal plants with no plant capacity provided.

Reference	[41]	[1]	[42]	[32]
Type of solar thermal system	Parabolic trough	Parabolic Trough Collectors (PTC) Solar Tower (ST)	Fresnel solar concentrator system	Solar Collectors (Glass). Does not specify the exact solar thermal system used.
Thermal output temp. (°C)	N/A	N/A	N/A	500 °C
Plant Capacity (MW)	N/A	N/A	N/A	N/A
Environmental assessment Software	SimaPro	N/A	SimaPro 7.1	SimaPro 8.5
Environmental Impact Assessment Method & System Boundary	N/A	N/A	Eco-Indicator 99 (Hierarchical), IPCC 2007 GWP100a, Cumulative Energy Demand Cradle to Grave	International Reference Life Cycle Data (ILCD), Impact 2002+, Cumulative Energy Demand, Eco-points 97, Eco-Indicator 99 & IPCC. Cradle to Grave
Environmental Impact (g CO2 eq/ kWh)	Median estimates of GHG emissions of 26 g CO_2 eq/ kWh for PT plants.	Noor I, Noor II & Noor III solar thermal plants can annually save 0.32, 0.41 & 0.30 Mt CO_2, respectively, totalling 1.03 Mt CO_2 equivalent.	Manufacturing &assembly of the solar collectors & receivers had the most impact on the environment.	End-of-life results reveal that the solar collector and the heat storage have the most impact on the environment.

climate change impact of a ST plant without TES was 65 % higher than the ST plant with TES. The ST plant with TES produced 9.8 gCO2eq/kWh whilst the plant without TES produced 31 gCO_2eq/kWh.

The effect of the cooling options used for solar thermal plants were also investigated. Studies have found that solar thermal plants with dry cooling had 5–7 % higher GHG emissions than wet-cooled plants [34,33]. However, the amount of water consumed by the wet-cooled PT plant was greater at 4.7L/kWh, compared to 1.1L/kWh for the dry-cooled plant. Although dry cooled plants have slightly higher GHG emissions than wet-cooled plants, they use significantly less water than wet-cooled plants and are suitable in places with very sunny and dry climates where solar thermal plants are usually located. The type of heat transfer fluid and storage medium also affects the environmental performance of solar thermal plants. Whitaker et al. [35] conducted an LCA of a ST plant that used a mixture of nitrate salts as the heat transfer fluid and storage medium and compared it to a similar plant that used synthetically derived salts. The LCA results showed that the plant using synthetic salts produced 12 % higher GHG emissions than the plant with mined nitrate salts. The water consumption of the plant with synthetic salt was also 4 % higher than when nitrate salts were used. This demonstrates that several factors can influence the environmental impact of a solar thermal plant such as the type of thermal storage medium, the type of cooling used (dry or wet-cooling), the auxiliary fuel, the inclusion of a TES in a solar thermal plant and the LCIA method used in the studies.

3.4. *Studies of solar thermal with no plant capacity provided*

This section discusses the environmental assessment of solar thermal plants with no capacity provided. Out of the four peer-reviewed studies, two were based on PT plants, one on a LFR plant and one of the papers did not specify the type of solar thermal technology used in the study as shown in Table 4. SimaPro software was used in three of the four papers whilst one paper did not state the environmental assessment software used. The direct normal irradiation (DNI) or location of a solar thermal plant can affect its environmental performance [42,40,37,36,41]. Mora et al. [42] reported that when the Fresnel solar concentrator system was located in places with high DNI levels, the amount of energy produced increased and the energy payback period of the system reduced. Kuenlin et al. [40] found that solar thermal plants located in places with high DNI levels had lower environmental impact than plants in locations with lower DNI levels. Hang et al. [37] conducted sensitivity analysis and found that the environmental performance of the solar thermal plant was most sensitive to the solar intensity which is represented by the DNI. Corona et al. [36] investigated the effect of DNI levels on the environmental performance of a solar thermal plant located in Chile, Mexico, Kingdom of Saudi Arabia (KSA), South Africa and Spain. The authors explained that the DNI determines the amount of energy collected by the heliostats and that higher electricity generation produces less environmental impact per functional unit. The LCA results of their study showed that Mexico had the lowest DNI and had the second highest environmental impact except for water stress. Spain was the next location with the lowest DNI and produced the highest environmental impacts, followed by KSA and Chile. Guillén-Lambea & Carvalho [41] reports that solar thermal plants located in places with higher DNI results in higher electricity production which leads to lower environmental impacts.

3.5. *GHG emissions of the solar thermal plants (g of CO_2eq/kWh)*

A number of authors reported data of GHG emissions generated from solar thermal plants [30,41,34,18,35]. These data were used to calculate the average GHG emissions that are presented in Fig. 7.

It can be seen that parabolic trough plants have a lower environmental impact than solar tower plants. Only one study each calculated the GHG emissions of a linear Fresnel and a solar dish plant, therefore their average GHG emissions could not be computed. Backes et al. [43] reported that the GHG emissions of a solar dish plant was 35 g CO_2 eq/

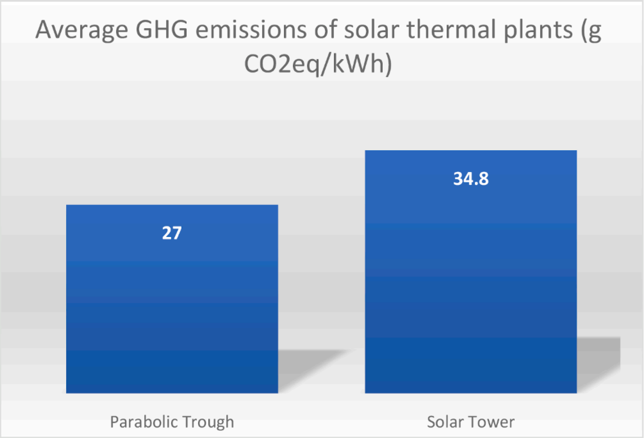

Fig. 7. The average GHG emissions of the solar thermal power plants.

kWh and Hang et al. [37] found that the linear Fresnel plant produced 31 g CO_2eq/kWh. PT plants are the most mature and developed of the solar thermal technologies which may contribute to them having lower GHG emissions than solar tower plants. Solar tower plants have large land use requirements and a plant design which requires more materials demands, which can lead to increased GHG emissions. Linear Fresnel plants have lower GHG emissions which can be attributed to their smaller land use requirements and simpler plant designs with less materials usage. Solar dish plants are still in the demonstrational stage and have large material demands which can result in higher GHG emissions [53]. Fig. 7 shows that PT plants have lower average GHG emissions that ST plants. This is corroborated by Burkhardt et al. [34] who reviewed nineteen references based on PT plants and 17 references on ST plants. The authors found that PT plants had a median estimate of 26 g CO_2/kWh compared to 38 g CO_2/kWh for ST plants. Guillén-Lambea & Carvalho [41] also confirmed that the median estimates of GHG emissions for PT plants was 26 g CO_2 eq/kWh. The average GHG emissions of the PT shown in Fig. 4 was 27 g CO_2 eq/kWh which is slightly above the median GHG emissions of 26 g CO_2 eq/kWh for PT plants reported by Guillén-Lambea & Carvalho [41] and Burkhardt et al. [34]. The average GHG emissions of the ST plant presented in Fig. 7 was 34.8 g CO_2eq/kWh which is less than the median estimates for GHG emissions of 38 g CO_2eq/kWh for ST plants reported by Burkhardt et al. [34].

Fig. 8 illustrates the proportion of software tools used in the environmental assessment of the plants. It can be seen that SimaPro was the most popular software used in 54 % of the studies which could be attributed to SimaPro being the most widely used LCA software in industry and academia. Piemonte et al. [10] states that SimaPro is one of the most used LCA software in the world. SAM software was used in 11 % of the studies, followed by Gabi, and then mathematical model and thermodynamics each used in 6 % of the studies. Umberto, Thermoflex + PEACE and matrix computations were the least common tools used in the environmental assessment of the solar thermal plants, while 8 % did not state the software tool.

Studies have found variability in the LCA results of solar thermal plants which they attribute to a number of factors. These include the scope of analysis, assumed performance characteristics, location of the solar thermal plant, data source, and the impact assessment methodology used [41,34]. Kuenlin et al. [40] reported that the solar dish plant had the best total environmental performance in the 4 impact categories of Human health, Ecosystem quality, Climate change and Resources followed by the solar tower, linear Fresnel and then the parabolic trough plant. This is in contrast with the LCA results of other studies, including this study which found that PT plants had lower environmental impacts than ST plants [41,34].

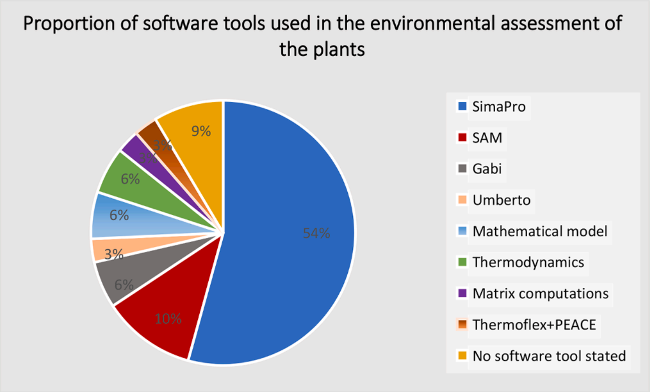

Fig. 8. Proportion of software tools used in the literature.

4.0. *Studies with integrated environmental & economic assessments of the solar thermal plants*

This section investigates the studies that conducted integrated environmental and economic assessment of the solar thermal plant. There were thirteen studies of integrated environmental and economic assessment of the plants as displayed in Table 5. A number of software tools were used in the assessment including System Advisor Model (SAM), SimaPro, Umberto, Gabi and Thermoflex + Peace software. The LCOE was the most popular economics metric used in eight studies, followed by capital costs used in six studies, then NPV used in three studies and finally the revenues and life cycle costs used in two studies each. SAM was the most commonly used software in the economic assessment of the plants while SimaPro was the most popular used for the environmental assessment of the plants.

Aseri et al. [45] compared the economic and environmental performance of a 50 MW parabolic trough (PT) and solar tower (ST) plant. The authors found that the wet-cooled PT plant produced less GHG emissions than the dry cooled plant and that the capital cost of the wet-cooled PT plant was lower than the dry-cooled PT plant. They also observed that the ST plant produced less GHG emissions than the PT plant and that the capital cost of the dry-cooled ST plant was less than both the wet-cooled and dry-cooled PT plant. Studies have reported that the LCOE of wet-cooled PT & ST plants are lower than their dry-cooled counterparts [46,47]. Hirbodi et al. [46] also observed that the LCOE values for both PT & ST plants decreased as the capacity of the plants increased from 20 MW to 200 MW. Furthermore, it was reported that dry-cooled ST plants achieved higher CO_2 emissions reductions than dry-cooled PT plants. The dry-cooled 100 MW ST plant with a thermal energy storage of 14hrs was the most efficient configuration with an annual reduction of 399 kilo-tons of carbon emissions as well as annual fossil fuel savings of 190 million m^3 of natural gas. Dabwan et al. [48] performed an economic-thermodynamic-environmental assessment of a 340 MW LFR integrated with a gas turbine power plant (GTPP) of different capacities ranging from 100 to 250 MW. The environmental assessment showed that integrating the LFR with a gas turbine capacity of 250 MW resulted in an annual carbon emissions savings of about 45 kilo-tonne of CO_2. In contrast, a larger carbon emission savings of 110.34 kilo-tonne of CO_2 was achieved annually when the LFR was integrated with a smaller gas turbine size of 100 MW. The authors also found that integrating the LFR with a gas turbine made the plant less expensive with lower LCOE values of $4.28 cent/kwh and $5.6 cent/kwh, whilst a standalone LFR plant was more expensive with a higher LCOE of $28.5 cent/kwh. This highlights the trade-offs that investors or owners of solar thermal plants may experience – to either have a solar thermal plant integrated with a fossil-fuel system that is less expensive but results in higher GHG emissions or use a standalone solar thermal plant that is more expensive but with lower GHG emissions. This is corroborated by Kuenlin et al. [40] who reported that although the environmental impact of a solar thermal plant reduced when very little or no fossil fuel is used, the LCOE of the plant increased. One solution suggested was for a large enough tax amount be levied on CO_2 to make solar thermal plants more attractive and financially viable than natural gas power plants.

A full environmental and economic assessment of a solar thermal plant including the external environmental costs of the plant was conducted by Corona et al. [49]. The authors performed a full environmental life cycle costing (LCC) of a 50 MW PT plant operating in hybrid mode with different natural gas inputs (between 0 % and 30 %). The LCC included both the internal and external costs of the plant. The internal costs are the purchase of materials and equipment incurred mainly during the extraction and manufacturing life cycle phase of the plant. The external costs assessed were the environmental costs associated with atmospheric emissions. The authors found that the external unit costs of the PT plant with 30 % natural gas were up to 8.6 times higher than in solar-only operation, due to the increased GHG emissions. It was reported that the internal costs increased from €82.8/MWh to €89/MWh

Table 5
Studies with environmental & economic assessments of solar thermal plant.

Reference	[45]	[46]	[50]	[43]	[48]	[13]	[40]
Type of solar thermal system	Parabolic Trough & Solar Tower	Solar Tower (ST) & Parabolic Plant (PT)	Parabolic Trough with biomass technology	Solar Dish plant	Linear Fresnel Plant integrated with a gas turbine	Linear Fresnel Reflectors	Comparison of 4 solar thermal plants: Parabolic trough, Linear Fresnel, Solar Tower and Solar dishes.
Plant Capacity (MW)	50 MW	20 MW; 50 MW; 100 MW; 200 MW	1 MW	33KW	340 MW	48 MW	N/A
Thermal output temperature (°C)	PT = 393 °C, ST = 574 °C	PT = 393 °C, ST = 565 °C	350 °C	720 °C	467.3 °C	270 °C	N/A
Environmental Assessment Software	Mathematical Calculations	SAM	SimaPro	GaBi SP40	Thermoflex + PEACE Software	SAM	SimaPro
Environmental Impact Assessment Method & System Boundary	N/A	N/A	Environmental Footprint Method, Cradle to Grave	CML 2001 (2016) Cradle to Use	Thermodynamics analysis N/A	Cradle to Gate	Impact 2002+ Cradle to Grave
Environmental Impact	PT (Wet) = 18.9 g – 19 g CO$_2$eq /kwh PT (Dry) = 22.6 g − 22.7 g CO$_2$eq /kwh ST (Dry) = 10.8 g − 11.3 g CO$_2$eq /kwh	100 MW ST plant with 14hrs TES reduces CO2 emissions by 399 kilotons. 100 MW PT plant with 6hrs TES reduces CO2 emissions by 228 kilotons	The PT produced 22 g CO$_2$eq/kwh	34.77 g CO$_2$eq/kwh	The LFR plant with a gas turbine capacity of 250 MW reduces CO$_2$ emissions by 45 kilo-tonnes but reduces CO$_2$ emissions by 110.34 kilo-tonnes when the LFR plant is integrated with a gas turbine of 100 MW.	The thermal plant will reduce carbon dioxide emissions by 420,672 tons annually.	Manufacturing & construction of the solar thermal plants had the most impact (86 % −99 %) in the 4 impact categories. Mainly due to the solar field, storage & heat transfer fluid.
Economic Assessment Software	SAM software	SAM software	Multi-regional Input-Output (MRIO)	Excel software	Thermoflex + PEACE software	SAM	N/A
Economic Assessment methods	LCOE & Capital costs	LCOE	Capital Cost	Life Cycle Cost, LCOE	LCOE	Capital Cost, NPV, LCOE	LCOE
Economic Impact (Internal)	**Capital Costs** PT (Wet) = \$193.6 million, \$196.8 million PT (Dry) = \$217 million, \$220.7 million ST (Dry) = \$169.8 million, \$179.3 million **LCOE (\$/MWh)** PT (Wet) = \$110.3/MWh, \$111.4/MWh PT (Dry) = \$131.2/MWh, \$133.8/MWh ST (Dry) = \$95.8/MWh, \$96.4/MWh	**LCOE** 100 MW PT (Dry) = 11.3 cents/kwh 100 MW PT (Dry) = 14.2 cents/kwh 100 MW ST (Wet) = 11cents/kwh 100 MW ST (Wet) = 13.6cents/kwh	**Capital Cost** \$7,015,052	LCC =€308,467 LCOE = €0.268/ kwh	**LCOE** Standalone LFR plant = \$28.5 cent/kwh LFR-GTPP = \$4.28 cent/kwh & \$5.6 cent/kwh	**Capital Costs** = \$393 million **NPV** = \$47 million **LCOE** = \$0.0382/kwh	The lower the environmental impact of the plant, the higher the LCOE value.
Economic Impact (External)	N/A	N/A	N/A	N/A	N/A	N/A	A carbon tax of \$60/ton of CO$_2$eq will make solar

(continued on next page)

Table 5 (*continued*)

Reference	[45]	[46]	[50]	[43]	[48]	[13]	[40]
							tower technology more attractive than natural gas power plants.

Reference	[51]	[47]	[49]	[28]	[44]	[19]
Type of solar thermal system	Solar Tower Plant	Parabolic trough (PT), Solar tower (ST) plants & Linear Fresnel (LFR) plant	Parabolic trough plant	Parabolic Trough Plant	Linear Fresnel power plant	Parabolic Trough
Plant Capacity (MW)	101 MW	50MW, 75MW & 100MW	50 MW	180 MW	50MW	50MW
Thermal Output Temperature (°C)	N/A	N/A	N/A	N/A	500°C	N/A
Environmental Assessment Software	GaBi software	Umberto NXT software	SimaPro 8.0 software	SimaPro 8.0.3 software	SAM software	SimaPro 8
Environmental Impact Assessment methods & system boundary	CML 2001 Cradle to Grave	N/A Cradle to Grave	IPCC 2013 Cradle to Grave	ReCiPe Midpoint & Endpoint (H perspective) Cradle to Gate	N/A N/A	Eco-indicator 99 (H) Cradle to Grave
Environmental Impact	The ST plant produced 24.3g CO_2eq/kwh	The ST plant produced 12.2g CO_2eq/kwh	The PT produced 27.6g CO_2eq/kwh	The PT produced 45.9 kg CO_2eq/MWh	The natural gas back-up system was the most significant contributor to GHG emissions, producing 95g CO_2 eq/kWh, contributing over 90% of the total emissions.	The solar field had the most environmental impact at 79.26%, followed by the storage system at 20.6%.
Economic Assessment Software	GaBi software	SAM software	SimaPro 8.0 software	N/A	SAM software	Thermo-economic analysis
Economic Assessment methods	Plant construction cost, NPV, Revenues	LCOE NPV Total Cost of Installation	Full Environmental LCC method (Internal & External Costs)	Life Cycle Cost	LCOE, Total installed costs	LCOE
Internal Economic Impact	Plant Construction Cost = €478,892,010 Revenues = €66.5/MWh NPV = €43,364,197	Highest LCOE (LFR) = 26.33 cent/kWh LCOE (PT) = 18.04 cent/kWh Lowest LCOE (ST) = 17.71 cent/kWh Wet Cooling gave the least LCOE values: LCOE (ST) = 17.1 cent/kWh LCOE (PT) = 15.24 cent/kWh Highest NPV = $461.05 million (100MW, wet cooled PT) Lowest NPV = $ 17.65 million (50 MW, dry cooled LFR) PT (100MW) has the highest total installation cost (TIC) of $643.90 million.	Total Plant Cost = €162.9 million Civil Engineering & Construction Cost = €97.1 million O&M Costs = €7.127 million Disposal Costs = €4.867 million Total revenues from electricity sales = 85.7€/MWh, Internal NPV = 2.95€/MWh.	LCC = €211/MWh	**LCOE of Plants with 8 hr Storage** ST = 29.88¢/kWh PT = 34.43 ¢/kWh Total Installed Costs (ST)= $309 million, (PT) =$312 million **Optimal LCOE & TIC prices were with Backup & 8hrs storage** LCOE (ST) = 23.5 /kWh LCOE (PT) = 24.12 /kWh	**LCOE** Solar field = $0.197/kwh Boiler =$0.234/kwh HP Turbine = $0.242/kwh LP Turbine =$0.242/kwh Condenser = $0.249/kwh Pump = $0.308/kwh Solar field = $17,635/h Boiler = $2526/h Condenser = $1104/h

(*continued on next page*)

Table 5 (*continued*)

Reference	[51]	[47]	[49]	[28]	[44]	[19]
		50MW ST has a TIC of $389.15 million.				
External Economic Impact	N/A	N/A	External costs of atmospheric emissions = 1.87€/MWh (realistic scenario) & 2.14€/MWh (ambitious climate change scenario)	N/A	N/A	N/A

and the external costs also rose from €1.87/MWh to €12.8/MWh (realistic scenario) when the share of natural gas was increased from 0 % to 30 % in the PT plant. The type of solar thermal technology impacts on the environmental performance of the plant. Kuenlin et al. [40] compared the environmental impact of four different solar thermal technologies; parabolic trough (PT), solar tower (ST), linear Fresnel (LFR) and solar dish (SD). The LCA results showed that the SD plant had the lowest environmental impact, followed by the ST, the LFR and then the PT plant. The low environmental impact of the SD plant can be attributed to it being the only plant without a TES system in the study. Furthermore, SD plants tend to have high efficiencies which contributed to its positive environmental performance. The SD plant was also the solar thermal technology with the highest thermal output temperature of 720 °C in the literature reviewed. The disadvantage of the LFR plant is its low efficiency which can impact on its environmental performance. The PT plant had the worst environmental performance which was attributed to its molten salt storage system comprised of two tanks as well as the synthetic oil used as the heat transfer fluid [40]. Ehtiwesh et al. [19] found that the solar field of a PT plant had the highest cumulative energy demand (CED) at 0.126 MJ/kWh, followed by the storage system at 0.035 MJ/kWh and then the power block at 0.003 MJ/kWh. This reveals that the solar field and the thermal energy storage are the subsystems that require more attention in reducing the energy demand and GHG emissions of solar thermal plants. The solar field also had the highest cost at $17,635/h, followed by the boiler at $2,526/h and then the condenser at $1104/h [19]. This highlights that additional effort should be directed in the research of cheaper but environmentally friendly materials for the solar field components in order to reduce the overall costs, whilst improving the environmental performance of solar thermal plants.

5. Conclusion

The paper presents a systematic review on the environmental impact of solar thermal systems assessed in the literature. Several factors that impact the environmental performance of solar thermal plants were identified. These included the type of solar thermal technology, heat transfer fluid, energy storage medium, auxiliary fuel, cooling method, life cycle impact assessment (LCIA) method, and the inclusion of thermal energy storage. The studies found that solar thermal plants produced significantly less GHG emissions than fossil-fuelled power plants. Natural gas used as auxiliary fuel increased the GHG emissions of the solar thermal plants. A better alternative is the replacement of natural gas with other auxiliary fuels such as biofuels that have less environmental impact. Studies found that using different environmental software tools and LCIA methods resulted in conflicting LCA results. Therefore, standardization is required in the environmental assessment software tools and LCIA methods to prevent discrepancies in the LCA results. Parabolic trough was the most popular technology used in twenty studies, followed by solar tower plant used in thirteen studies, linear Fresnel plant in six studies and solar dish used in three studies. This highlights the lack of environmental assessment studies based on linear Fresnel and solar dish plants.

SimaPro was the most preferred software used in nineteen studies for the environmental assessment of the plants. This was followed by SAM software used in four studies, Gabi used in two studies and Umberto and Thermoflex + PEACE software used in one study each. Data collected from the literature was used to calculate the average GHG emissions of the plants which showed that parabolic trough plants had the lowest GHG emissions followed by solar tower plants. Only one study provided the GHG emissions of a linear Fresnel and a solar dish plant, hence there was insufficient data to calculate the average GHG emissions of these plants. More studies are required on the GHG emissions of linear Fresnel and solar dish plants in order to understand and compare their environmental impact with other solar thermal technologies. Environmental and economic assessment of the solar thermal plants were often conducted separately in the literature, with only thirteen studies conducting an integrated environmental and economic assessment. More research is recommended using integrated environmental and economic assessments of solar thermal plants, especially for linear Fresnel and solar dish plants which were the least studied solar thermal technologies in the literature reviewed.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

Acknowledgement

This project is funded from the EU Horizon 2020 research and innovation programme, Application of Solar Thermal processes in Industrial Processes (ASTEP), under grant agreement No 884411.

References

[1] O. Achkari, A. El Fadar, Latest developments on TES and CSP technologies – Energy and environmental issues, applications and research trends, Appl. Therm. Eng. 167 (2020) 114806.
[2] UNFCCC, 2022. About the Secretariat. Available at: About the Secretariat | UNFCCC. [Accessed on 17th May 2022].
[3] European Commission, 2022a. 2030 Climate Target Plan. Available at: https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en. [Accessed on 18th January 2022].
[4] European Commission, 2022b. The Just Transition Mechanism: making sure no one is left behind. Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en. [Accessed on 16th May 2022].
[5] European Commission, 2022c. EU funding possibilities in the energy sector. Available at: https://energy.ec.europa.eu/topics/funding-and-financing/eu-funding-possibilities-energy-sector_en. [Accessed on 16th May 2022].
[6] European Commission, 2022d. Renewables in the EU: the support framework towards a single energy market | E3P (europa.eu). Available at: https://e3p.jrc.ec.europa.eu/publications/renewables-eu-support-framework-towards-single-energy-market [Accessed on 22nd June 2022].
[7] European Commission (2021a). Heating & Cooling. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en. [Accessed on 12 July 2021].

[8] S. Holler, A. Winkelmann, J. Pelda, A. Salaymeh, Feasibility study on solar thermal process heat in the beverage industry, Energy 233 (2021) 121153.
[9] V. Piemonte, M. de Falco, A. Giaconia, P. Tarquini, G. Iaquaniello, Life cycle assessment of a concentrated solar power plant for the production of enriched methane by steam reforming process, Chem. Eng. Trans. 21 (2010) 25–30, https://doi.org/10.3303/CET1021005.
[10] V. Piemonte, M.D. Falco, P. Tarquini, A. Giaconia, Life Cycle Assessment of a high temperature molten salt concentrated solar power plant, Comput. Aided Chem. Eng. 85 (5) (2011) 1101–1108.
[11] I.T. Herrmann, A. Moltesen, Does it matter which life cycle assessment (LCA) tool you choose? - a comparative assessment of Simapro and Gabi, J. Clean. Prod. 86 (2015) 163–169.
[12] R. Speck, S. Selke, R. Auras, J. Fitzsimmons, Choice of Life Cycle Assessment software can impact packaging system decisions, Packag. Technol. Sci. 28 (7) (2015) 579–588.
[13] M. Ghodbane, E. Bellos, Z. Said, B. Boumeddane, A. Khechekhouche, M. Sheikholeslami, Z.M. Ali, Energy, financial, and environmental investigation of a direct steam production power plant driven by linear Fresnel solar reflectors, J. Sol. Energy Eng. 143 (2) (2021), https://doi.org/10.1115/1.4048158.
[14] A. Arabkoohsar, M. Sadi, M. Sadi, A.A. Dk, Thermodynamics, economic and environmental analyses of a hybrid waste-solar thermal power plant, J. Therm. Anal. Calorim. 144 (2021) 917–940, https://doi.org/10.1007/s10973-020-09573-3.
[15] B. Corona, G. San 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) (2014) 1264–1275, https://doi.org/10.1007/s11367-014-0728-z.
[16] 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 (2014) 580–587, https://doi.org/10.1016/j.renene.2013.12.023.
[17] U. Desideri, F. Zepparelli, V. Morettini, E. Garroni, Comparative analysis of concentrating solar power and photovoltaic technologies: Technical and environmental evaluations, Appl. Energy 102 (2013) 765–784, https://doi.org/10.1016/j.apenergy.2012.08.033.
[18] M. Zhang, Z. Wang, C. Xu, H. Jiang, Embodied energy and energy analyses of a concentrating solar power (CSP) system. Energy Policy. 42 (2012) 232–238.
[19] 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 (2016) 145–155.
[20] A. Berrada, K. Loudiyi, R. El Mrabet, Introduction to hybrid energy systems, in: A. Berrada, R. El Mrabet (Eds.), Hybrid Energy System Models, Academic Press, 2021, pp. 1–43.
[21] I. Dincer, Y. Bicer, Energy conversion, in: I. Dincer (Ed.), Comprehensive Energy System, Elsevier, 2018, pp. 895–946.
[22] M. Kamran, M.R. Fazal, Solar Energy Renewable energy conversion systems, Academic Press, 2021, pp. 109–152, https://doi.org/10.1016/B978-0-12-823538-6.00008-7.
[23] S. Qazi, Solar Thermal electricity & solar insolation, in: S. Qazi (Ed.), Standalone PV Systems for Disaster Relief & Remote Areas, Elsevier, 2017, pp. 203–237.
[24] J. Sun, Hybrid solar power system, in: A.K. Azad (Ed.), Advances in Clean Energy Technologies, Academic Press, 2021, pp. 405–448.
[25] S. Dabiri, M.F. Rahimi, Basic introduction of solar collectors and energy and exergy analysis of a heliostats plant. Proceedings of the 3rd International Conference and Exhibition on Solar Energy, 2016.
[26] The Open University, 2023. Power Towers. https://www.open.edu/openlearn/mod/oucontent/view.php?id=73759&section=10.1.
[27] M.U.H. Joardder, P.K. Halder, M.A. Rahim, M.H. Masud, Solar pyrolysis: Converting waste into asset using solar energy, in: M.G. Rasul, A.K. Azad, S. C. Sharma (Eds.), Clean Energy for Sustainable Development, Academic Press, 2017, pp. 213–235.
[28] B. Corona, G. San Miguel, Environmental analysis of a Concentrated Solar Power (CSP) plant hybridised with different fossil and renewable fuels, Fuel 145 (2015) 63–69, https://doi.org/10.1016/j.fuel.2014.12.068.
[29] 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 (2019) 310–322.
[30] G. Gasa, A. Lopez-Roman, C. Prieto, L.F. Cabeza, Life cycle assessment (LCA) of a concentrating solar power (CSP). Sustainability. 13 (7) 10.3390/su13073672 3672.
[31] 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) (2020), https://doi.org/10.1002/ep.13388.
[32] M. Mahmud, N. Huda, S. Farjana, C. Lang, Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment, Energies 11 (9) (2018) 2346.
[33] 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.
[34] 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) (2011) 2457–2464.
[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) (2013) 5896–5903.
[36] 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 (2016) 413, https://doi.org/10.3390/en9060413.
[37] Y. Hang, K. Balkoski, P. Meduri, Life cycle analysis of linear Fresnel solar power technology. ASME Power Conference, Boston, Massachusetts, USA, 29 July – 1 August 2013, 2013.
[38] 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 (2017) 187–200, https://doi.org/10.1016/j.solener.2017.08.018.
[39] O. Kizilkan, A. Kabul, I. Dincer, Development and performance assessment of a parabolic trough solar collector-based integrated system for an ice-cream factory, Energy 100 (2016) 167–176.
[40] A. Kuenlin, G. Augsburger, L. Gerber, F. Maréchal, Life cycle assessment and environomic optimization of concentrating solar thermal power plants, in: Proceedings of the 26th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS2013), 16-19 July 2013, Guilin, China.
[41] S. Guillén-Lambea, M. Carvalho, A critical review of the greenhouse gas emissions associated with parabolic trough concentrating solar power plants, J. Clean. Prod. 289 (2021) 125774.
[42] C. Mora, A. Cascini, M. Gamberi, A. Graziani, M. Bortolini, E. Gasparri, E. Ferrari, Life cycle assessment of a fresnel solar concentrator system for micro-cogeneration (2012).
[43] J.G. Backes, A. D'Amico, N. Pauliks, S. Guarino, M. Traverso, lo, Brano,, V., Life cycle sustainability assessment of a dish-Stirling concentrating solar power plant in the Mediterranean area, Sustainable Energy Technol. Assess. 47 (2021), https://doi.org/10.1016/j.seta.2021.101444.
[44] S. Mihoub, Design, economic, and environmental assessments of linear Fresnel solar power plants, Environ. Prog. Sustain. Energy 39 (3) (2020), https://doi.org/10.1002/ep.13350.
[45] T.K. Aseri, C. Sharma, T.C. Kandpal, Estimation of capital costs and techno-economic appraisal of parabolic trough solar collector and solar power tower based CSP plants in India for different condenser cooling options, Renew. Energy 178 (2021) 344–362, https://doi.org/10.1016/j.renene.2021.05.166.
[46] K. Hirbodi, M. Enjavi-Arsanjani, M. Yaghoubi, Techno-economic assessment and environmental impact of concentrating solar power plants in Iran, Renew. Sustain. Energy Rev. 120 (2020), 109642, https://doi.org/10.1016/j.rser.2019.109642.
[47] L. Salisu, J.S. Enaburekhan, A.A. Adamu, Techno-economic and life cycle analysis of energy generation using concentrated solar power (CSP) technology in Sokoto State, Nigeria, J. Appl. Sci. Enviro. Manage. 23 (5) (2019) 775, https://doi.org/10.4314/jasem.v23i5.1.
[48] Y.N. Dabwan, G. Pei, G. Gao, J. Li, J. Feng, Performance analysis of integrated linear fresnel reflector with a conventional cooling, heat, and power tri-generation plant, Renew. Energy 138 (2019) 639–650.
[49] 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 (2016) 758–768, https://doi.org/10.1016/j.solener.2016.06.059.
[50] S. Banacloche, I. Herrera, Y. Lechón, Towards energy transition in Tunisia: Sustainability assessment of a hybrid concentrated solar power and biomass plant, Sci. Total Environ. 744 (2020) 140729.
[51] 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, Procedia CIRP 69 (2018) 395–400, https://doi.org/10.1016/j.procir.2017.11.049.
[52] Y. Filali Baba, H. Ajdad, A. Al Mers, A. Bouatem, B.B. Idrissi, S. El Alj, Preliminary cost-effectiveness assessment of a Linear Fresnel Concentrator: Case studies, Case Stud. Therm. Eng. 22 (2020), 100730, https://doi.org/10.1016/j.csite.2020.100730.
[53] M.I. Soomro, A. Mengal, Y.A. Memon, M.W.A. Khan, Q.N. Shafiq, N.H. Mirjat, Performance and economic analysis of concentrated solar power generation for Pakistan, Processes 7 (2019), https://doi.org/10.3390/pr7090575.