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Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with different storage capacity in molten salts

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A R T I C L E I N F O

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Thermal energy storage (TES)
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Life cycle assessment (LCA)
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A B S T R A C T

Although studies on the levelized cost of energy (LCoE) of concentrating solar power (CSP) plants were published in recent years, these studies were not related to the environmental impact generated. To fill this literature gap, this study compares the environmental impacts generated by four tower solar thermal plants with different storage capacities, 3, 6, 9, and 17.5 equivalent hours in nominal conditions were considered, being the plant of 17.5 h, a plant in operation. Results show that the environmental impacts generated throughout its useful life decrease when storage capacity increases. But when the storage capacity goes from 9 h to 17.5 h, the impacts generated are practically the same. Of the four plants analyzed, the most environmentally efficient plant is the one with a storage capacity of 9 h.

1. Introduction

Thermal energy storage (TES) is one of the fundamental pillars for the path towards decarbonisation. Its introduction in concentrating solar power (CSP) plants seeks to improve their performance and flexibility in order to achieve better use of energy on demand. In addition, this is so because when the TES is integrated, the CSP plant can work at full load for hours even in the absence of sun and CSP plant operation can be compared to conventional power generation plants. The TES system allows the plant to partially detach the power block from both, predictable and unpredictable solar variations of instantaneous solar radiation, increasing the time window for energy supply [1].

Moreover, several studies agree that CSP plants are a good alternative to achieve the objectives set worldwide in relation to climate protection. Viebahn et al. [2] made several approximations and concluded the study with the forecast of reaching, in 2050, an installed capacity of CSP plants of 120 GW_{el}, 405 GW_{el} or even 1000 GW_{el} worldwide, representing in this last forecast 13–15 % of the world demand for electricity. In addition, the study emphasized the good results of the life cycle assessment (LCA) offered by CSP plants, with impacts that could reach average values of 18 $gCO_2eq./kWh_{el}$ compared to advanced systems powered by fossil fuels (130–900 $gCO_2eq./kWh_{el}$).

Global policies that advocate the introduction of renewable energies in the electricity market thereby seek to reduce greenhouse gas emissions generated, mainly by the combustion of fossil fuels. A CSP plant without TES allows electricity to be produced during the hours of sunshine, replacing electricity generated by fossil fuels [3]. Despite this improvement, when a TES is introduced to a CSP plant, the environmental impacts are considerably reduced. The incorporation of the TES system allows electricity to be generated in a longer time slot, independently of the sun (it stores the energy captured by the solar field when it is not needed, and this is discharged when there is no sun). In addition, the TES system allows the reduction of electricity consumption from the grid, necessary for the ordinary operation of the plant by allowing hot startups from the TES or even continuous operation along several days, and consequently a considerable reduction in environmental impacts when it is compared to CSP plants without storage. Without forgetting that TES allows the power block to operate at nominal and constant input operating conditions (temperature, power) leading to better efficiency, longer life and less maintenance, positive effects in terms of environmental impacts. Gasa et al. [4] presented a comparative study of the LCA of two tower CSP plants, one without a TES system and the other with a conventional molten salts TES system. This study concluded that the environmental impact measured with the GWP climate change indicator, according to the IPCC2013 method, is 67 % lower when the tower CPS plant includes a TES system with 17.5 h

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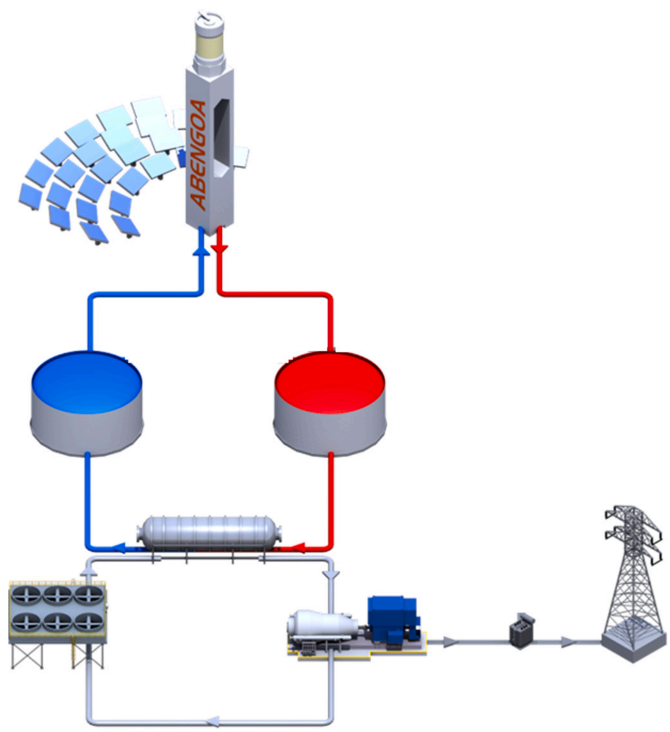

Fig. 1. Molten salt tower plant scheme [4].

of storage capacity (9.8 gCO_2 eq/kWh compared to at 31gCO_2 eq/kWh from a CSP plant without storage).

All these studies indicate that storage capacity conditions not only the operational structure of the CSP plant, but also its economic and environmental efficiency. For this reason, optimizing the configuration of each of the plant operating areas is almost mandatory, especially, the TES system, since an increase in the size of the TES entails an increase in the size of several components, such as the solar field, the tower, and the receiver. This ultimately affects both the economic evaluation as well as the environmental impacts associated with the plant.

As the presence of a TES system in the tower CSP plants allows to reduce environmental impacts, the present study aims to analyze whether the increase in storage capacity always implies a reduction in the environmental impacts generated throughout the entire useful life and if there is an optimal storage capacity. No study to-date has directly compared the environmental impacts generated by tower CSP plants of the same design but with different storage capacity. For example, Whitaker et al. [5] made a LCA of a CSP tower plant with a two-tank TES system with mixture of mined nitrate salts designed for 6 h of full load-equivalent storage. Then, it was compared with a thermocline-based storage system, synthetically derived salts, and natural gas auxiliary power as design alternatives, but without changing the hours of storage. Madaeni et al. [6] compared various storage capacity value calculation methods to determine their effectiveness but does not analyze their environmental impacts. Klein et al. [7] compared the different environmental impacts obtained from CSP plants with wet and dry cooling and with three power backup systems: a minimal one, one with molten salt thermal energy storage and, finally, with a heat transfer fluid heater heat fueled by natural gas. Burkhardt et al. [8], although they focused their analysis on a parabolic trough CSP plant, the effects of different design alternatives of dry cooling, a thermocline TES, and synthetically derived nitrate salt are evaluated. This analysis concluded that CSP can significantly reduce GHG emissions compared to fossil fueled generation; however, dry cooling may be required in many locations to minimize water consumption.

The literature includes studies on the influence of the storage capacity in the LcoE of CSP plants. For example, Gorman et al. [9] evaluated a one-dimensional thermodynamic model developed for a 111.7 MWe CSP plant with redox-active metal oxide as heat storage medium and integrated heat transfer agent and different storage capacities, 6–14 h. This study showed that as the storage capacity increased and with it the solar factor, the LCoE decreased but when the storage capacity increased from 12 h to 14 h of storage capacity, no improvement in the LCoE was observed and for storage capacities greater than 14 h the LCoE worsened. Guedez et al. [10] analyzed the TES integration strategies of CSP plants, in Spain, simulating different storage capacities, from 1 h to 15 h using TRNSYS. This study showed that a plant configuration accounting for 12 h of storage capacity the obtained electricity costs were minimal. Jorgenson et al. [11] compared the net cost of CSP-TES to PV deployed with battery storage with different solar multiple, TES size and batteries capacity. In the case of CSP-TES, they analyzed from 6 to h 18 h of storage capacity. The study determined that the most expensive CSP-TES configuration had a storage capacity of 18 h and a solar factor of 3.

Therefore, this paper studies for the first time, the impact of changing the storage capacity of a tower CSP plant, with the aim of evaluating if the optimum found in techno-economical analysis is the same to the environmental optimum.

2. Methods

2.1. Description of the considered CSP plants

Concentrating solar power plants (CSP) in tower configuration (Fig. 1), also known as central receiver system (CRS) are made up of a solar field, where mirrors called heliostats reflect the solar rays, concentrating the energy in the solar receiver, which converts this concentrate solar flux into heat and then transfers this energy to a heat transfer fluid (HTF).

The present study focuses on tower CSP plants with a conventional molten nitrate salt (60 wt% $NaNO_3$, 40 wt% KNO_3) thermal energy storage system. This plant uses this solar salt as heat transfer fluid. The molten salt is driven by the pumps from the cold tank at 290 °C to the receiver. There, the HTF is heated to 565 °C and sent to the hot tank. The pumps installed in the hot tank send the stored salts to the steam generator that works at 130 bar in an independent loop, which allows the power block to run autonomously. The location selected for this study is the Atacama Desert, with a yearly total DNI higher than 3300 kWh/m^2, one of the places with the highest DNI in the World.

The storage capacity of a TES system can be measured by the hours of storage (in terms of hours of operation at nominal conditions from the storage). It should be noted that the TES system is not charged through the electrical consumption of the grid, but is charged from the solar field. Therefore, when the storage system in a CSP plant is designed, its capacity is always related to the dimensioning of the solar field [6,12].

For the case under study, four tower CSP plants were studied, each with a different storage capacity. These capacities were selected in order to cover different market needs, two peak load configurations and a baseload configuration (based on IEA CSP roadmap). To carry out the comparison, the best configuration of each of the CSP plants under study (solar multiple, tower and receiver size, etc.) was obtained by minimizing the levelized cost of energy (LCOE) of each case:

$$Levelized\ cost = \frac{-Co - \frac{\sum_{n=1}^{N} Cn}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Qn}{(1+d_{real})^n}} \tag{1}$$

where Q_n (kWh) is the electricity delivered by the system to the grid (and/or load if applicable) in year n; N is the analysis period in years as defined on the financial parameters page; C_0 is the project equity investment amount; C_n is the annual project costs at year n, as listed under costs and benefits above; d_{real} is the real discount rate defined; and

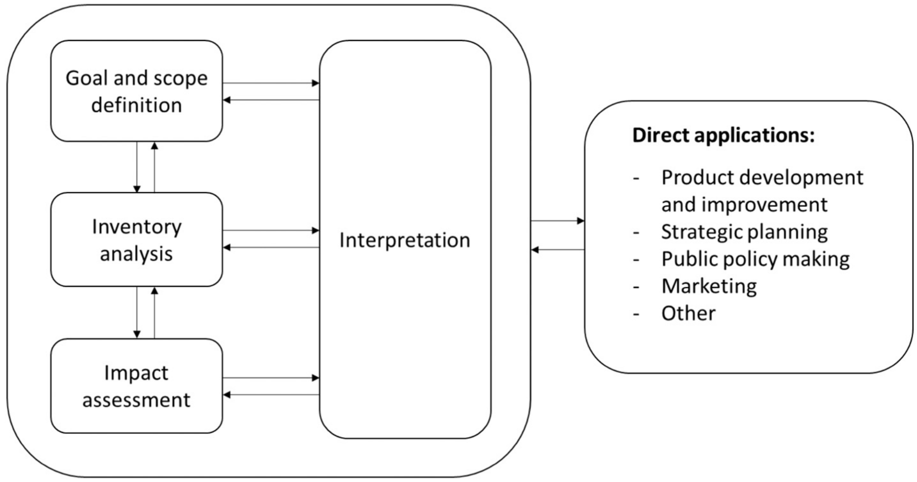

Fig. 2. Life cycle assessment framework [15].

$d_{nominal}$ is the discount rate with inflation.

The dimensioning study for each case was performed using proprietary commercial-level software for simulations, which provided the technical requirements of each configuration (number of heliostats, solar multiple, tower size, electricity production, parasitics, etc.).

2.2. LCA methodology

2.2.1. Life cycle assessment

Life cycle assessment (LCA) is an analytical methodology, which allows quantifying the sustainability of a process or product by evaluating the environmental impacts generated (discharges, waste, emissions into the atmosphere, consumption of raw materials and energy) throughout its life. The LCA considers the entire life of the product or process to be evaluated, starting from its origin, that is, the extraction and processing of raw materials, through production, transport and distribution, to the use, maintenance, reuse, recycling and disposal in landfill at the end of its useful life [13].

ISO 14040 [14] and ISO 14044 [15] standards regulate the LCA methodology of a process or a product. According to these standards, this assessment is broken down into the following four phases, as Fig. 2 indicates:

Stage 1. Goal and scope definition: This phase is decisive since it will condition the result of the analysis. In this phase, it is determined how big part of a life cycle will be taken into consideration in the assessment, and what is the chosen scope. Functional units, system boundaries, and limits to the analysis are set to outline where in the life cycle the study begins and where it ends, and to identify what processes within the technical system will be assessed.

Stage 2. Life cycle inventory analysis (LCI): This phase includes a collection of the data concerning the materials and energy flow within the considered system. This includes all the environmentally important inputs and outputs.

Stage 3. Life cycle impact assessment (LCIA): In this phase the evaluation takes place of the potential environmental impacts, stemming from all inputs and outputs obtained in the LCI.

Stage 4. Interpretation: This is the last phase and includes the process of evaluating all the results obtained in order to draw conclusions.

The environmental impacts associated with the materials and energy flow of this experimental study have been obtained from the Ecoinvent database [16]. Of all the environmental impact evaluation methods included in this database, this study used ReCiPe 2016 and IPCC 2013 (GWP) methods.

The structure of the ReCiPe 2016 method facilitates the interpretation of environmental impacts with the help of complementary midpoint and endpoint methods. The method identifies several impact category indicators, which form the basis for an analysis at the Midpoint level. In addition, there are three damage indicators that allow analysis of environmental impacts at the Endpoint level: effects on human health, effects on the quality of ecosystems, and reduction of resources [17]. On the other hand, the IPCC 2013 method uses climate change as impact category by evaluating the Global Warming Potential (GWP) indicator. This indicator allows to measure the possible global warming effect derived from the atmospheric emission of 1 kg of particular greenhouse gas compared to the emission of 1 kg of carbon dioxide [18]. The gases that contribute to global warming of the earth surface have a long atmospheric life. The GWP indicator allows evaluating the effects generated by the gases emitted in the long term (GWP 100a) or in the short term (GWP 20a).

2.2.2. Aim and scope

The objective of this study is to compare the LCA of various tower configuration concentrating solar power (CSP) plants resulting from designing different thermal energy storage capacities. The study uses as base case a commercial baseload plant with 17.5 h of storage. It is well known in the industry that very high values of nominal TES hours do not minimize the LCOE of the plant. However, there are commercial CSP projects in baseload configuration where the capacity factor is specified as the design requirement, even at the cost of a higher LCOE. Under maximum capacity factor criterion, periods of up to 17.5 h are considered in commercial plants and for this reason it is also considered in this study. However, to evaluate the impact of the TES capacity in the LCA, three hypothetical configurations are defined varying the storage capacity but maintaining the same nominal power level (110 MW): a second baseload configuration with 9 h of TES and two peak load configurations that use 6 and 3 h (based on the IEA CSP technology roadmap). These four tower CSP plants have a gross production of 110 MWel with a supposed useful life of the CSP plant is 30 years.

2.2.3. Functional unit

In order to compare the four CSP plants, “1 kWh of net electricity fed to the grid” is defined as the functional unit. The different impacts obtained in each of the LCAs will be expressed with respect to this functional unit.

2.2.4. System boundary

To carry out the life cycle assessment of these four CSP plants,

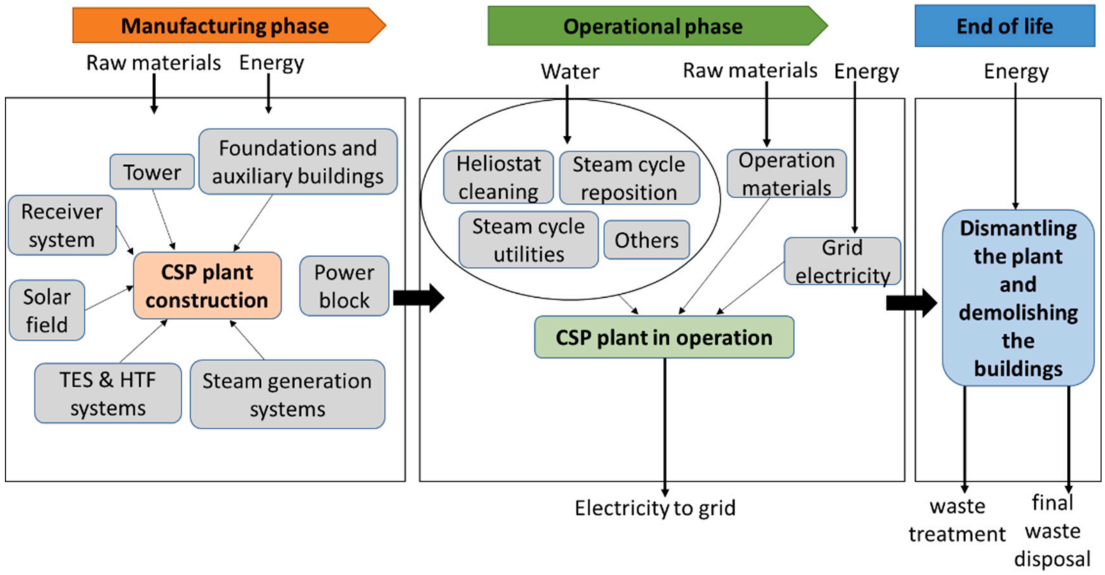

Fig. 3. System boundary of a CSP plant [4].

Table 1
General characteristics of the tower CSP plants with different storage capacity.

Variable	Unit	Storage time			
		3 h	6 h	9 h	17.5 h
Total area	m^2	4,002,341	4,621,510	5,677,740	7,425,982
Gross power	MW	110.00	110.00	110.00	110.00
MS	–	1.80	2.00	2.40	2.60
Produced energy	kWh	437,688,226	533,239,422	645,338,304	797,110,016
Capacity factor	%	48.10	58.60	71.00	87.60
LCOE	–	8.29	7.42	6.89	6.93
Number of heliostats	–	5712	6422	7766	10,600
Tower height	m	176.00	181.00	195.00	218.00
Receiver power	MW	478.10	531.20	637.50	690.00
TES capacity	MWh_t	796.90	1593.70	2390.60	4648.40
Volume of salts	m^3	4155.00	8309.00	12,464.00	24,235.00
Reflective area	m^2	792,094.00	890,551.00	1,076,927.00	1,469,923.00
Water	m^3	71,664.50	83,636.00	100,707.00	130,655.00
Nitrate salts	ton	7774.40	15,546.93	23,321.33	45,345.99

defining which stages are going to be considered and what inputs and outputs each of these stages will have will be very important [19]. For the present study, all the parts that constitute a CSP plant have been considered and, for each of these parts, the impacts generated both in the manufacturing phase and in the operational phase, as well as its end of life (cradle to grave), as shown in Fig. 3.

The comparative study of the four tower CSP plants was carried out taking into account the following phases of the life cycle [20]:

- Manufacturing phase: this phase includes the construction of each one of the components, from the acquisition of their raw materials until they are installed on site.
- Operational phase: this phase includes all the consumption necessary for the operation of the plant. In this case, the consumption of electricity from the grid, water and the chemical products necessary to treat the process water have been considered.
- End-of-life phase: this phase includes activities related to the decommissioning of the plant.

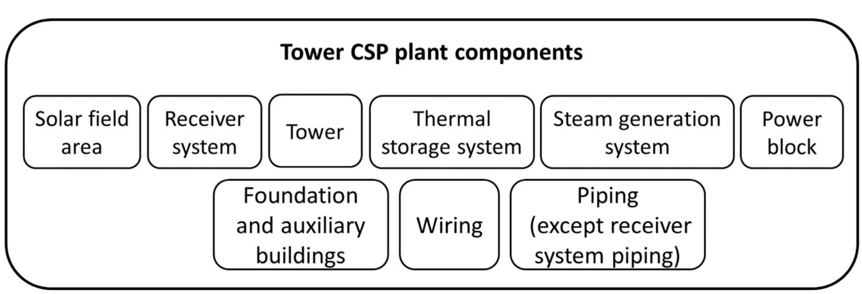

Fig. 4. Considered components in manufacturing phase.

Table 2
Materials and weights used in manufacturing inventory.

Inputs/ outputs	CSP plant - thermal storage capacity of 3 h	CSP plant - thermal storage capacity of 6 h	CSP plant -thermal storage capacity of 9 h	CSP plant - thermal storage capacity of 17.5 h	Unit
Solar field area components					
Flat glass coated	$5.7{\cdot}10^3$	$6.4{\cdot}10^3$	$7.8{\cdot}10^3$	$1.1{\cdot}10^4$	ton
Steel, low-alloyed	$1.9{\cdot}10^4$	$2.1{\cdot}10^4$	$2.6{\cdot}10^4$	$3.6{\cdot}10^4$	ton
Zinc coat, pieces	$1.5{\cdot}10^5$	$1.7{\cdot}10^5$	$2.0{\cdot}10^5$	$2.7{\cdot}10^5$	m^2
Steel, unalloyed	$1.7{\cdot}10^3$	$1.9{\cdot}10^3$	$2.2{\cdot}10^3$	$3.1{\cdot}10^3$	ton
Lubricating oil	$3.1{\cdot}10^2$	$3.5{\cdot}10^2$	$4.2{\cdot}10^2$	$5.7{\cdot}10^2$	ton
Concrete	$5.1{\cdot}10^4$	$5.8{\cdot}10^4$	$7.0{\cdot}10^4$	$9.5{\cdot}10^4$	m^3
Silicone product	$5.7{\cdot}10^1$	$6.4{\cdot}10^1$	$7.7{\cdot}10^1$	$1.1{\cdot}10^2$	ton
Electronics, for control units	$8.0{\cdot}10^1$	$9.0{\cdot}10^1$	$1.1{\cdot}10^2$	$1.5{\cdot}10^2$	ton
Receiver system					
Reinforcing steel	$1.6{\cdot}10^3$	$1.6{\cdot}10^3$	$1.7{\cdot}10^3$	$1.7{\cdot}10^3$	ton
Steel, chromium steel 18/8, hot rolled	$2.2{\cdot}10^2$	$2.3{\cdot}10^2$	$2.4{\cdot}10^2$	$2.5{\cdot}10^2$	ton
Silicone-based coating	$5{\cdot}10^{-1}$	$6{\cdot}10^{-1}$	$7{\cdot}10^{-1}$	$8{\cdot}10^{-1}$	ton
Refractory, basic	$1.8{\cdot}10^2$	$2.0{\cdot}10^2$	$2.4{\cdot}10^2$	$2.6{\cdot}10^2$	ton
Stone wool	$2.1{\cdot}10^1$	$2.3{\cdot}10^1$	$2.4{\cdot}10^1$	$2.5{\cdot}10^1$	ton
Tower					
Concrete	$1.5{\cdot}10^4$	$1.5{\cdot}10^4$	$1.7{\cdot}10^4$	$1.9{\cdot}10^4$	m^3
Reinforcing steel	$2.9{\cdot}10^3$	$3.0{\cdot}10^3$	$3.2{\cdot}10^3$	$3.6{\cdot}10^3$	ton
Excavation, hydraulic digger	$1.0{\cdot}10^4$	$1.1{\cdot}10^4$	$1.2{\cdot}10^4$	$1.3{\cdot}10^4$	m^3
Steam generation system					
Reinforcing steel	$8.2{\cdot}10^1$	$8.2{\cdot}10^1$	$8.2{\cdot}10^1$	$8.2{\cdot}10^1$	ton
Steel, low-alloyed	$1.0{\cdot}10^2$	$1.0{\cdot}10^2$	$1.0{\cdot}10^2$	$1.0{\cdot}10^2$	ton
Steel, chromium steel 18/8, hot rolled	$3.5{\cdot}10^2$	$3.5{\cdot}10^2$	$3.5{\cdot}10^2$	$3.5{\cdot}10^2$	ton
Stone wool	$8.4{\cdot}10^{-2}$	$8.4{\cdot}10^{-2}$	$8.4{\cdot}10^{-2}$	$8.4{\cdot}10^{-2}$	ton
Glass fiber	$2.3{\cdot}10^0$	$2.3{\cdot}10^0$	$2.3{\cdot}10^0$	$2.3{\cdot}10^0$	ton
Power block[a]					
Steel, chromium steel 18/8, hot rolled	$3.4{\cdot}10^2$	$3.5{\cdot}10^2$	$3.6{\cdot}10^2$	$3.7{\cdot}10^2$	ton
Reinforcing steel	$2.4{\cdot}10^2$	$2.6{\cdot}10^2$	$2.8{\cdot}10^2$	$3.0{\cdot}10^2$	ton
Steel, low-alloyed	$5.3{\cdot}10^2$	$5.3{\cdot}10^2$	$5.3{\cdot}10^2$	$5.3{\cdot}10^2$	ton
Steel, unalloyed	$7.5{\cdot}10^1$	$7.5{\cdot}10^1$	$7.5{\cdot}10^1$	$7.5{\cdot}10^1$	ton
Cast iron	$6.0{\cdot}10^{-2}$	$6.0{\cdot}10^{-2}$	$6.0{\cdot}10^{-2}$	$6.0{\cdot}10^{-2}$	ton
Copper	$1.8{\cdot}10^1$	$1.8{\cdot}10^1$	$1.8{\cdot}10^1$	$1.8{\cdot}10^1$	ton
Aluminum	$6.2{\cdot}10^1$	$6.2{\cdot}10^1$	$6.2{\cdot}10^1$	$6.2{\cdot}10^1$	ton
Stone wool	$2{\cdot}10^0$	$2{\cdot}10^0$	$2{\cdot}10^0$	$2{\cdot}10^0$	ton
Zinc coat, pieces	$6.1{\cdot}10^3$	$6.1{\cdot}10^3$	$6.1{\cdot}10^3$	$6.1{\cdot}10^3$	m^2
TES system					
Nitrate salts, for solar power application	$7.7{\cdot}10^3$	$1.6{\cdot}10^4$	$2.3{\cdot}10^4$	$4.5{\cdot}10^4$	ton
Steel, chromium steel 18/8, hot rolled	$6.6{\cdot}10^2$	$7.6{\cdot}10^2$	$9.1{\cdot}10^2$	$1.2{\cdot}10^3$	ton
Reinforcing steel	$8.1{\cdot}10^2$	$9.2{\cdot}10^2$	$1.1{\cdot}10^3$	$1.4{\cdot}10^3$	ton
Stone wool	$3.0{\cdot}10^2$	$3.5{\cdot}10^2$	$4.2{\cdot}10^2$	$5.8{\cdot}10^2$	ton
Foundation and auxiliary buildings					
Concrete	$5.1{\cdot}10^3$	$5.8{\cdot}10^3$	$7.1{\cdot}10^3$	$9.7{\cdot}10^3$	m^3
Reinforcing steel	$4.2{\cdot}10^2$	$4.9{\cdot}10^2$	$5.9{\cdot}10^2$	$8.0{\cdot}10^2$	ton
Excavation, hydraulic digger	$3.9{\cdot}10^3$	$4.5{\cdot}10^3$	$5.4{\cdot}10^3$	$7.4{\cdot}10^3$	m^3
Building, hall	$2.5{\cdot}10^3$	$2.9{\cdot}10^3$	$3.5{\cdot}10^3$	$4.8{\cdot}10^3$	m^2
Wiring					
Cable	$1.1{\cdot}10^3$	$1.2{\cdot}10^3$	$1.5{\cdot}10^3$	$1.9{\cdot}10^3$	km
Piping (except receiver system piping)					
Reinforcing steel	$2.9{\cdot}10^2$	$2.9{\cdot}10^2$	$2.9{\cdot}10^2$	$2.9{\cdot}10^2$	ton

[a] Power cycle components and water tanks constitute the power block system.

2.2.5. Impact inventory

The environmental impacts generated by each of the inputs and outputs included in this comparative study were obtained from the Ecoinvent v3.7.1 database. Each data or activity of the Ecoinvent database corresponds to a geographical location. For this study, the selected data was from the geographical area RoW (Rest of the world). ReCiPe2016 and IPCC2013 GWP were the quantitative indicators chosen to carry out the comparative study.

2.2.6. Data inventory

Abengoa provided the quantification of the inventory of the CSP plant with a storage capacity of 17.5 equivalent hours in nominal conditions based on real data. For the plants with lower storage capacities, 3, 6, and 9 equivalent hours, their inventory of inputs and outputs was obtained by scaling the values of the plant with a storage capacity of 17.5 h using the technical information obtained in the dimensioning simulations as scale factors. Even so, the steam generation system components and piping (except the specific of the receiving system) were not scaled, so the inventory for these components was the same for all four CSP plants. Table 1 shows the different characteristics of the assessed tower CSP plants.

The data included in the inventory of the manufacturing phase and the final disposal phase were classified into nine groups, as shown in Fig. 4. This classification allowed a good analysis of the impacts associated with the solar thermal plants that are the object of this study.

Table 2 shows the quantities of the different inputs and outputs that were considered in the inventory stage of the manufacturing and final disposal phase.

In the operational phase, the inputs considered were the grid electricity consumption, the water consumption, and the chemical products, which are added to the water for its treatment (Table 3). As for the electrical energy data chosen from the Ecoinvent database, it was the

Table 3
Consumption considered in the four CSP plants with different storage capacity.

Parameter	CSP plant - thermal storage capacity of 3 h	CSP plant - thermal storage capacity of 6 h	CSP plant -thermal storage capacity of 9 h	CSP plant - thermal storage capacity of 17.5 h	Unit
Grid electricity consumption (offline)	6.3	5.6	4.8	1.9	GWh/y
Water	$3.5{\cdot}10^4$	$4.1{\cdot}10^4$	$5.0{\cdot}10^4$	$6.4{\cdot}10^4$	m^3/y
Chemicals for process water treatment	$3.9{\cdot}10^1$	$4.5{\cdot}10^1$	$5.5{\cdot}10^1$	$7.0{\cdot}10^1$	ton/y

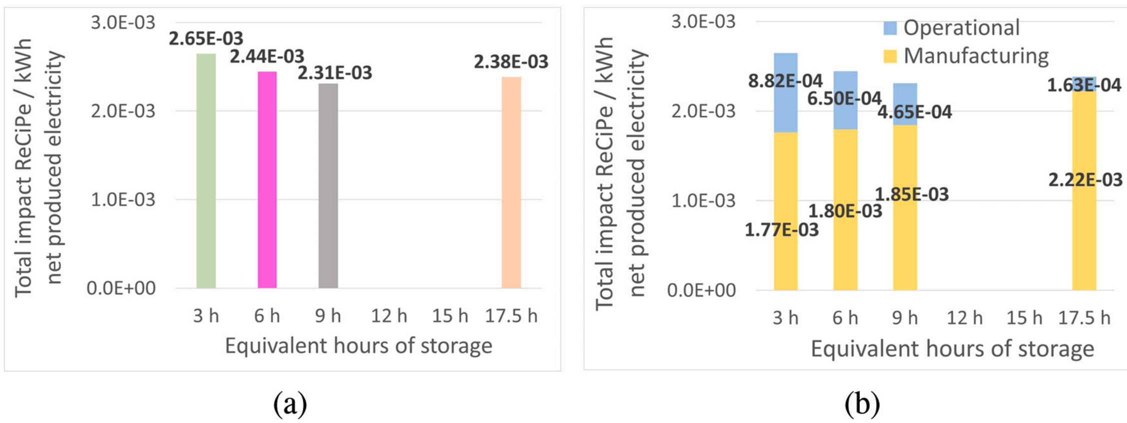

Fig. 5. ReCiPe indicator per kWh of net produced electricity. (a) Total impact; (b) impact of the manufacturing and operational phases.

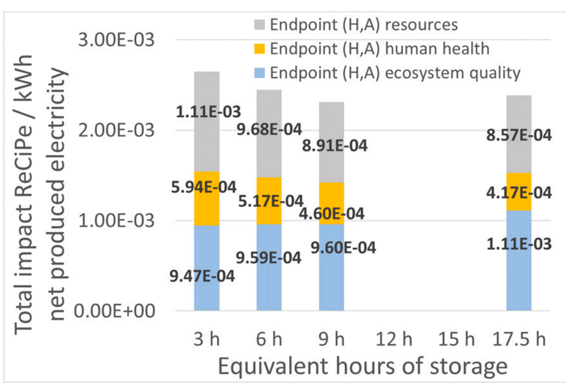

Fig. 6. Endpoint ReCiPe categories per kWh of net produced electricity.

energy mix of 2017 in Spain.

3. Results and discussion

The results of the environmental impacts generated by each of the CSP plants are expressed based on the chosen functional unit, 1 kWh of net produced electricity.

The total of the environmental impacts generated (including inputs and outputs of the manufacturing, operational and final disposal phases), according to the ReCiPe method and for the four CSP plants with tower configuration and with different thermal storage capacity, are shown in Fig. 5. As the storage hours increase, the ReCiPe impact points per functional unit decrease, but when the storage capacity goes from 9 h to 17.5 h of storage, no improvements are observed (Fig. 5a). Fig. 5b shows that, in the four plants analyzed, almost all the environmental impacts are generated during the manufacturing phase and the operational phase impacts are smaller in comparison. As the storage capacity increases, the contribution of the impacts from the manufacturing phase increases and the impacts from the operational phase decrease.

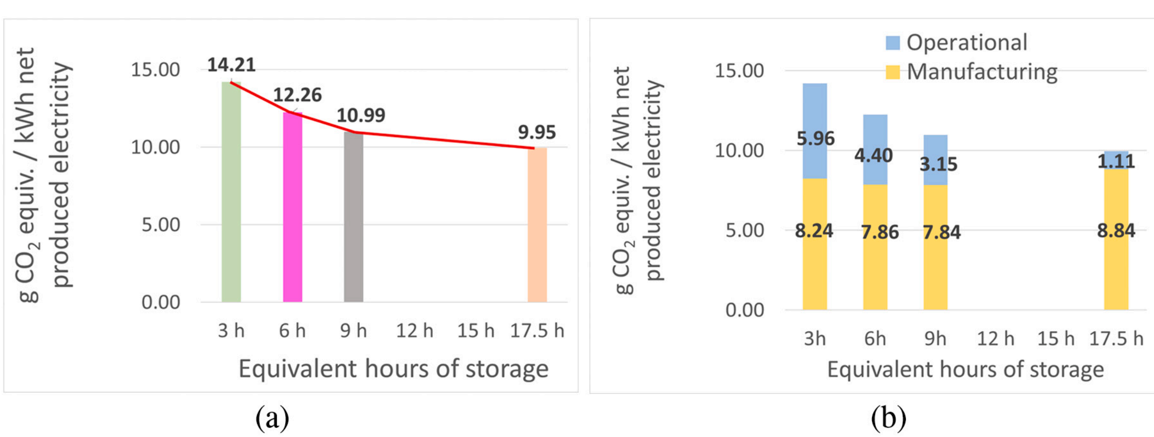

Fig. 7. IPCC method: GW20a indicator per kWh of net produced electricity. (a) Total impact; (b) impact of the manufacturing phase and operational phase.

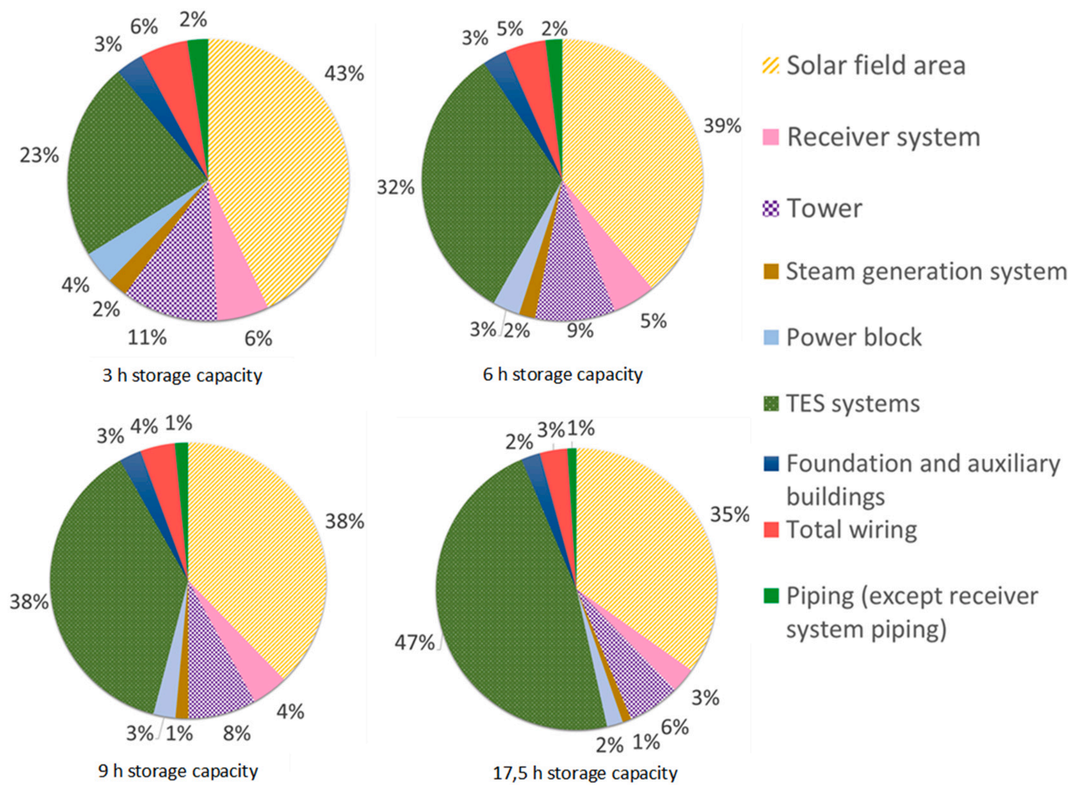

Fig. 8. Contribution to the impacts of each CSP component considered (ReCiPe impact points).

As storage hours increase from 3 h to 17.5 h, as Fig. 6 shows, the impact points for resource and human health decrease while the points for ecosystem quality slightly increased. For the four CSP plants analyzed, the impacts on the resource and on the quality of the ecosystem are higher and very similar, while the impacts on human health are lower.

As the storage hours increase, from 3 h of storage to 9 h, the gCO_2 equivalents released into the atmosphere per functional unit decrease, but when the plant goes from 9 h to 17.5 h, the gCO_2 equivalents per functional unit are practically the same, so that there was no noticeable improvement (Fig. 7a). The four plants analyzed, almost all the gCO_2 are generated during the manufacturing phase and the operational phase

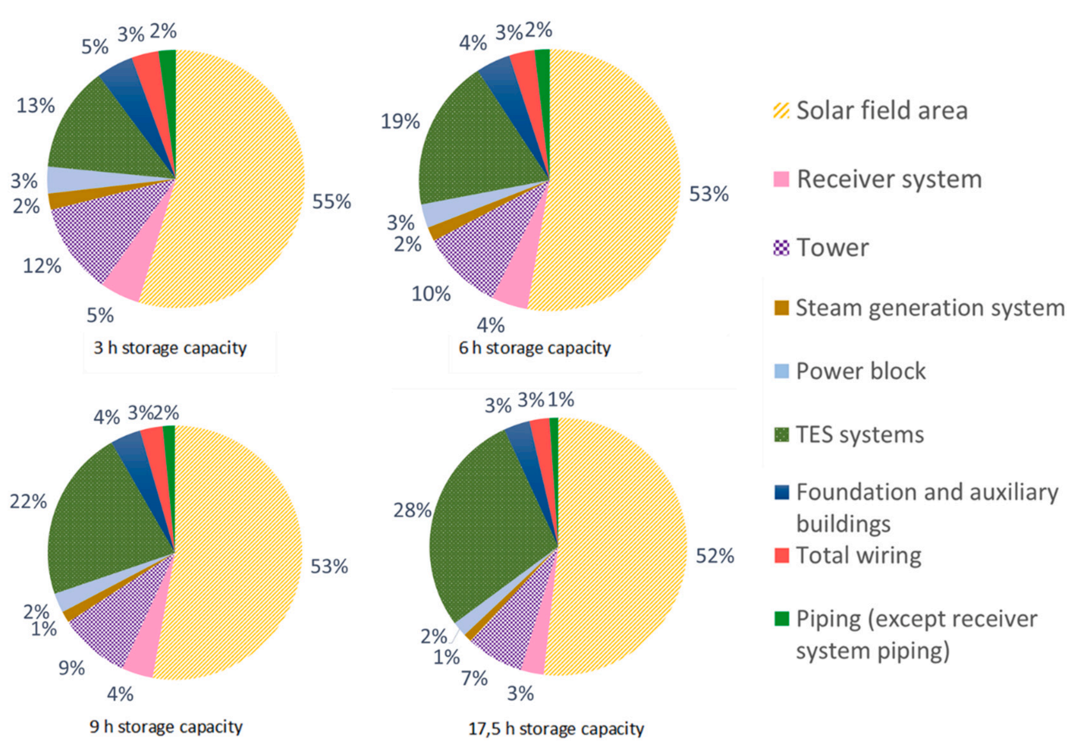

Fig. 9. Contribution to the impacts of each CSP component considered (IPCC method-GWP 20a).

impacts are smaller in comparison. As the storage capacity increases, the contribution of the gCO_2 from the manufacturing phase is very similar, while the impacts generated in the operational phase of the plant decrease (Fig. 7b).

When the contribution of each system that integrates a tower CSP plant is analyzed in its manufacturing phase, Fig. 8 shows that the systems that most influence the global environmental impacts of the plants, if the ReCiPe method is used, are the solar field area, the TES system and the tower, but its percentage varies as storage capacity increases. For a CSP plant with 3 h of thermal storage capacity, the system with the greatest impact is the solar field (43 %), followed by the TES system (23 %) and the tower (11 %). For a plant with 6 h of thermal storage capacity, the system with the greatest impact is the solar field (39 %), followed by the TES system (32 %) and the tower (9 %). For a plant with 9 h of thermal storage capacity, the systems with the greatest impact are the solar field and the TES system (both with a contribution of 38 % of the global impacts) followed by the tower (8 %). Finally, for a plant with 17.5 h of thermal storage capacity, the system with the greatest impact is the TES system (47 %), followed by the solar field (35 %) and the tower (6 %). Therefore, for tower CSP plants with thermal storage capacities of a few hours, the solar field is the system that contributes the most to the overall impact generated by the plants when we evaluate the manufacturing phase. On the other hand, for plants with storage capacities of many hours, the TES system is the one that contributes the most.

Fig. 9 shows the percentages of contribution, of the different systems of a tower CSP plant, to the impacts calculated with the climate change indicator at 20 years, according to the IPCC2013 method. The system that contributes the most to the impacts on climate change, in the four CSP plants analyzed with different storage capacity, is the solar field area, followed by the TES system and the tower. As the storage capacity of the plant increases, the contribution percentage of the solar field area to the impacts of climate change practically does not vary, however the contribution to the impacts of the TES system increases.

Both indicators (impact points according to the ReCiPe method and climate change indicator according to the IPCC2013 method) show that the systems with more impact are the solar field and the TES systems. Despite this, while with the ReCiPe method the impacts generated by the solar field area decrease and the impacts generated by the TES system increase when the storage capacity increases, when the IPCC2013 method is used, whatever the storage capacity, the system that contributes the most to climate change is the solar field system.

4. Conclusions

From a point of view of the levelized cost of energy (LCoE) the CSP technology with thermal energy storage (TES) is still superior than other energy sources, even so the CSP plant with TES presents low LCoE with long hours of storage. Several studies show that a CSP plant with 12–13 h storage capacities achieves low LCOEs and high interest rate of return (IRRs) [21,22]. However, CSP plants designed with smaller storage capacities can be beneficial at a technical-economic level if they work in a peak strategy or operations without restrictions, as they are profitable due to their lower investment costs [10].

At a strategic level, it is interesting to be able to establish a correlation between the LCoE results and the LCA results. The results obtained in this comparative study on the impacts generated by tower CSP plants with different storage capacities allow us to establish that, as the storage capacity of the plant is increased 3 h (3 h, 6 h, and 9 h), the impacts generated throughout its useful life decrease. But when the storage capacity goes from 9 h to 17.5 h (increasing its storage capacity by almost 9 h, in this case increasing two-fold), the impacts generated are practically the same, whether they are evaluated with the ReCiPe impact point method or with the indicator of climate change GWP of the IPCC 2013 method. Of the four tower CSP plants evaluated, the most environmentally efficient plant is the one with a storage capacity of 9 h.

When evaluating the impacts of the plants according to the manufacturing and disposal phase and the operational phase, both for the ReCiPe method and for the IPCC 2013 method, the manufacturing phase is the one that has the greatest contribution. As the CSP plant increases its storage capacity, the impacts generated during the manufacturing and disposal phase increase. This is because as storage capacity increases, the solar field increases, as does the tower, and other areas of the CSP plant. However, the impacts generated in the operational phase decrease, because the increase in storage capacity allows the need to use electricity from the grid to be reduced.

The study carried out shows that in a tower CSP plant, the three components with the greatest impact on the environmental analysis are the solar field, the TES system, and the tower. Depending on the method used in the analysis, the results vary. For the ReCiPe method, as the storage capacity increases, it goes from being the component of the solar field that has the greatest impact to being the TES system. The tower CSP plant with 9 h of storage is the plant that presents the same proportion of impacts for the solar field and TES system components (38 % for both components). When using the IPCC 2013 climate change method, the component that contributes the most to global plant impacts is the solar field for all plants.

CRediT authorship contribution statement

Gemma Gasa: Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Cristina Prieto:** Conceptualization, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Anton Lopez-Roman:** Investigation, Writing – original draft. **Luisa F. Cabeza:** Conceptualization, Methodology, Resources, Data curation, Writing – original draft, Supervision, Project administration, Funding acquisition.

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.

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