Life cycle assessment of thermochemical energy storage integration concepts for a concentrating solar power plant

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Abstract

This paper presents an original life cycle assessment (LCA) of a concentrating solar power (CSP) plant with thermochemical energy storage (TCES). The studied CSP plant is a hypothetic solar tower plant with a Rankine power cycle, and the TCES material used is calcium hydroxide. Based on three proposed TCES integration concepts, detailed sizing and the associated emission inventory are performed for four main groups that constitute the CSP plant, including the solar field, the solar tower, the storage system and the power cycle. Various midpoint impact categories are evaluated using the IMPACT 2002+ method embedded in the SimaPro 7.3 software. A sensitivity analysis is performed to identify the most influencing elements of the CSP plant on the environmental impacts. LCA results show that the CSP plant with different TCES integration alternatives has comparable global warming potential (approximately 11 kg $CO_{2.eq}$/MWh) and energy payback time (approximately 4 months). The additional environmental burden due to the addition of the TCES system is relatively small (about 30%). The use of calcium hydroxide for the TCES has noticeable midpoint impacts on the respiratory inorganics, the terrestrial ecotoxicity and the mineral extraction. Solar field group (heliostat mirrors) is generally the most sensitive and environmental impacting factor of the CSP installation. The Turbine integration concept has the smallest environmental impacts among the three concepts proposed.

KEYWORDS

concentrating solar power (CSP), environmental impact, life cycle assessment (LCA), midpoint categories, thermal energy storage (TES), thermochemical

1 | INTRODUCTION

The global energy demand and the energy-related CO_2 emission are estimated to increase by 30 and 15%, respectively, between 2017 and 2040.[1] Clean energy technologies using renewable energy sources have experienced remarkable growth in recent years to meet the growing energy needs, to reduce the air pollution and to limit the global warming. As one of the typical low-carbon technologies, the Concentrating Solar Power (CSP) is expected to play a more and more important role for an "electrifying future," owing to its relatively high efficiency, low operating cost and good scale-up potential.[2] The total installed capacity of CSP globally was around 5.5 GW at the end of the year 2018, increased by a factor of 4.2 compared to that in 2010.[3] The global weighted average levelized cost of energy of CSP in 2018 was 0.185 USD/kWh, 26% lower than in 2017 and 46% lower than in 2010.[3]

CSP technology, when equipped with thermal energy storage (TES) systems, could allow for the shifted electricity production to the periods when it is most needed or valuable. The option of low-cost TES can thus improve the adaptability and dispatchability of the CSP plants, which is considered as central to its cost-effectiveness and competitiveness. TES systems seem indispensable for the future more powerful CSP plants still under construction or planned all over the world.[4,5]

The vast majority of TES systems in CSP plants are based on sensible heat storage (mostly molten salts), for their reliability, low cost and a large amount of feedback obtained.[5,6] However, their low energy density results in significantly increased equipment sizes for high storage capacities, making them less competitive for large-scale powerful CSP plants. Latent heat-based TES technology using Phase Change Materials (PCMs) is also proposed for their higher storage capacity compared to sensible heat technology and almost constant charging or discharging temperature.[7] Nevertheless, additional enhancement measures are usually needed to augment their limited thermal conductivity.

Over the last decade, growing interests have been focused on the thermochemical energy storage (TCES) technology which is mainly based on reversible endothermic/exothermic chemical reactions involving a large amount of reaction heat. The TCES technology using suitable materials could have the highest energy storage density, thus seems very promising in future CSP plants.[5] Abundant literature is available on the selection, development and properties characterization of various TCES material candidates, as reviewed in the works (Refs. 8, 9). The latest advances are made on the enhancement of mass transfer during combination and also the enhancement of heat transfer during decomposition.[10] Many researchers worked on the design and test of proper TCES reactors as described in the work (Ref. 11). Recently, great efforts have also been devoted to the integration issue, which is the appropriate coupling of the TCES system with the power generating cycle of the CSP plant.[12,13]

Meanwhile, the environmental impacts of CSP plants as well as their associated TES systems need to be estimated, for the purpose of comparing different power production technologies and design alternatives. Hence the Life Cycle Assessment (LCA) has been introduced, which is recognized as a holistic and standard method for quantifying environmental impacts of a product or a process from "the cradle to the grave", allowing comparisons in a standardized way.[14,15] This method provides a structured analysis of inputs and outputs covering the whole life-cycle within a generic environmental evaluation framework.[16] A great number of LCA studies on the environmental profiles of CSP plants have been reported in the last decade, as has been synthesized in a recent state-of-the art review by Lamnatou and Chemisana.[17] CSP plants (together with low-cost TES) generally present Global Warming Potential (GWP) of less than 40 g CO_{2eq}/kWh and Energy Payback Time (EPBT) less than 1 year,[17] indicating significantly reduced environmental impacts compared to conventional power plants based on fossil sources.[18,19]

Relatively fewer LCA works in the literature include or focus on the TES materials/systems for CSP plants. In terms of TES materials, it has been reported that the environmental impacts could be reduced by switching from synthetic molten salts to mined salts,[20,21] to recycled industrial ceramics[22] or to concrete).[23] AISI 347H seems better than INCONEL 617 for being used as the containment material for molten salts.[24] In terms of integration concept, commonly used two-tank (molten salt) sensible TES concept is recommended to be substituted by single-tank thermocline concept[20,21] or by passive concept (a tubular heat exchanger integrated into storage (concrete) materials).[23] Few LCA studies involve the latent TES, with the notable exception of Ref. 25. In their study, three TES systems have been compared including (a) molten salts sensible system (two-tank); (b) concrete sensible system (passive tubular exchanger), and (c) PCM latent system (passive finned-pipes module). LCA results show that the molten salt system presents the highest global environmental impacts followed by the PCM system, and the concrete system is the most environmental friendly. Nevertheless, the ranking may be different for different scenarios.[25]

The above literature survey highlights that more investigations about the TES on the environmental profile of the whole CSP plant are needed, as concluded in Ref. 17. Moreover, there is a need for the adoption of midpoint and endpoint approaches (e.g., IMPACT 2002+) as useful supplement for some frequently-used indicators such as GWP, embodied energy and EPBT.[17] Further investigation is particularly needed for the TCES technology which seems pretty promising, but also the most complicated one with a large variety of TCES materials, reactor designs, and integration concepts proposed. Nevertheless, to the best of the authors' knowledge, no LCA study involving TCES systems in CSP plants has been reported in the open literature.

Previously a conceptual study on the coupling of the TCES system with the Rankine cycle of a hypothetic solar power tower (SPT) plant has been reported.[26] Based on the three proposed integration concepts, the present study seeks to fill the research gap by providing, *for the first time*, an LCA of the CSP plant with TCES integration. The main objectives of this paper are then threefold: (a) to compare the environmental performance of three proposed TCES integration alternatives for the SPT plant; (b) to provide more information for CSP systems based on various midpoints categories by adopting the IMPACT 2002+ method; and (c) to evaluate and compare the environmental impacts of four main groups constituting the CSP plant (e.g., solar field, solar tower, TES unit, and power cycle), so as to identify the most influencing and sensitive factors.

This paper will then contribute to expand the limited literature and to provide additional insights on the environmental impacts of CSP plants with TES, especially with TCES. The results obtained may be used to assist in the decision-making process in evaluating and selecting appropriate TES technologies and integration concepts for future CSP plants from the life cycle point of view.

2 | REFERENCE SPT PLANT AND TCES INTEGRATION CONCEPTS

This section recapitulates the reference SPT plant (without TES) as well as the three integration concepts. Note that for each concept, the components of the whole installation are divided into four groups,[25] including the Rankine group (power cycle), the TCES group, the solar field group (heliostats, concentrators), and the solar tower group, as marked by different colors in Figure 1. The reason for this categorization is to evaluate their separate environmental impacts and to make a proper comparison. The reaction couple is $CaO/Ca(OH)_2$, which is found to be a pertinent TCES material for high-temperature

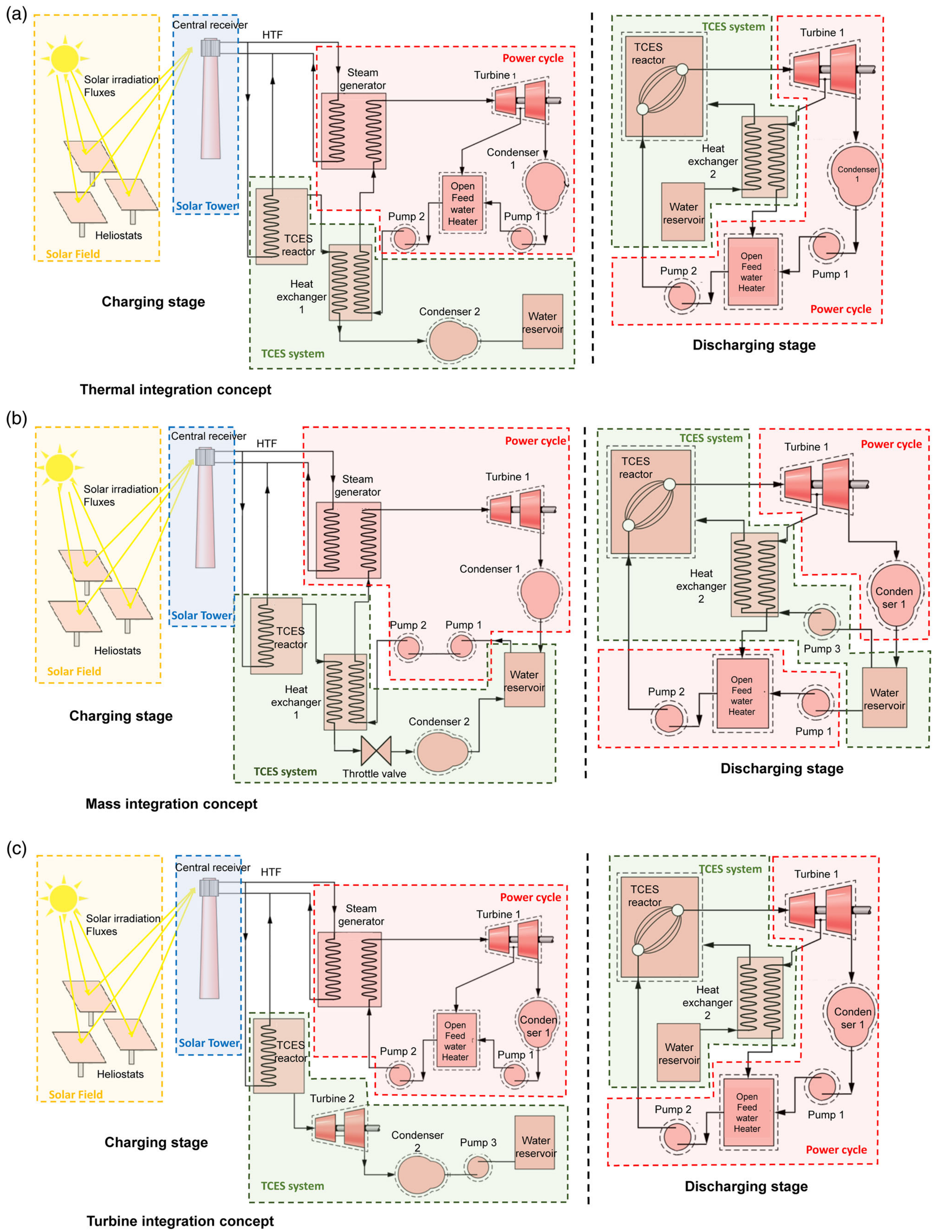

FIGURE 1 Schematic view of the concentrating solar power (CSP) with thermochemical energy storage (TCES) integration. (a) Thermal Int. concept; (b) Mass Int. concept; (c) Turbine Int. concept. Adapted from Ref. 26 [Color figure can be viewed at wileyonlinelibrary.com]

use,[5] including good reversibility, atmospheric operating pressure, low material cost, environment-friendly, and abundant experimental feedback.

2.1 | Reference SPT plant without TES (Ref. Case)

The reference case studied is a 100 MW_{el} SPT plant (schematically shown in Figure A1 of the supplemental material). The solar field group is comprised of heliostats while the solar tower group is mainly composed of the tower and the central solar receiver at the top. The conventional regenerative Rankine cycle includes a steam generator, a turbine, a condenser, an open feedwater heater and pumps. The TES group is not included in this reference SPT plant.

2.2 | Thermal integration (Thermal Int.)

The Thermal Int. concept is shown in Figure 1a. The additional TCES group includes a TCES reactor, a water reservoir, a second condenser and two heat exchangers. During the charging stage (endothermic reaction), $Ca(OH)_2$ salts in the TCES reactor are decomposed into CaO and water vapor at 500°C (1 bar). The water vapor is partially condensed in the heat exchanger 1 to preheat the working fluid of the power circuit, then completely condensed in the condenser 2 and stored as the saturated liquid (100°C, 1 bar) in the separate water reservoir. During the discharging stage, the liquid water in the reservoir is firstly heated up and vaporized by the steam extracted from the turbine of the principal Rankine circuit via the heat exchanger 2. The saturated vapor (100°C, 1 bar) enters then into the TCES reactor and reacts with the CaO salts for heat release. The TCES reactor serves as the steam generator to run the power cycle steadily. The power circuit and the TCES group are thermally coupled with each other but without direct mass contact or exchange.

2.3 | Mass integration (Mass Int.)

The Mass Int. concept is shown in Figure 1b. Compared to the Ref. Case, a TCES group is added including a TCES reactor, a second condenser, a throttle valve, a third pump and two heat exchangers. Different from the Thermal Int. concept, the Rankine power cycle and the TCES circuit are coupled and share the same working fluid with mass exchange. The water vapor generated in the TCES reactor during the charging stage is stored as saturated water (41°C, 0.008 MPa) in the common water reservoir. During the discharging stage, the stored liquid water is pressurized by pump 3 and then evaporated into saturated vapor (100°C, 0.1 MPa) by high temperature extracted steam via the heat exchanger 2. The exothermic reaction between the saturated vapor and the CaO salts in the TCES reactor provides needed heat to run the Rankine cycle.

2.4 | Turbine integration (Turbine Int.)

The Turbine Int. concept is schematically shown in Figure 1c. The TCES group is composed of a TCES reactor, a second turbine, a second condenser, a third pump, a water reservoir, and a heat exchanger. During the charging stage, high temperature water vapor (500°C, 1 bar) from the TCES reactor passes through the turbine 2 to valorize a part of its thermal energy as power production. It will finally be stored as sub-saturated water (41.5°C, 0.1 MPa) in a water reservoir. The discharging stage is the same as that of the Thermal Int.

3 | METHODOLOGY

LCA is a standardized, mature, systems-oriented analytical tool assessing potential impacts of products or services using a life cycle perspective.[27] LCA involves the definition of goal and scope, inventory analysis, impact assessment, and interpretation, following the general guidelines described in ISO 14040 (Principles and Framework) and ISO 14044 (Requirements and Guidelines).

3.1 | Method and indicators

Different LCA methods and environmental indicators have been used for CSP plants, as summarized in Ref. 17. This study is based on the IMPACT (IMPact Assessment of Chemical Toxics) 2002+ embedded in the SimaPro 7.3 software. IMPACT 2002+ is actually an adapted impact assessment method by proposing a feasible implementation of a combined midpoint/damage approach linking the environmental evaluation results of the inventory flow list via 15 midpoint categories (e.g., GWP, human toxicity, respiratory inorganics, non-renewable energy used, etc.), which can then be regrouped into four damage categories (human health, ecosystem quality, climate change, resources).[28] In fact, the midpoint/damage approach performs environmental impact assessment of a process at relatively early stages in the cause-effect chain (midpoint categories) and as far back as possible in the cause-effect chain (damages categories).[29] Compared to the assessment performed with “endpoint” methods, the midpoint methods lead to more accurate results.[30] All midpoint scores expressed in different units (of a reference substance) can be normalized into “eco-point,” by introducing some weighting factors. This normalized score (eco-point) permits then an easy comparison of different midpoint categories.

Specifically for power plants, the GWP (kg CO_2 eq/MWh) and the EPBT will be discussed in more detail, the latter refers to the time required to recover primary energy consumption throughout its life cycle by its own energy production, defined as:

$$EPBT = \frac{\text{Total primary energy required throughout the life cycle}}{\text{Annual primary energy generated}} \quad (1)$$

3.2 | Functional unit and assessment boundary

The functional unit quantifies the performance requirements of the CSP plant, providing a reference for all the design alternatives (TCES integration concepts). This LCA study is based on a constant production rate of 100 MW_{el} of the principal Rankine cycle and a 25 year-lifetime.

The assessment boundary is shown in Figure 2. The extraction and processing of materials are taken into account. Regarding CSP plant maintenance during its operation, only the mirror cleaning of the heliostats is considered. Transport is taken into account as if the materials had been transported to the Switzerland, close to the France where the hypothetical CSP plant is located. Note that the dismantling and the disposal of the CSP plant were not addressed due to the lack of industrial feedbacks, rendering this study a "cradle-to-gate" approach.

4 | SIZING AND EMISSIONS INVENTORY

Conventional components libraries (e.g., Ecoinvent, LCA Food DK, USA Input Output Database) are not adequate for the power plant with such a high production rate. The proper sizing and estimation of the materials used for every individual component are thereby necessary. Note that the component selection and sizing are based on the results of energy analysis reported in Ref. 26.

4.1 | Solar field

The solar field is composed of heliostats reflecting and focusing solar rays on the high temperature solar receiver. Its sizing depends on the needed energy to run the Rankine cycle ($Q_{SG,C}$) and to charge the TCES reactor ($Q_{R,C}$) as well as the Direct Normal Irradiance (DNI) of the plant site.

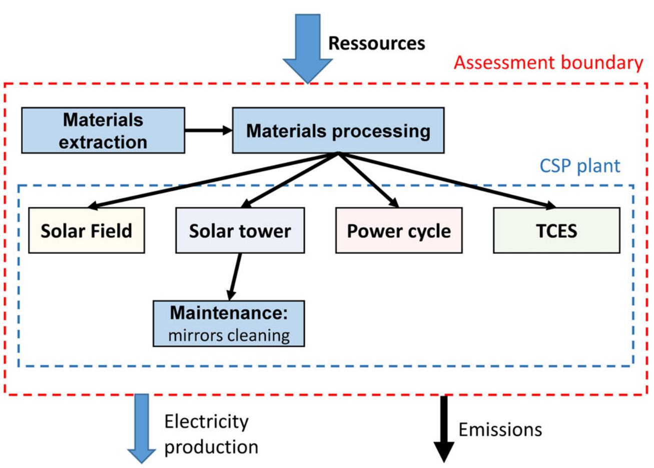

FIGURE 2 Definition of the assessment boundary [Color figure can be viewed at wileyonlinelibrary.com]

$$\text{Heliostats surface area} = \frac{Q_{SG,C} + Q_{R,C}}{DNI} \quad (2)$$

Supposing an average DNI of 700 W/m^2 (for Themis power plant located in the eastern Pyrenees, France), the estimated mirror surface area (S_m) is 388,930 m^2 for the reference case, 920,228 m^2 for the Thermal Int. concept, 943,001 m^2 for the Mass Int. concept and 842,918 m^2 for the Turbine Int. concept, respectively.

Heliostats are mainly composed of metal and mirrors. Their emissions are due to materials extraction, transformation, shaping, and maintenance. Heliostat maintenance by mirrors washing plays an important role because the mirror reflectivity decreases when it is getting dirty. The washing frequency depends on the environment condition and economic policy. Generally, a cleanout every 2 weeks is economically advantageous.[31] In addition, the water must be demineralized to prevent the fouling and transported by trucks to be sprayed on the mirrors.

Several studies have been performed on the LCA of heliostats.[32,33] Supposing that the heliostats used in this conceptual study are similar to those of Gemasolar (mirror of 120 m^2)[33] and that the washing frequency is the same (every 2 weeks during 25 years), identical emissions per square meter seem to be reasonable. Table 1 lists the emission inventory for 1 m^2 of heliostat.

4.2 | Solar tower & receiver

The height of the solar tower has been sized following the quick sizing rules determined by Ref. 34. Heliostats density (d_H) is defined as the ratio of the mirrors surface to the ground surface, generally varying between 0.2 and 0.25. The height of the solar tower (TH) could then be determined as a function of the mirror surface areas (S_m), following Equation (3).[34]

TABLE 1 Emissions inventory for 1 m^2 of heliostat[33]

	Quantity	Library	Name
Heliostat			
Mirror	10 kg	Ecoinvent	Flat glass coated, RER
Steel structure	35.22 kg	Ecoinvent	Reinforcing steel, RER
Steel structure building	35.22 kg	Ecoinvent	Steel product manufacturing, RER
Concrete foundations	0.026 m^3	Ecoinvent	Concrete, sole plate and foundation, CH
Concrete foundations building	0.026 m^3	Ecoinvent	Excavation, hydraulic digger, RER
Maintenance			
Demineralized water	550.31 kg	Ecoinvent	Water, deionized, CH
Water transport	39.62 tkm	Ecoinvent	Transport, lorry 3.5-16 t, average, RER

Note: RER represents Europe and CH represents Switzerland.

$$TH = \sqrt{\frac{4 \times S_m}{80.4375 \times \pi \times d_H}} (\mathrm{m}) \quad (3)$$

The estimated solar tower height is thus (240–270 m) for the Thermal Int., (244–273 m) for the Mass Int., (231–258 m) for the Turbine Int., and (157–175 m) for the Ref. Case, respectively. The height has the same order of magnitude as those of existing solar plants having comparable heliostats surface areas (e.g., Atacama-1 (Chile): S_m = 1,484,000 m^2; TH = 243 m; Ashalim Plot B (Israel): S_m = 1,052,480 m^2; TH = 250 m; Crescent Dunes Solar Energy Project (United-States): S_m = 1,197,148 m^2; TH = 195 m[35]). Hence, a height of 250 m has been chosen for the SPT plant in this study.

The emissions of the solar tower are due to the materials extraction, transformation and shaping. No exchanges are considered to occur between the solar receiver and the outside during the life of the plant. Based on the estimation of Kuelin et al.,[33] a proportional rule has been adopted to determine the emissions of the current hypothetical solar tower, as listed in Table 2.

4.3 | Rankine power cycle

Similar components are involved in the Rankine cycle group of the three TCES integration concepts as well as the reference plant. However, their power and operational conditions vary. Hence, each component has to be selected and sized based on its critical operation point, for example, the one that requires the largest volume and the transfer surface area. The sizing of various heat exchangers (including evaporators and condensers) is based on the shell-and-tube concept.[36] Carbon steel, cheaper and less polluting than stainless steel, was chosen whenever possible. Pumps and turbines were sized based on the reference 37. Additional assumptions as follows were made for the estimation: (a) concrete supports were neglected; (b) water and steam pipes connecting components were neglected; and (c) water contained in the Rankine cycle was neglected. The sensitivity of these assumptions will be evaluated later to show whether they will have a significant impact.

TABLE 2 List of the solar tower and receiver emissions for the concentrating solar power (CSP) plant in this study

	Quantity	Library	Name
Stainless steel structure	10,696 kg	Ecoinvent	Chromium steel 18/8, RER
Stainless steel structure manufacturing	10,696 kg	Ecoinvent	Chromium steel product manufact., RER
Cold pipes	6,714 kg	Ecoinvent	Reinforcing steel, RER
Cold pipes manufacturing	6,714 kg	Ecoinvent	Steel product manufact., RER
Hot pipes	6,714 kg	Ecoinvent	Reinforcing steel, RER
Cold pipes manufacturing	6,714 kg	Ecoinvent	Steel product manufact., RER
Foundations concrete	9,054 m^3	Ecoinvent	Concrete, sole plate and foundation, CH
Foundation holes	357 m^3	Ecoinvent	Excavation, hydraulic digger, RER
Reinforcing steel	905,357 kg	Ecoinvent	Reinforcing steel, RER

The mass amount required for various Rankine power cycle components is gathered in Table A1 of the supplemental material. The emissions are due to the materials extraction and transformation. No exchange is considered to occur between the Rankine cycle group and the outside during the life of the plant. Table 3 lists the Rankine cycle emissions for different integration concepts.

4.4 | TCES group

The TCES reactor as the major component of the TCES group is designed based on the concept of a plate-type heat exchanger composed of CaO, expanded natural graphite (ENG) and stainless steel. The mass of reactive salts (m_{CaO}) is determined following the energy analysis, with 20% overestimation of the masses needed. The mass of ENG is supposed to represent about 10% of the mass of CaO. The total volume of the composites (V_{comp}) can be calculated by Equation (4):

$$V_{comp} = \frac{(1-\tau).m_{CaO}}{\tau \times \tilde{\rho}_{ENG}} \quad (4)$$

$$\tau = m_{CaO}/m_{comp} \quad (5)$$

where $\tilde{\rho}_{ENG}$ (kg/m^3) is the bulk density of ENG. By fixing the dimensions of composite plate (6 m in length, 1 m in width, and 3 mm in thickness), it is then possible to determine the number of composite plates (n_{comp}), which equals to the number of stainless steel heat exchanger plates (n_{HEP}).

$$n_{comp} = n_{HEP} = \frac{V_{Comp}}{l_{comp} \times w_{comp} \times t_{comp}} \quad (6)$$

Assuming that the envelope, the diffusers and the internal connections account for 10% of the total mass of the plate-type heat exchanger (m_{HEP}), the required total mass of stainless steel is:

$$m_{HEP} = n_{HEP} \times (l_{comp} \times w_{comp} \times t_{HEP}) \times \rho_{ss} \times (1 + 10\%) \quad (7)$$

where t_{HEP} and ρ_{ss} are the thickness of each heat exchanger plate (2 mm) and the density of the stainless steel (7.8 × 10^3 kg/m^3), respectively. The sizing and mass estimation of other components of the TCES group (e.g., heat exchangers, turbine, pump, etc.) follow the

TABLE 3 Rankine power cycle emissions inventory

Material	Library	Name	Thermal Int.	Mass Int.	Turbine Int.	Ref. Case
Stainless steel (kg)	Ecoinvent	Chromium steel 18/8, at plant/RER S	212,000	212,000	212,000	212,000
Carbon steel (kg)	Ecoinvent	Steel, low-alloyed, at plant/RER U	1,151,000	1,151,000	1,058,000	1,151,000

TABLE 4 TCES group emission inventory

Material	Library	Name	Thermal Int.	Mass Int.	Turbine Int.	Ref. Case
Stainless steel (kg)	Ecoinvent	Chromium steel 18/8, at plant/RER S	11,643,100	11,844,100	11,944,100	0
Carbon steel (kg)	Ecoinvent	Steel, low-alloyed, at plant/RER U	685,000	685,000	267,000	0
ENG (kg)	Ecoinvent	Graphite, at plant/RER U	1,235,700	1,289,000	1,289,000	0
$Ca(OH)_2$ (kg)	Ecoinvent	Lime, hydrated, packed, at plant/CH U	14,697,000	15,327,000	15,327,000	0

Abbreviations: ENG, expanded natural graphite; TCES, thermochemical energy storage.

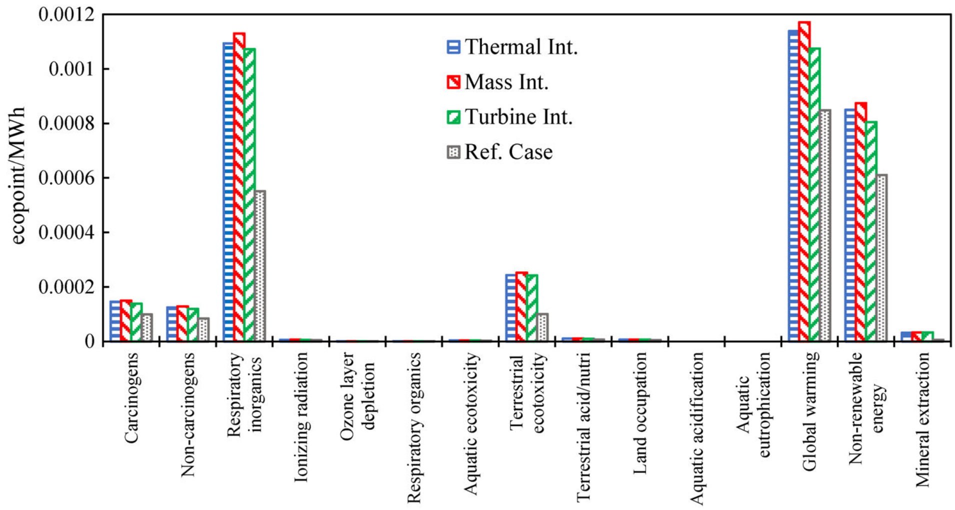

FIGURE 3 Comparison on normalized midpoint impacts for different thermochemical energy storage (TCES) integration concepts [Color figure can be viewed at wileyonlinelibrary.com]

same procedure as presented for the Rankine power cycle. The mass required for various components of the TCES group is listed in Table A2 of the supplemental material.

The emissions of the TCES components are due to the materials extraction and transformation. No exchange is considered to occur between the thermal storage and the outside during the lifetime of the CSP plant. Table 4 lists the TCES group emissions for different integration concepts.

5 | RESULTS AND DISCUSSION

5.1 | Comparison of the TCES integration concepts: Normalized midpoint impacts

Figure 3 shows a comparison on various normalized midpoint categories for different TCES integration concepts in the SPT plant. It can be observed that among various midpoint categories, the SPT plant (with or without TCES) has significant impact on respiratory inorganics, global warming, and non-renewable energy; noticeable impact on carcinogens, noncarcinogens, and terrestrial ecotoxicity and negligible impact on the rest categories.

The normalized midpoint impacts of three TCES integration concepts are close in each category. Among them, the Turbine Int. has the least impact followed by the Thermal Int. and the Mass Int. This ranking is in accordance with the results of energy and exergy analyses presented in Ref. 26. The Ref. Case without TCES shows smaller environmental impacts than other concepts with TCES, particularly in the respiratory inorganics category. The absence of TCES materials (e.g., calcium hydroxide) and a smaller solar field (heliostat mirrors) may explain this difference.

5.2 | Comparison of the components share: Midpoint impact

Figure 4 shows the contribution of the four groups for the 15 midpoint impact categories. The three integration concepts have similar

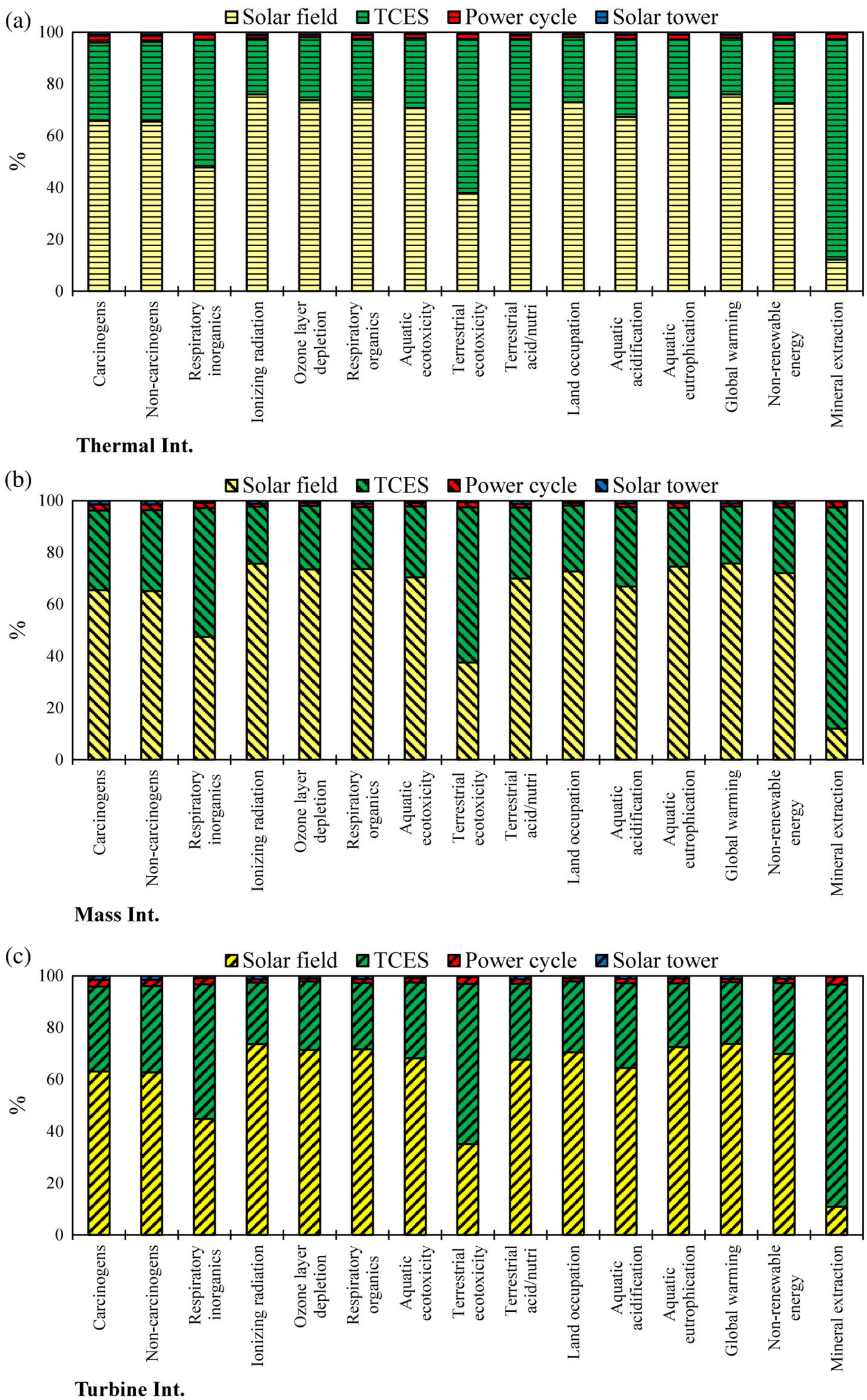

FIGURE 4 Proportion of midpoint impacts from different component groups. (a) Thermal Int.; (b) Mass Int.; (c) Turbine Int [Color figure can be viewed at wileyonlinelibrary.com]

contribution for each midpoint category. The slight difference is due to the use and the sizing of relevant components for different SPT plant concepts. While the combined contribution of the solar field and the TCES groups to the total midpoint impact is dominant in each category, the impacts of solar tower and Rankine power cycle groups are negligible.

For the respiratory inorganics, the terrestrial ecotoxicity, and the mineral extraction, the impacts from TCES group are dominant due to the involvement of $CaO/Ca(OH)_2$. For the rest 12 categories, the solar field group is the most impacting factor.

5.3 | GWP and EPBT

Figure 5 shows a comparison on the GWP (kg $CO_{2.eq}$/MWh) for different TCES integration concepts, as well as the contribution of each components' group. The solar field group is the most impacting factor (≈75%) on GWP, followed by the TCES group. The solar tower and the Rankine power cycle groups represent a negligible contribution (≈3%). Regarding the TCES integration concepts, the Turbine Int. has the lowest GWP impact (10.64 kg $CO_{2.eq}$/MWh), followed by the

Thermal Int. (11.27 kg $CO_{2.eq}$/MWh) and the Mass Int. (11.59 kg $CO_{2.eq}$/MWh). This difference is mainly due to the different sizes of the solar field. Compared to the Ref. Case without storage (8.39 kg $CO_{2.eq}$/MWh), the GWP increase due to the TCES integration is about 6%. This moderate increase can be attributed to the higher daily power production rate owing to the TCES integration.

Table 5 lists the EPBT for the CSP plant with different TCES integration concepts; the Ref. Case is also included for comparison. Among the three concepts with TCES integration, the Turbine Int. has the shortest EPBT (120 days) followed by the Thermal Int. (127 days), and the Mass Int. (130 days). The EPBT for the Ref. Case without storage is about 90 days, 30 days shorter than that for Turbine Int. For all these cases, the ratio of EPBT to a 25 years lifetime is really small (<1.5%).

5.4 | Comparison with other CSP LCA studies

Compared to other LCA results reported in the literature, the values of GWP (about 11 kg $CO_{2.eq}$/MWh) and EPBT (about 4 months) obtained in this study are within the same order of magnitude as those obtained for different electricity production technologies[38] and for CSP plants (GWP < 40 $kgCO_{2.eq}$/MWh; EPBT≈1 year[17]). Besides various simplifications made for the assessment boundary (i.e., excluding the impacts of site improvement activities, foundations and piping accessories), several design choices can further explain the lower GWP and EPBT values.

The choice of a wet instead of a dry cooling condenser may decrease the GWP from 28 kg $CO_{2.eq}$ /MWh to 24 kg $CO_{2.eq}$/MWh.[20] The use of mined salts as the heat transfer fluid (HTF) instead of synthetic salts can reduce the GWP by 38% (24 $kgCO_{2.eq}$/MWh against 39 $kgCO_{2.eq}$/MWh).[20] This part has been neglected in the current study. Furthermore, the choice of TES materials strongly influences the GWP value[39]: a Thermocline/Mullite system leads to 17 kg $CO_{2.eq}$/MWh versus 2 kg $CO_{2.eq}$/MWh for a Thermocline/basalt system. In the current case, the use of $CaO/Ca(OH)_2$ as the storage material reduces the impacts on GWP compared to other storage materials such as liquid salts or ceramics. Finally, a natural gas backup system can increase the GWP impact by about 10%.[21] The absence of a backup system in the TCES integration concepts contributes to a lower environmental impact. In future studies, these simplified factors may have to be considered to render a more detailed analysis.

5.5 | Sensitivity analysis

The sensitivity analysis aims at evaluating the possible variation of the concerned indicators (e.g., GWP, nonrenewable energy) when some parameters are varied from their designed values. This kind of analysis

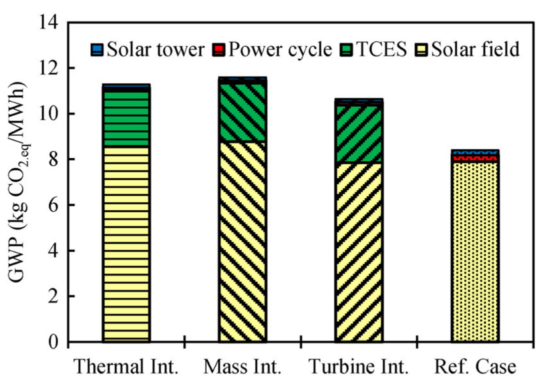

FIGURE 5 Global warming potential for different thermochemical energy storage (TCES) integration concepts [Color figure can be viewed at wileyonlinelibrary.com]

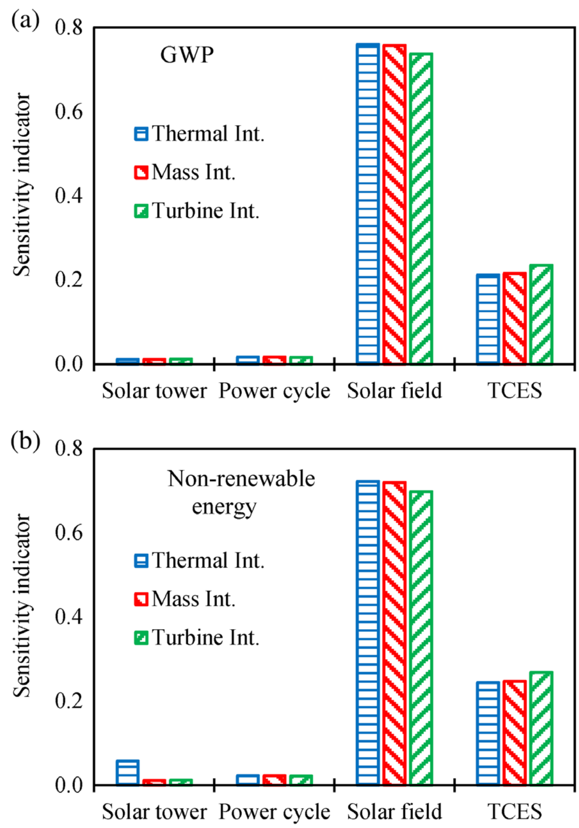

FIGURE 6 Sensitivity analysis results. (a) Global Warming Potential (GWP); (b) Nonrenewable energy [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Energy payback time (EPBT) for different thermochemical energy storage (TCES) integration concepts

	Thermal Int.	Mass Int.	Turbine Int.	Ref. Case
EPBT (days)	127	130	120	90
Ratio to a 25 years lifetime (%)	1.39	1.42	1.31	0.99

is useful since some parameters and quantities are estimated with assumptions and approximations at the design stage. The most influencing factors identified have then to be determined with the greatest precision so as to minimize the uncertainties of the LCA. In contrast for less influencing parameters, the estimation could be more or less approximate.

The sensitivity analysis performed in this study is mono parametric "one-at-a-time" approach. Each input value x_i is individually modified around a relative variation $\Delta x_i/x_i$. The value of the impact I_j for x_i enables to calculate the variation ΔI_j and the relative impact variation $\Delta I_j/I_j$. The sensitivity indicator (S) is defined as the ratio of the relative variation of the output quantity to the input value:

$$S = \frac{\Delta I_j / I_j}{\Delta x_i / x_i} \tag{8}$$

A relative variation ($\Delta x_i/x_i$) of 20% was applied individually to each component in this study. It may be observed from Figure 6 that the solar field group is the most sensitive group of the CSP installation. A small variation in its sizing or in its emissions inventory will result in a significant uncertainty in the calculation of the overall environmental impacts. The TCES group, less sensitive than the solar field, remains as the element that should be carefully designed and sized (especially for the TCES reactor). The solar tower and the Rankine power cycle groups are relatively insensitive elements. Some approximate values of their masses may not affect much the results of the LCA.

6 | CONCLUSION AND PERSPECTIVES

This paper presents an original comparative study of the environmental impacts of a CSP plant with the TCES integration. The LCA is performed using the IMPACT2002+ method. Based on the analysis results obtained, the following main conclusions could be reached:

- The SPT plant with different TCES integration alternatives has the same level of GWP (approximately 11 kg $CO_{2.eq}$/MWh) and EPBT (approximately 4 months). Compared to the reference plant without storage (8.5 kg $CO_{2.eq}$/MWh; 3 months), the additional environmental impact due to the TCES system is relatively small (approximately 30%). This is mainly because of more than 65% higher daily power production rate owing to the TCES integration (higher dispatchability).
- The use of $CaO/Ca(OH)_2$ in the TCES system results in noticeable influences on the respiratory inorganics, the terrestrial ecotoxicity, and the mineral extraction categories.
- Solar field group (heliostat mirrors) is generally the most sensitive and environmental impacting group of the CSP installation while the solar tower and the Rankine power cycle groups are relatively insensitive and less impacting elements.
- Among the three integration concepts proposed, the Turbine Int. has the smallest environmental impacts followed by the Thermal Int., and then the Mass Int.

The main limitations of this study are as follows.

- The results obtained pertain to the specific hypothetical TCES integration concepts in the SPT plant employed here, since no such plant is actually in operation. The sizing and mass estimation may not be so precise.
- The definition of the assessment boundary is simplified (e.g., round-the-clock operation all through the year, neglecting site improvement activities, HTFs, foundations, and disposal phase, etc.). Some environmental impacts may have been underestimated.

Additional LCA research is thus necessary to confirm the results and tendency reported here, by adopting more realistic estimations and precise sizing of the components based on real operational experiences and feedback. In parallel, the dynamic simulation of the whole installation under real conditions is the ongoing work, providing updated data for alternative energy production scenarios. Finally, multi-objective optimization under energetic, economic, and environmental considerations for multiple criteria decision making is the future direction.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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