Life Cycle Assessment (LCA) of Several Concentrating Solar Plants (CSP) in Tower Configuration with Different Storage Capacity in Molten Salts

Gemma Gasa[1], Antón Lopez-Roman[2], Cristina Prieto[3], Luisa F. Cabeza[1]

[1] GREiA Research Group, Universitat de Lleida, Lleida (Spain), luisaf.cabeza@udl.cat

[2] Abengoa Energia, Sevilla (Spain), anton.lopez@abengoa.com

[3] University of Seville, Department of Energy Engineering, Seville (Spain), cprieto@us.es

Abstract

The objective of this study is to analyse the impact of the thermal energy storage system (TES) in the life cycle assessment (LCA) of a concentrating solar power plant (CSP) with central receiver technology. The study uses a base case of a plant with 110 MW_{el} and 17.5 hours of direct storage with molten salts. First, this plant was compared with a plant of equal power but without storage. Subsequently, the LCAs of four plants with different thermal energy storage capacities, 3, 6, 9 and 17.5 equivalent hours, were compared. The results show that TES is key for solar thermal plants, not only to guarantee dispatch capacity, but also to reduce their environmental impact. Comparing different thermal storage capacities, the most environmentally efficient plant of those analysed is the one with a storage capacity of 9 h.

Keywords: Concentrating solar power (CSP) plant; tower plant; thermal energy storage (TES); storage capacity; life cycle assessment (LCA); environmental impact

1. Introduction

The use of renewable energies to replace fossil fuels seeks to implement sustainable energy development worldwide and contribute to the mitigation of climate change. With this, it is possible to break with the trend of associating the economic development of a country and its energy consumption with the increase in greenhouse gas emissions. The current global concern to mitigate climate change has made renewable resources attractive in world economies to reduce the environmental and health impacts derived from the normalized use of fossil fuels. As countries agree to pursue cleaner energy transition goals by reducing the use of fossil fuels, it is clear that energy storage to promote renewable energy penetration is vital. The dispatch capacity of renewable electricity increases when storage is included in energy supply systems. Thermal energy storage (TES) is one of the fundamental pillars on the path to decarbonization. Its introduction in solar thermal plants (CSP) seeks to improve its performance and flexibility to achieve a better use of energy on demand (Papadopoulou et al. 2020).

One of the commercial renewable energy systems is the production of solar thermal electricity (STE), produced in so-called solar thermal plants (CSP). A CSP generates electricity thanks to mirrors, which allow the sun's rays to be concentrated, reaching high temperatures in the receiver, between 400 °C and 1000 °C, with the ultimate goal of driving a thermal engine, usually a steam turbine, to generate electricity to feed the electrical network. The incorporation of the TES system in CSPs makes it possible to generate electricity in a longer time slot, regardless of the sun. The TES system stores the energy captured by the solar field when it is not needed, and it is discharged when there is no sun (Forrester, 2014), so the operation of the CSP plant can be compared with conventional power generation plants (Liu et al. 2016).

The literature includes studies on the influence of the storage capacity in the LCoE of CSP plants (Gorman et al. 2021; Guedez et al. 2014) but no studies on its environmental influence were found. Therefore, the objective of this study is, in a first phase, to analyze whether the advantages of the thermal energy storage system in a CSP at the manageability level are linked to a reduction in environmental impacts when compared to a CSP, with the same configuration. , but without a TES system. In addition, in a second phase, it is intended to analyze if 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 from the environmental point of view. Analyzing the storage capacity was considered important since it conditions not only the operational structure of the CSP plant, but also its economic and environmental efficiency. It is almost mandatory to optimize the configuration of each of the plant operation areas, 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 and the environmental impacts associated with the plant (Guedez et al., 2014).

2. Description of the considered CSP plants

Given that initially we wanted to evaluate the effect of thermal energy storage on the LCA of a CSP with a tower configuration, it was considered necessary to compare it with a CSP without storage. The base case of a 110 MWel tower plant with 17.5 hours of direct thermal energy storage using molten nitrate salts (60% $NaNO_3$, 40% KNO_3) was compared with a plant of equal power, but without storage.

For the second part of the study, the impact for different thermal energy storage times was analyzed, since the storage capacity conditions not only the operational structure of the CSP plant, but also its economic and environmental efficiency. For the present study, four storage capacities were considered: 3, 6, 9 and 17.5 equivalent hours in nominal conditions.

3. Methodology

Life cycle assessment is a methodology that allows evaluating the environmental loads associated with a product, process or activity, identifying and quantifying the energy, materials consumed and waste released into the environment throughout the entire life cycle.

The LCAs included in this study were carried out in accordance with ISO 14040 and 14044 standards and the environmental impact assessment methods of the different assessment phases (manufacturing, operation and end of life) were ReCiPe, at impact points, and IPCC2013 – GWP, in $kgCO_2eq$.

In this study, “1 kWh of net electricity injected into the grid” was chosen as the functional unit, and in accordance with ISO 14040 and 14044 standards, the final LCA results are expressed in terms of this functional unit. In addition, an assumed useful life of the CSP plant of 30 years was used.

The inventory of inputs and outputs included in the case of the tower solar thermal plant with 17.5 hours storage was drawn up with real data provided by Abengoa. For the case of the inventory of the tower CSP plant without storage, a fictitious configuration was assumed and for this, inventory values were obtained by scaling values of the CSP plant with storage.

Under the criterion of the maximum capacity factor, 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 assess the impact of TES capacity on LCA, three hypothetical configurations are defined varying the storage capacity, but maintaining the same nominal power level (110 MW): a second base load configuration with 9 hours of TES and two peak load configurations using 6 and 3 hours (based on the IEA CSP technology roadmap). These four CSP plants in tower configuration have a gross output of 110 MWel.

4. Results

As shown in Fig. 1a, the total impact per functional unit of a plant without storage, calculated with the ReCiPe methodology, was almost double that of a CSP plant with storage.

When breaking down this impact taking into account the phase of the life cycle in which it is generated (manufacturing phase and operational phase), the results are different if the CSP plant has a TES system. In the case of CSP without storage, the impact was generated in practically the same proportion, but for CSP with storage, almost all the impact generated takes place during the manufacturing phase, with that of the operational phase being very small in comparison.

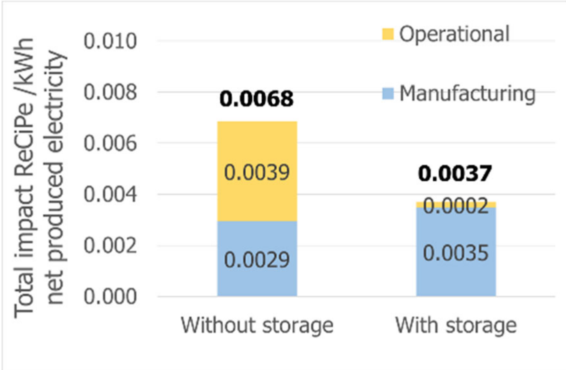
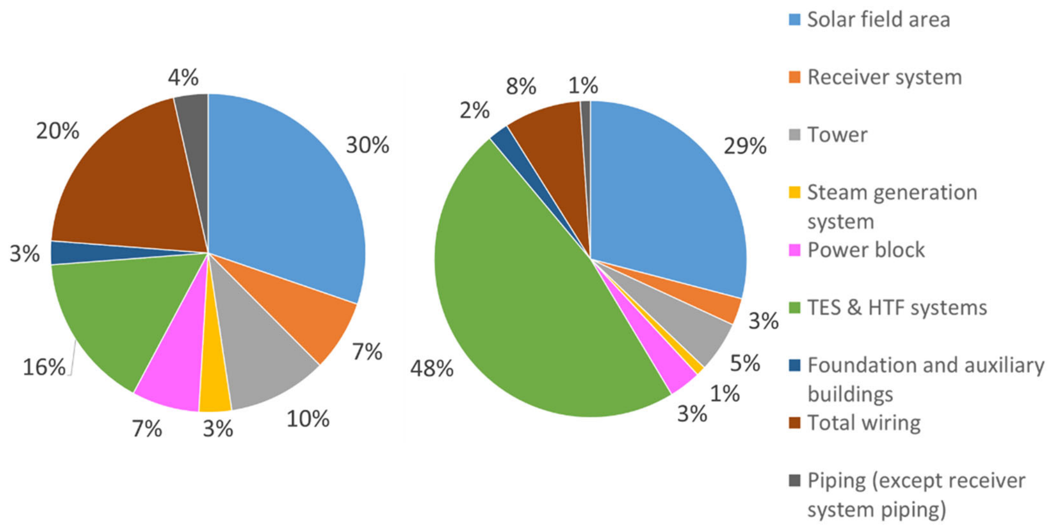


Fig. 1: Environmental impact: ReCiPe indicator per kWh of net electricity produced (Gasa et al., 2021)

Figure 2 shows the contribution of each system in the CSP plant to the total impact points evaluated with the ReCiPe indicator. The main objective of this figure is to be able to see which system of the CSP plants had the most influence on the global environmental effects considering all phases of the cycle of life. For a CSP plant without storage (Fig. 2a), the system with the highest impact was the solar field (30%), followed by the wiring (20%), and the heat transfer fluid (HTF) system (16%). The other parts of the plant generated an impact equal to or less than 10% of the total impact. In the case of a CSP plant with storage (Fig. 2b), the system with the greatest impact was the TES system (48%), followed by the solar field (29%). The other plant systems generated an impact of less than 10% of the total.



(a) **(b)**

Fig. 2. Contribution to the impacts of each component of the CSP considered (ReCiPe impact points): (a) without storage; (b) with storage (Gasa et al., 2021)

After verifying that CSPs with storage generate less environmental impact than a plant without storage, four plants of equal power with different hours of storage were compared.

The total of the environmental impacts generated, according to the ReCiPe method and for the four CSP plants with tower configuration and with different thermal storage capacity, are shown in Fig. 4. As the hours of storage increase, the points of ReCiPe impact per functional unit decrease, but when the storage capacity goes from 9 hours to 17.5 hours of storage, no improvements are observed (Fig. 4a). Fig. 4b shows that, in the four plants analyzed, almost all environmental impacts are generated during the manufacturing phase. As storage capacity increases, the contribution of manufacturing phase impacts increases and operational phase impacts decrease.

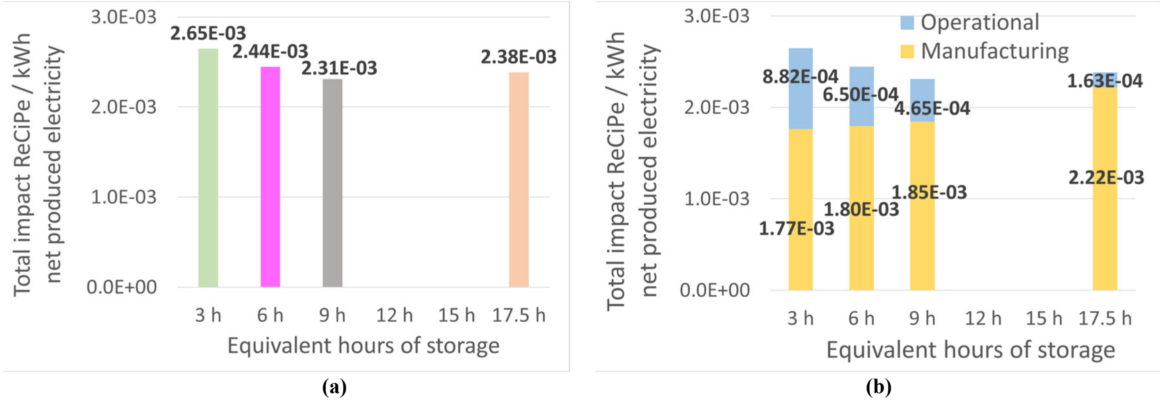


Fig. 3. Impacts according to the ReCiPe indicator per kWh of net electricity produced: (a) total impact; (b) impact generated in the manufacturing and operation phases (Gasa et al., 2022)

5. Conclusions

After comparing the environmental impacts generated by a CSP plant with tower configuration with thermal storage and one without thermal storage the following conclusions can be drawn:

- The CSP plant without storage has a higher environmental impact than the plant with storage.
- The impact of the operational phase determined the difference between the two plants, and this can be attributed to the consumption of electricity from the grid required by CSP plants without storage.
- The CSP tower plant systems that generated the highest impact were the solar field and the HTF and TES systems.

The results obtained on the impact generated by CSP plants with tower configuration and with different storage capacities allowed to establish that:

- When the storage capacity is increased in periods of 3 hours (3 h, 6 h and 9 h), the impacts generated throughout their useful life decrease, however, when the storage capacity increased from 9 h to 17.5 h, the impact generated is very similar.
- As the CSP plant increases its storage capacity, the impact generated during the manufacturing 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 impact generated in the operation phase is reduced, since the increase in storage capacity makes it possible to reduce the need to use electrical energy from the grid.

6. Acknowledgements

This work is part of PCI2020-120695-2 projects funded by Ministerio de Ciencia e Innovación - Agencia Estatal de Investigación (MCIN/AEI/10.13039/501100011033) and by the European Union “NextGenerationEU”/PRTR”. This work was partially funded by the Ministerio de Ciencia e Innovación - Agencia Estatal de Investigación (AEI) (PID2021-123511OB-C31 - MCIN/AEI/10.13039/501100011033/FEDER, UE) and by the Ministerio de Ciencia, Innovación y Universidades - Agencia Estatal de Investigación (AEI) (RED2018-102431-T- MCIU/AEI). The authors would like to thank the Catalan Government for the quality accreditation given to their research group GREiA (2017 SGR 1537). GREiA is a certified agent TECNIO in the category of technology developers from the Government of Catalonia. This work is partially supported by ICREA under the ICREA Academia programme.

7. References

Papadopoulou, A. G.; Vasileiou, G.; Flamos, A., 2020. A comparison of dispatchable RES technoeconomics: Is there a niche for concentrated solar power? Energies 13 (18), 4768.

Liu, M.; Steven , N.H.; Bell, S.; Belusko, M.; Jacob, R.; Will, G.; Saman, W.; Bruno, F., 2016. Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. Renew Sustain Energy Rev 53, 1411–1432.

Gorman, B.T.; Lanzarini-Lopes, M.; Johnson, N.G.; Miller, J.E.; Stechel, E.B., 2021. Techno-Economic Analysis of a Concentrating Solar Power Plant Using Redox-Active Metal Oxides as Heat Transfer Fluid and Storage Media. Front Energy Res 9, 1–18.

Guédez, R.; Spelling, J.; Laumert, B.; Fransson, T., 2014. Optimization of thermal energy storage integration strategies for peak power production by concentrating solar power plants. Energy Procedia 49, 1642–1651.

Gasa, G.; López-Román, A.; Prieto, C.; Cabeza, L.F., 2021. Life Cycle Assessment (LCA) of a Concentrating Solar Power (CSP) Plant in Tower Configuration with and Without Thermal Energy Storage (TES). Sustainability 13(7), 3672

Gasa, G.; López-Román, A.; Prieto, C.; Cabeza, L.F., 2022. Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with different storage capacity in molten salts. Journal of Energy Storage 53, 105219