SolarPACES 2023, 29th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Advanced Materials, Manufacturing, and Components

https://doi.org/10.52825/solarpaces.v2i.826

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Published: 28 Aug. 2024

Assessment of Greenhouse Gas Emissions isplaced by Molten Salt Storage in CSP Plants Compared to Conventional Power Plants

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Abstract. Molten salts are the most widely used thermal energy storage system in Concentrated Solar Power (CSP) plants, accounting for 50% of the installed capacity. Many studies have conducted life cycle assessments of the Greenhouse Gas (GHG) emissions produced within the CSP ecosystem; however, it has not yet been standardized for molten salt storage. This study compares GHG emissions of molten salt storage in CSP with conventional coal and natural gas power plants, to measure the environmental impact they can have in the CSP ecosystem. This was achieved with the use of simulations for 48 operational CSP plants worldwide using the system advisor model with their respective operation conditions. Results show that for the three configurations studied, CSP plants would result in annual 3,99 MMtCO2eq of emissions displaced when compared to a coal power plant and 1,61 MMtCO2eq compared to a natural gas power plant.

Keywords: Greenhouse Gas Emissions (GHG), Molten Salts, Concentrated Solar Power (CSP), CO_{2eq}, Thermal Energy Storage (TES), System Advisor Model (SAM)

1. Introduction

Concentrated solar power (CSP) plants have a worldwide installed capacity of 6,3 GW_e, primarily located in Spain (2,3 GW_e), United States (1,5 GW_e), China (0,6 GW_e), Morocco (0,5 GW_e), and South Africa (0,5 GW_e) (August 2022) [1]. They can be combined with a thermal energy storage (TES), making possible to produce energy at any time of day, even when no sunlight is available. The most widely used TES system is molten salt, accounting for 50% of the total CSP installed capacity. Molten salts are a non-eutectic mixture of sodium and potassium nitrate, with thermal properties that allow for high temperature ranges and cycle efficiencies. An increasing TES demand in upcoming projects suggests that molten salts will play a critical role in the future for electricity generation and energy curtailment [2], [3].

The rise of public policies enforced by governments are increasing the request for renewable alternatives in the power generation sector as means to reduce greenhouse gas (GHG) emissions. Thus, the quantification of equivalent emissions saved by renewable energy sources is needed. Several authors have carried out life cycle assessments (LCA) focusing on GHG-emission by CSP plants [4-8]. However, most of their work centers on single CSP configurations or smaller data ranges of TES with molten salts. Recently, Gemma, *et al.* [9] conducted a LCA of a CSP plant with molten salts, contemplating four storage capacities ranging from 3 to 17,5 full load hours, considering exclusively a solar tower configuration. Therefore, the amount of equivalent GHG emissions displaced by CSP plants with molten salts TES has not yet been determined. This study compares GHG emissions of molten salt storage in CSP with conventional coal and natural gas power plants, to serve as a benchmark of the environmental impact they can have in the CSP ecosystem.

2. Methodology

2.1 SAM performance models and solar resources

A technical database of currently operating CSP plants with molten salt storages was compiled using SolarPACES open-source data for all CSP projects worldwide [10]. Subsequently, the technical parameters required for each SAM performance model were verified against other freely available data. Each applicable CSP project is simulated in System Advisor Model (SAM). This study only includes the performance models for electric power generation by CSP, namely Parabolic Through Collector (PTC), Solar Tower (ST), and Linear Fresnel (LF). Solar dish configuration is excluded due to its low number of operational plants, having a negligible impact in results. The PTC and ST performance models were validated with the SAM case studies [11], [12], in the case of the Fresnel plant there is no information available on the operational data for an entire year to validate the results. In this case the validation of the SAM model is based on a NREL report for the performance of the model [13].

Typical Meteorological Year (TMY) data from Solcast are used as the solar resource to simulate energy performance of each one of the 48 CSP performance models at its respective site. For each site, a 60 min time resolution of several parameters (DNI, air temperature, wind speed, others) are collected and a set of 12 months from the multi-year period is chosen that best represent the characteristic meteorological conditions of average years over the long-term period (temporal coverage from 2008 to 2018). Due to the non-economic approach in this study, P50 is used as the best estimate, which refers to 50% of the years exceeding the value of a data set. Furthermore, a few assumptions and simplifications are selected for the performance models:

- Zero degradation rate on the lifetime which do not consider a decrease of systems electricity output from year to year throughout the analysis period.
- Best-case plant operation, with 100% system availability (no outages, no maintenance, no dispatch control, no grid curtailment).
- No fossil-fueled auxiliary backup heater, but parasitic thermal field and storage freeze protection from gross electric power output or grid.

2.2 Electric power generated by the storage system

The evaluation of the GHG emissions displaced by molten salt storage in a CSP plant requires at first the calculation of the percentage of electric power generated by the storage system (E_{TES}) in relation to the total electric power to the grid (E_{grid}). Related hourly thermal- and electrical energy values (Q_{TES}, Q_{PC}, E_{grid}) from each simulation are summed up over one year to set up a comparative value. Total thermal energy discharged by the storage tank (Q_{TES}) relative to the total thermal energy supplied to the power cycle (Q_{PC}) is defined as thermal fraction (X_{TES}):

$$\boldsymbol{X_{TES}} = \frac{Q_{TES}}{Q_{PC}} \qquad (1)$$

As a simplified model, cycle thermal efficiency (η_{cycle}) and gross to net conversion efficiency (η_{gnc}) are estimated as constant values at the design point. X_{TES} is consequently equal to the electrical fraction between E_{TES} and E_{grid}.

$$\boldsymbol{E_{grid}} = Q_{PC} \cdot \eta_{cycle} \cdot \eta_{gnc} \tag{2}$$

$$\boldsymbol{E_{TES}} = X_{TES} \cdot E_{grid} \tag{3}$$

E_{TES} is the one-year value based on simulation results over a period of 8 760 hours. In addition, the total electric energy generated by the storage during its operating period to date (t_{op}) is calculated between the defined reference time for evaluation (t_{ref} = August 2022) and the start time of the plant operation (t_{start}).

$$\boldsymbol{t_{op}} = t_{ref} - t_{start} \tag{4}$$

2.3 Emission intensity factor

CO_2 equivalent emission intensity factors ($c_{CO2,eq}$) over a 30 year lifetime of two conventional power plants (carbon and natural gas) and an average renewable solar power plant (CSP plants) are defined. In general, this factor is quantified as the emission rate of a given pollutant relative to the intensity of a specific activity. Regarding the power generation sector, $c_{CO2,eq}$ is defined as the ratio of the quantity of equivalent CO_2-emissions ($kg_{CO2,eq}$) released per energy produced (MWh_e).

The integrated life cycle assessment (LCA) of electricity sources from the UNECE [14] is used as a basis, which indicates global mean values for the year 2020.This study only focuses on the climate change category, which represent the radiative forcing as GWP, integrated over 100 years (GWP 100), based on IPCC baseline model. Regarding the power generation sector, total lifetime GHG-emissions released per total energy produced ($c_{GHG,tot}$) is divided into two phases, the construction of a power plant ($c_{GHG,cons}$) and the power generation ($c_{GHG,pg}$). It should be noted that GHG-emissions are expressed here in CO_2 equivalent values, which are based on a GWP value of 100. Furthermore, methane leakage is included for the conventional power plants model, but its leakage rate is not considered specifically in a sensitive analysis here.

$$\boldsymbol{c_{GHG,tot}} = c_{GHG,cons} + c_{GHG,pg} \tag{5}$$

The emission intensity factor for CSP plants is modified to a weighted value, considering the energy performance from each technology in the SAM simulations ($E_{grid,PTC}$, $E_{grid,ST}$, $E_{grid,LF}$). Individual emission intensity factors are considered in the calculation, showing that ST ($c_{GHG,ST}$=21,7 kg_{CO2eq}/MWh_e) emits significantly less on a life cycle basis than and PTC/LF ($c_{GHG,PTC,LF}$=42,0 kg_{CO2eq}/MWh_e) due to a higher estimated capacity factor.

$$\boldsymbol{c_{GHG,CSP}} = \frac{E_{grid,PTC} \cdot c_{GHG,PTC} + E_{grid,ST} \cdot c_{GHG,ST} + E_{grid,LF} \cdot c_{GHG,LF}}{E_{grid,tot}} \quad (6)$$

2.4 GHG assessment

The calculated annual values E_{TES} of each simulated CSP plant are summed up to generate an annual total value $E_{TES,a}$ of all 48 CSP plants with molten salt storage. In addition, $E_{TES,t}$. represents the total electric energy generated by the storages during their operating period to date t_{op}:

$$\boldsymbol{E_{TES,a}} = \sum_{1}^{n} E_{TES} \quad (7)$$

$$\boldsymbol{E_{TES,t}} = \sum_{1}^{n} E_{TES} \cdot t_{op} \quad (8)$$

These calculated energies $E_{TES,a}$ (annual, operating period) are multiplied with the determined emission intensity factors c_{GHG} (carbon, natural gas, CSP) to calculate the quantity of equivalent GHG-emissions m_{GHG} (total, construction, power generation). This means, that a conventional or non-conventional power plant would emit a specific amount of GHG emissions, producing the same amount of electricity.

$$\boldsymbol{m_{GHG}} = c_{GHG} \cdot E_{TES\ a,t} \quad (9)$$

The assessment of total GHG emissions displaced by solar salts used in CSP plants as TES to conventional power plants requires only the consideration of net emissions. This means, that the GHG emissions from the CSP plant itself must be subtracted to report only the displaced GHG-emissions, as follows:

$$\boldsymbol{m_{GHG,SS}} = m_{GHG,conv.} - m_{GHG,CSP} \quad (10)$$

3. Results and Discussion

3.1 Simulations

Until August 2022, 115 CSP plants are operational worldwide with an installed capacity of 6 314 MW_e. Table 1 shows, that 48 of the 115 CSP plants are installed with a molten salt storage (41.7%). Regarding the installed capacity of these plants with 3 152 MW_e, molten salt storages account about the half of the total installed capacity (50.0%).

Table 1. *Installed capacity and quantity of total operational CSP plants worldwide and with molten salt storage (August 2022)*

Country	Total CSP plants MW_e (-)	CSP plants with molten salt storage MW_e (-)
Spain	2 310 (51)	1 021 (22)
USA	1 501 (10)	360 (2)
China	596 (14)	525 (11)
Morocco	533 (5)	510 (3)
South Africa	500 (6)	450 (5)
Rest of world	874 (29)	286 (5)
Total	**6 314 (115)**	**3 152 (48)**

The total expected annual generation of all 48 plants based on the technical database is 11.51 TWh_e, whereas simulation results show an annual generation of 12.15 TWh_e. This means a +5.6% higher energy production, which is mainly based on best-case plant operation. A summary for the three different types of operational CSP plants with molten salt storage are presented in Table 2 and are used for the discussion in this section.

Table 2. Summarized simulation results for operational CSP plants with molten salt TES.

Type	Quantity	$\mathbf{P_T}$ (GW_e)	$\mathbf{E_{grid,a}}$ (TWh_e)	$\mathbf{E_{grid,t}}$ (TWh_e)	$\mathbf{X_{TES}}$ (%)	$\mathbf{E_{TES,a}}$ (TWh_e)	$\mathbf{E_{TES,t}}$ (TWh_e)	$\mathbf{m_{SS}}$ (MMt)
PTC	34	2.39	8.55	64.41	29.0	2.48	19.26	1.20
ST	12	0.70	3.34	11.79	43.3	1.45	4.78	0.18
LF	2	0.06	0.26	0.86	47.3	0.12	0.44	0.02
Total	**48**	**3.15**	**12.15**	**77.06**	**-**	**4.05**	**24.48**	**1.40**

Table 2 provides the simulation results for the 48 currently operational CSP plants using molten salts as a TES system. It presents the type of technology simulated, with its installed capacity ($\mathbf{P_T}$), electric energy to the grid annually/totally ($\mathbf{E_{grid\ a,t}}$), thermal fraction of storage to power cycle ($\mathbf{X_{TES}}$), electric energy generated by the storage annually/totally ($\mathbf{E_{TES\ a,t}}$) and the molten salt quantity ($\mathbf{m_{SS}}$).

The emission intensity factors for the three power generation technologies are shown in Figure 1. The LCA considers a lifetime of 30 years, and its scope of inventory contemplates the construction and power generation phase.

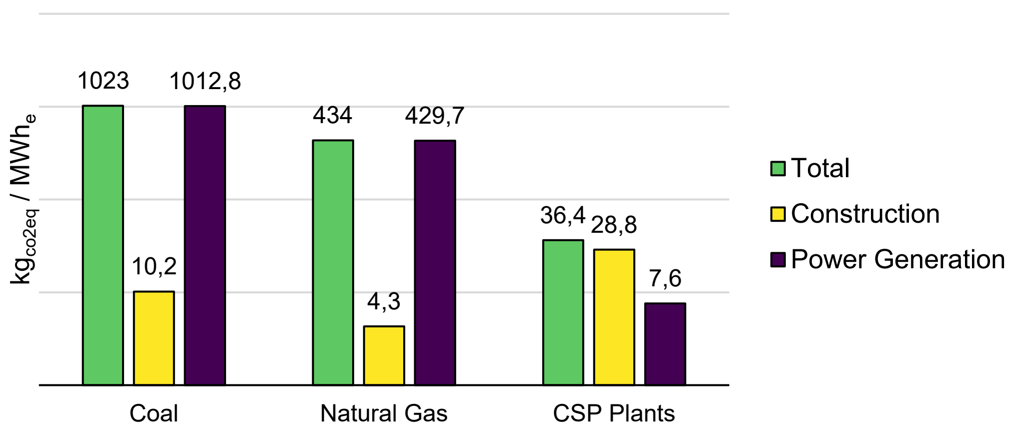

Figure 1. *Emission intensity factors for coal, natural gas power plants and CSP power plants divided into total, construction, and power generation phase [14].*

The assessment is mainly made using the emission intensity factors, as these represent the quantity of equivalent GHG-emissions in kg_{CO2eq} to generate 1 MWh_e of electricity. Figure 2 shows the absolute values of equivalent GHG-emissions that are released by conventional power plants and CSP plants, when generating the same electric energy (4.05 TWh_e annually and 24.48 TWh_e in total).

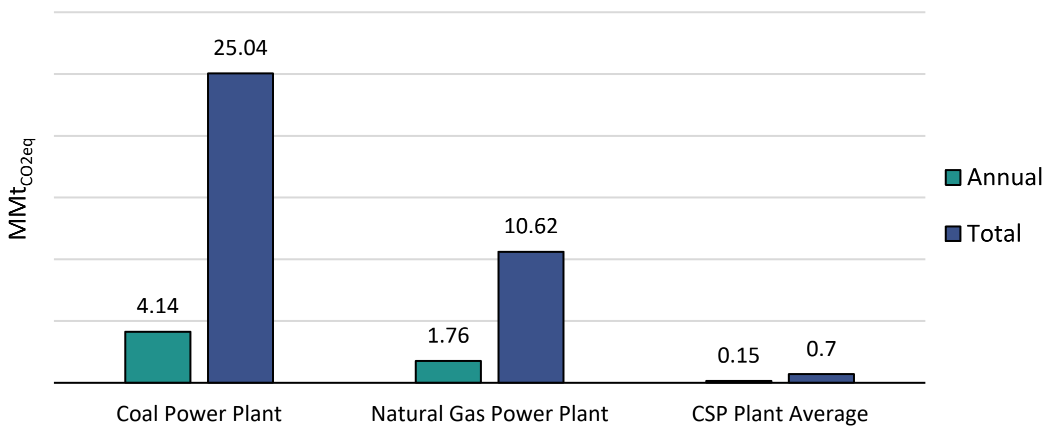

Figure 2. *Total CO_2 equivalent emissions for each technology in MMt (million metric tons).*

Figure 2 shows the total CO2eq emissions for each type of power plant every year (annual) and in its full operational period (total). Two life cycle phases dominate the environmental impact of conventional power plants of coal and natural gas. Firstly, the extraction of coal or natural gas production, which accounts about 15% of total GHG-emissions through lifetime. Both, coal and natural gas extraction from coal miners and gas fields are still using fossil fuels in their large machines and for their post processing plants. In addition, methane leakage is a key role for the extraction industry and especially for natural gas distribution. Secondly, and with a significantly higher impact, is the combustion of fossil fuels for electricity production in conventional power plants, which represents more than 80% of the total GHG-emissions.

CSP, as most renewable technologies, have embodied their GHG-emissions in the infrastructure of the plant. Comparing only the GHG-emissions from the power generation phase between CSP and the two conventional technologies, coal plants emit 137 times and natural gas 58 times more than CSP plants per year when generating the same amount of electricity. The construction and production of the CSP components itself account for 28.8 kg_{CO2eq}/MWh_e. At first glance, this seems to be considerably higher than the values from coal or natural gas but are still drastically small in relation to the total values of several hundreds or even thousand. Considering the total average emission intensity factor of 36.4 kg_{CO2eq}/MWh_e for all simulated CSP plants, equivalent GHG-emissions result in 0.15 MMt_{CO2eq} per year and 0.70 MMt_{CO2eq} in total.

3.2 Displaced GHG-emissions by molten salts

The displaced GHG-emissions of solar salts are shown in Table 3, comparing the emissions that conventional power plants would release by generating the same energy as from all molten salt storages. This would result in annual displaced GHG-emissions of 3.99 MMtCO2eq compared to a coal power plant and 1.61 MMtCO2eq to a natural gas power plant.

Table 3. *Displaced GHG-emissions of the energy generated (annually, in total) by the molten salt storages compared conventional power plants (carbon, natural gas)*

GHG-emissions $\mathbf{m}_{GHG}$ [MMtCO2eq]	Coal power plant		Natural gas power plant	
	Annual	Total	Annual	Total
Total	3.99	24.34	1.61	9.92

3.3 Emissions produced per kWh_e

Lastly, Table 4 shows the quantity of CO_{2eq} emissions produced by the molten salt storage relative to the kWh_e energy dispatched to the grid for each CSP configuration.

Table 4. *GHG-emissions of the energy generated annually to the grid by each CSP technology with molten salts.*

Type	kgCO2eq / kWhe (Annually)
PTC	0.012
ST	0.009
LF	0.020
Total	**0.012**

4. Conclusion

This work has found that CSP plants produce most of their GHG-emissions during the construction phase, unlike conventional power plants which do during the power generation phase. Most notably, the study has shown that CSP plants with molten salt storage displaced 3.99 MMt_{CO2eq} emissions when compared to conventional coal power plant and 1.61 MMt_{CO2eq} emissions when compared to a natural gas plant.

The previously presented methodology can be extended and adapted for the obtention of the displaced CO_{2eq} emissions of other relevant technologies, such as wind or PV.

Data availability statement

All data used in the study is publicly available and has been appropriately referenced in the article, following all recommended best practices.

Author contributions

Conceptualization, F.D., M.C., A.S., V.T., Investigation, A.S., V.T., Methodology A.S., V.T., I.M., Programming A.S., V.T., Writing - original draft A.S., V.T., Writing - review & editing, V.T., I.M., C.F., C.H., M.C., Supervision, M.C., I.M. and F.D.

Competing interests

The authors declare no competing interests.

Funding

Authors acknowledge the generous financial support provided by CORFO under project 13CEI2-21803.

Acknowledgement

We are grateful for the support and contribution of ANID and CORFO.

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