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CSP+MED Plant Coupled to a Seawater Pipeline from the Mining Industry in Northern Chile: A Case Study

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Abstract. The study evaluated the use of mining seawater pipelines in a CSP+MED plant at commercial scale based on solar tower molten salts technology, with 111.2 MWe and 13 hours of thermal energy storage in northern Chile. The plant is coupled to the biggest seawater pipeline in the country, from Centinela mining facility. Results shown that the CSP+MED plant required all the seawater pumping capacity of the pipeline in order to cool the thermal cycle of the CSP plant using the MED plant. In terms of electricity production, the MED plant integration affects significantly the annual electricity production of the plant, when compared with an optimized CSP plant and to a CSP plant with the same design but without the MED plant and considering a once through cooling system, lowering the electricity production an 46.05% and 25.82% respectively. On the other hand, the CSP+MED plant integration produces 14.06 hm^3 of freshwater annually, which translated in an additional income equivalent to 28.14 MM USD each year, which is substracted from the OPEX costs of the plant for the LCoE calculations. For this reason, the results showed that the lowest LCoE is reached by the CSP+MED plant configuration, but is highlighted that the economic analysis assumed an ideal situation, and further business models must be studied in order to share the benefits of the seawater pipeline integration between the CSP+MED plant owner and the mining facility that owns the seawater pipeline.

Keywords: Concentrated Solar Power (CSP), Multi-Effect Desalination (MED), System Advisor Model (SAM), Solar Thermal Desalination

Introduction

Northern Chile presents the highest levels of Direct Normal Irradiance (DNI) in the world, but at the same time has several water scarcity problems [1], being the Atacama Desert the driest desert on earth. The first concentrating solar power (CSP) plant in Chile, Cerro Dominador, is situated in the Antofagasta Region, a location with high energy demand and seawater pipelines, which primarily serve the mining industry [2].

The potential of thermal desalination based on multi-effect distillation (MED) coupled with CSP plants has been recognized by several authors [1] [3] [4], but the study presented by C. Mata et al. [5] showed the high cost associated with seawater transportation to the location of the CSP plant, compromising the economic feasibility of the integration. J. Gacitúa et al. [6] proposed the use of seawater pipelines, already installed in the Antofagasta Region by the mining industry, investigating its potential as a solution to improve the performance of the CSP plants using wet cooling systems, and evaluated a small-scale integration of a MED-CSP plant with this methodology, assuming a minimal impact on the seawater pipeline.

This study aims to evaluate the use of mining seawater pipelines in a CSP+MED plant at commercial scale, considering the freshwater production and the handling of the brine produced by the desalination process.

Methodology

A hybrid CSP+MED plant, based on a 111.2 MWe Solar Tower plant, was simulated using System Advisor Model (SAM) software from NREL, considering a 13h of thermal energy storage (TES) and a solar multiple (SM) of 2.5, a configuration proposed in the long-term energy planning from the Chilean government [7]. The plant is located in Maria Elena (Lat 22.9 °S, Lon 69.3 °W), Antofagasta Region in Chile, in the same location evaluated in the study of J. Gacitúa et al. [6]. The MED plant is based on the model presented in the study of C. Mata et al. [8], considering a forward-feed configuration of 14 effects and 13 pre-heaters. The MED plant has 6 units of 10 000 m^3/day of freshwater production at nominal capacity, and each unit requires steam at 70 °C at the first effect. The seawater temperature is assumed to be 20 °C fixed, with a salinity of 35 g_{salt}/kg_{water}, producing freshwater and brine with a salinity of 63 g_{salt}/kg_{water}. The gain output ratio (GOR) of the plant is 10.4 at nominal conditions, calculated with the following equation [4], where D_t corresponds to the freshwater production in m^3/h, Q_{MED} is heat transferred in the first effect in kJ/h, λ_s is the latent heat at saturation temperature of 70 °C (2 333 kJ/kg) and ρ is the water density (1 000 kg/m^3).

$$D_t = \frac{Q_{MED} \cdot GOR}{\lambda_s \cdot \rho} \tag{1}$$

The plant configuration proposed considers the possibility to connect the MED plant in parallel with an once through cooling system, to allow different seawater consumptions from the plant, as shown in Figure 1.

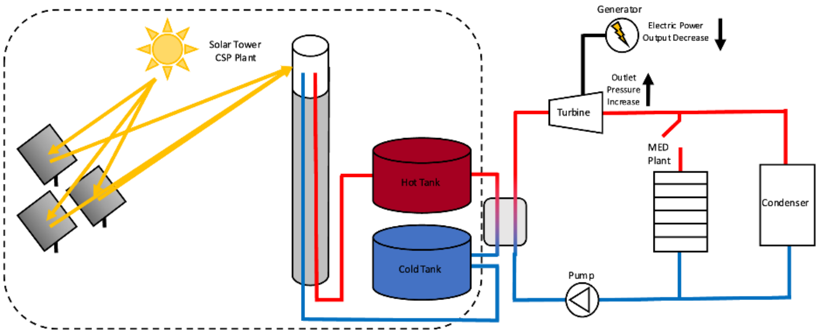

Figure 1*. Integration scheme for CSP+MED plant with once trough cooling system in parallel.*

The study also considered the economic assessment of the plant in terms of the Levelized Cost of Energy (LCoE) from the CSP plant, considering the impact of the water production from the integration of the power block with the MED plant. The impact of the integration with the MED plant mainly affects two aspects related with the LCoE, first the annual electricity production from the plant decreases due to the modifications applied to the power cycle, raising the operational conditions of the low-pressure turbine. On the other hand, there is a positive impact with the water production, which could be considered as a reduction in the annual operation and maintenance costs of the plant in case of selling the water produced. The following equation presents the LCoE.

$$LCoE = \frac{\sum_{t=0}^{N} \frac{I_t}{(1+r)^t} + \sum_{t=0}^{N} \frac{OM_t - P_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}} \quad (2)$$

Where r corresponds to the discount rate (7%), N the evaluation period of 30 years [9], E_t the annual electricity generation, I_t the CAPEX, OM_t the OPEX and P_t the income from the freshwater produced, which is sold at 2 USD/m^3 [6]. This analysis also considers a degradation rate of 0.5% annual for the electricity generation.

Results and Discussion

The analysis considered a full capacity MED plant to be integrated with the 111.2 MWe CSP plant, operating at maximum capacity. The CSP+MED plant is strategically located near to the seawater pipeline of Centinela mining operation, the biggest seawater pipeline in the country, with a nominal capacity of 1.5 m^3/s. Centinela is currently building an additional seawater pipeline, which will be operative in 2025, with a nominal capacity of 1.15 m^3/s, according to COCHILCO [10]. Considering these values, the maximum seawater pumping capacity of Centinela will correspond to 2.65 m^3/s in 2025. The seawater is used directly in the mining process since its use with different salinities has been proven in the copper mining industry [11] [12].

The CSP+MED plant simulations were performed in SAM. In order to integrate the MED plant to the CSP scheme, the operating pressure of the condenser from the power block was increased, corresponding to the thermodynamic properties of a condensing temperature of 70 °C and 31.18 kPa of pressure. Considering these operation parameters, the results of the SAM simulations for the CSP+MED plant reveal an annual gross electricity generation of 406.59 GWh, in comparison with 547.33 GWh for a CSP plant without the MED integration. The MED plant has a freshwater production of 14.07 hm^3, with a plant efficiency of 44.4% assuming full desalination of freshwater.

To operate at maximum capacity, the plant requires 31.66 hm^3 of seawater annually, producing 17.59 hm^3 of brine annually. The maximum seawater flowrate required for the CSP+MED, plant equivalent to a maximum seawater pumping capacity of 2.69 m^3/s. These results implied that the CSP+MED plant required all the seawater pumping capacity of the pipeline, considering the additional capacity that will be available in 2025. Then, 44.4% of the seawater is desalinated, and the remaining brine, which reached a salinity level of 63 g_{salt}/kg_{water} is returned to the pipeline for its use at the mining facility.

The feasibility of the solution evaluated in this integration, considering the MED plant operation at full capacity is compromised by the level of usage of the seawater pipeline, since it is required all the seawater pumped in the process when the CSP plant is operating at nominal capacity, returning approximately a brine flow of 1.49 m^3/s to the seawater pipeline which could be used at the mining process.

A relevant aspect for the plant operation corresponds to the fact that the CSP plant does not operate in a 24/7 regime, for this reason there are certain periods of time each day in which the CSP plant, and therefore the MED plant were not operative. Considering this fact, the total seawater pumped to operate the MED plant for 1 year, obtained as a result in the analysis, corresponds to 31.66 hm^3. On the other hand, the maximum seawater pumped during 1 year of operation was calculated to carry out a comparison. This value was calculated based on the assumption that the seawater pumping system works at full capacity in a regime 24 hours per 7 days a week, obtaining a total of 84.83 hm^3 annual seawater pumped as maximum value.

Based on these results, the percentage of the maximum total annual seawater pumped corresponds to 37.32%. The comparison between the total annual desalinated water against the maximum annual seawater pumped showed that the annual desalinated water represents

16.59% of the maximum annual seawater pumped. This value is relevant because it represents the water that cannot return to the seawater pipeline to be used in the mining process, considering that the brine resulting in the desalination process can return to the seawater pipeline to be used in the mining process.

In order to study the level of usage of the current seawater pumping capacity in the Centinela mining facility, corresponding to 1.5 m^3/s, the maximum annual seawater pumped based on this capacity was compared to the real annual seawater pumped reported by Antofagasta Minerals in 2022. The results, show that the current maximum annual seawater pumped in Centinela corresponds to 47.30 hm^3, and the seawater pumped by Centinela in 2022, reported in the Sustainability Report for 2022 [13], corresponds to 26.76 hm^3. Based on this values, the seawater usage corresponds to 56.57% of the maximum pumping seawater capacity, which opens the door to consider the use of seawater storage systems in order to integrate the MED plant to the CSP.

Table 1 summarizes the results presented in this section, considering the analysis of the level of usage of the seawater pumped to the Centinela mining facility, regarding the freshwater production in the MED plant, which corresponds to water that cannot return to the seawater pipeline to be used in the mining process.

Tab. 1. *Technical results from the SAM simulations for the CSP+MED plant integration*

Parameter Name	Units	Value
Maximum seawater pumping capacity	m^3/s	2.65
Required seawater pumping capacity	m^3/s	2.69
Annual freshwater production	hm^3	14.07
MED plant efficiency	%	44.4
Annual seawater requirement	hm^3	31.66
Annual brine production	hm^3	17.59
Brine flowrate returning to the pipeline	m^3/s	1.49
Percentage of the maximum seawater pumping capacity used by Centinela in 2022	%	56.57
Maximum annual seawater pumped	hm^3	84.83
Total annual desalinated water compared with maximum annual seawater pumped	%	16.59

The results presented in the Table 1, show that there is a noticeable difference between the seawater used by the MED plant in terms of the instantaneous seawater pumping capacity and the total annual seawater pumped to the mining facility.

Finally, an economic analysis was conducted in order to determine the LCoE for the CSP plant considering the MED integration, and the economic value of the desalinated water. The analysis considers the impact of freshwater production for the CSP+MED plant, with a market value of 2 USD/m^3 for the freshwater, which is considered as an additional income which is subtracted from the operational costs of the CSP plant in the LCoE analysis. On the other hand, to compare the LCoE of the CSP plant considering the MED integration, the same plant was simulated based on the same design optimized for the MED plant integration but considering a higher efficiency for the cycle power and a lower condensing temperature at the end of the low-pressure turbine to 6.77 kPa, this implies that the CSP plant design is limited to the thermal capacity due to the seawater pipeline usage to evacuate the heat at the condenser. An additional simulation considering the CSP plant design optimized for electricity generation on site without restrictions was carried out, with an annual electricity generation of 752.56 GWh.

Tab. 2. *Economic results of the plant*

Parameter Name	Units	Value
Economic value of the annual desalinated water	MM USD	28.14
LCoE of the CSP plant with the MED integration, considering the income of the freshwater price	USD/MWh	44.30
LCoE of the CSP plant without MED integration, considering the same design	USD/MWh	86.76
LCoE of the CSP plant without MED integration, considering an optimized design for electricity generation	USD/MWh	63.10

Based on the electricity generation of each plant configuration, it is noticeable that the seawater pipeline integration for freshwater production with a MED plant limits the electricity generation of an ideal CSP plant optimized for the electricity generation in the location, lowering the annual electricity generation approximately 46.05%, and if we considered the comparison between the CSP plant with the same design but with and without MED integration the annual electricity generation decrease is 25.82%.

Conclusion

The results from the analysis developed in this study show the impact on the electricity generation when a MED plant is integrated to a CSP plant at commercial scale, considering a CSP plant of 111.2 Mwe with a solar multiple of 2.5 and 13 hours of TES. The results show that impact on the plant design significantly affects the electricity generation, lowering the annual electricity production a 46.05% when compared with an ideal CSP plant with wet cooling and no restrictions on its design. On the other hand, when compared with a CSP plant which considers the same design of the one with the MED integration, but without the thermal efficiency limitations in the thermal cycle and with a lower condensing pressure at the end of the low-pressure turbine, the CSP+MED plant generates 25.82% less annual electricity.

The results of the economic analysis showed that there is an additional income due to the freshwater production, and due to the connection with the seawater pipeline the transport cost of the seawater to the CSP plant site is avoided. In this case the annual income is considerable, corresponding to 28.14 MM USD, which is subtracted from the OPEX costs of the plant, this affects considerably the levelized cost of energy calculation. The results show that under these considerations, the CSP+MED plant presented a lower LCoE when compared to CSP plants analysed, even considering the fact that there is a significant decrease in the electricity production, reaching a LCoE value of 44.30 USD/MWh.

It is important to clarify that the economic results are evaluated under an ideal scenario, because under a real scenario should be considered a business model that allows the seawater usage from the mining pipeline, that benefits not only the CSP plant but also the mining facility that owns the seawater pipeline. This is very important, because the CSP+MED plant integration implies several modifications on the seawater flowrate directed to the mining facility, changing not only the flowrate but also the salinity, and opening the door to new investments that are required for the CSP+MED plant operation, such as a seawater storage system.

Data availability statement

There is no relevant additional data to this article beyond the presented content.

Author contributions

Conceptualization, C.F. and F.G., investigation, C.F., methodology C.F., writing – original draft C.F. and F.G., writing – review & editing, C.H., Supervision F.D and C.H.

Competing interests

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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