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# Techno-Economic Performance Analysis of a CSP-Driven CCGT With Stratified TES at Various DNI Levels and Demand Conditions Based on Transient Simulation

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**Abstract.** In this work, an innovative CSP plant concept comprising a combined Brayton and Organic Rankine Cycle (ORC) and a stratified Thermal Energy Storage (TES) is investigated. A dynamic model of the plant is developed and used to perform annual simulations to investigate the plant at different locations under a variety of DNI levels and demand conditions. The focus of the study is on the dynamic behavior, in terms of response time to the demand profile and changing the operation mode, for example, from charging to discharging (dispatchability). Annual yield and LCOE calculations are performed for every scenario. Results show two optimization opportunities, in the first one, by means of a sensitivity analysis the design is adjusted and it is possible to increase 10% of the electricity production. A second analysis shows the possibility of including an operational mode that maximizes the use of TES and increases electricity production by 11%. The application of both strategies results in a 21% increase in electricity.

## INTRODUCTION

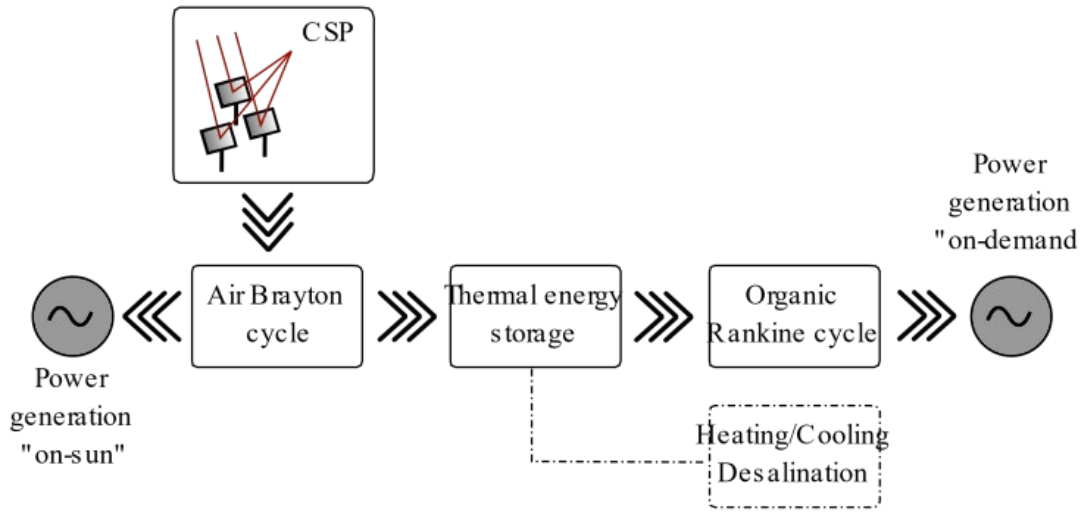
The POLYPHEM project design is taken as a case study. This plant combines an open Brayton cycle with an Organic Rankine Cycle. The bottom cycle uses air as the working fluid and is composed of a micro gas turbine, a solar receiver and a heat exchanger that recovers the heat at the turbine outlet and transfers it to the lower cycle. The lower cycle uses oil as the working fluid and the heat is transported to a single tank stratified thermal energy storage and the ORC unit. Three standard operating modes describe the loading of the storage and the operation of the ORC using heat directly from the heat exchanger or consuming the stored energy.

This design represents several advantages for the flexibility of small-scale tower CSP plants that can be used as decentralized systems. The main design challenge is to achieve an optimal configuration of the components to minimize the LCOE. This paper presents the OPTIPHEM tool developed by Fraunhofer ISE for the design, modeling, simulation and optimization of CSP Plants. The selection of the main parameters for the simulations and optimization is also presented, and an analysis of an additional operation mode to increase the electricity production is performed. As an optimization constraint, the target LCOE proposed by the POLYPHEM project is considered [1]. Finally, the results are compared between the proposed scenarios showing the opportunities for the use of this design.

## METHODOLOGY

Fig. 1 represents the plant concept studied in this work [2]. The modelling of such a plant faces challenges such as the reduced efficiency of its components due to part-load operation (e.g. operating the gas turbine outside its nominal shaft speed) resulting from the fluctuating demand and meteorological conditions. Additionally, during transient operation - when accelerating the gas turbine to a higher shaft speed - certain operating parameters deviate significantly

from the values related to the initial and the stabilized steady states. The modelling of the dynamic behavior during these transient periods is also a challenge that is addressed in this study.

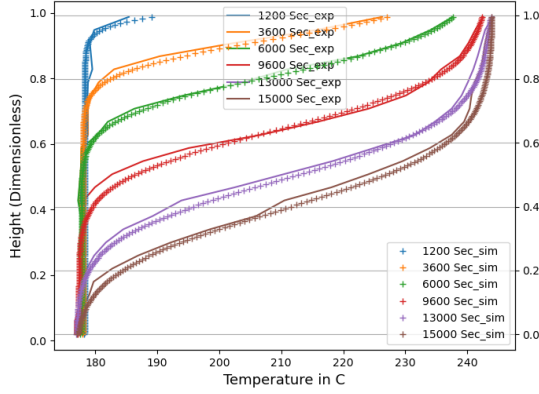


**FIGURE 1.** Schematic flow diagram of the prototype plant.

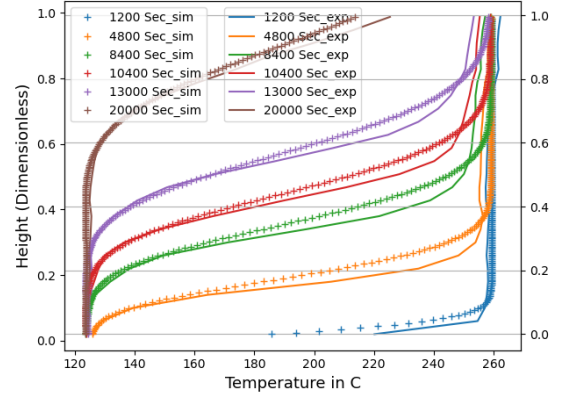
Flexible and scalable models for the simulation of the components of the plant have been created in the Fraunhofer in-house simulation tool ColSim CSP [2,3]. The in-house design tool devISE CSP [4] is also further developed to create an initial design and provide the main parameters for the simulation and optimization [5].

The plant model contains a micro gas turbine and compressor using characteristic curves for variable shaft speeds [3]. The model calculates the operational line that describes the acceleration and deceleration assuming the maximum efficiency in every shaft speed. According to the thermal input, the parameters pressure ratio, mass flow rate and efficiency of the compressor are found in every time step. The receiver is modeled with a discretized approach covering all relevant heat loss mechanisms and incorporating absorbed solar radiation as input from ray tracing simulations [4]. A validated model for the air-cooled ORC unit based on empirical equations was developed too. The detailed explanation, key-assumptions and performance curves of these component models can be found in [6].

Additionally, a validated model for the stratified dual media TES based on CFD approach and correlations was implemented. The stratified energy storage uses concrete as filler material and Jarytherm® [7] thermal oil as HTF. The implemented model, in general, is based on a finite volume approach [8] with some assumptions to simplify the solution: one-dimensional discretization of the domain was performed and only a detailed solution of the energy equation was calculated. The model incorporates heat exchange between the working fluid, the filler material and the tank wall, including transient convection in the tank fluid, transient axial conduction in the tank wall and heat loss to the surroundings [9]. In Fig. 2 and 3, temperature profiles obtained from numerical simulations are plotted together with the experimental data of POLYPHEM prototype storage. The controller is able to operate the plant under two different operating strategies [6] that aim to reveal the performance penalty due to following various type of load profile. To perform the annual simulations, typical meteorological year data is used (Data source Meteonorm). For one of the locations, a scaling method was used to bring the profile provided by Meteonorm closer to the real behavior [10].



**FIGURE 2.** Comparison of experimental data and TES model simulations for a charge process from 180 °C to 250 °C with mass flow of 0.2 kg/s.



**FIGURE 3.** Comparison of experimental data and TES model simulations for a discharge process from 250 °C to 130 °C with mass flow of 0.2 kg/s.

### Main Parameters for the Simulations and Optimization

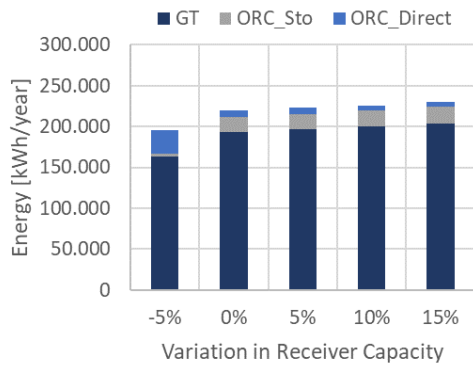
Two locations with DNI over 2900 kWh/m<sup>2</sup> per year are selected, Keetmanshoop in Namibia and Antofagasta in Chile. A variable demand profile is selected for the first location, resembling a residential profile, considering that access to electricity [6] in this country is less than 60% of the population [11]. For Antofagasta a constant demand is assumed resembling an industrial profile considering the mining activity in the region. The components capacities of the preliminary design calculated by OPTIPHEM tool chain and its target cost are listed in Table 1.

**TABLE 1.** Preliminary design components capacities and target cost.

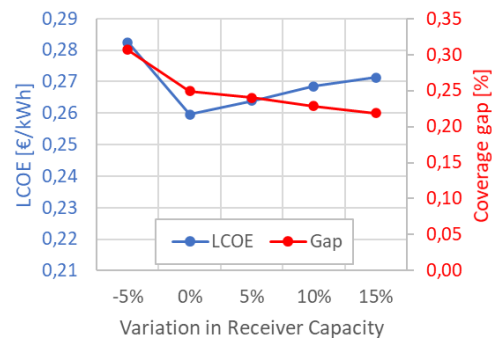
Component	Capacity / Size	Cost target
Solar field	2060 m <sup>2</sup>	100 €/m <sup>2</sup>
Solar receiver	534 kW <sub>th</sub>	400 €/kW <sub>th</sub>
Solarized micro gas-turbine	76.5 kW <sub>el</sub>	1500 €/kW <sub>el</sub>
Organic Rankine Cycle	22 kW <sub>el</sub>	2500 €/kW <sub>el</sub>
Thermal energy storage	2000 kWh	28 €/kWh
Recovery heat exchanger	125 m <sup>2</sup>	120 €/m <sup>2</sup>

## RESULTS

Annual simulations are performed for the two selected locations considering the preliminary design obtained in OPTIPHEM. Additionally, various sensitivity analyses were performed by varying the capacities of the solar receiver and the TES in an attempt to find the best configuration for each condition followed by discussing the differences and potential for technology improvement. The results of the simulations at Keetmanshoop, Namibia show that the preliminary design of the solar receiver by OPTIPHEM turns out to be economically optimal. The increase in the size of the solar field and the capacity of the solar receiver result in an increase in electricity production and a reduction in the gap between demand and supply (see Fig. 4 and 5).

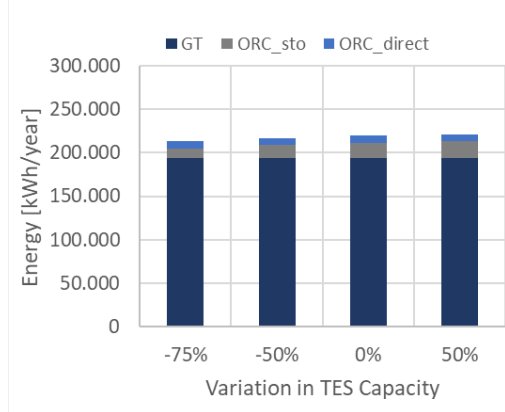


**FIGURE 4.** Electricity production for different receiver capacities in Keetmanshoop, Namibia.

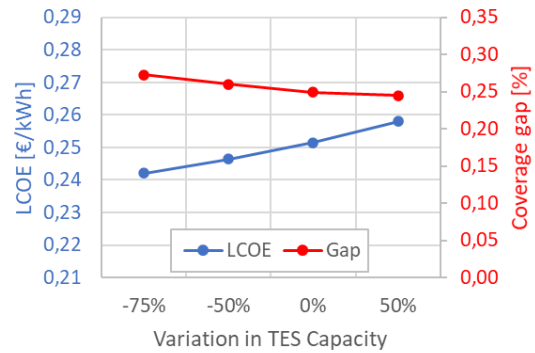


**FIGURE 5.** LCOE and Gap in the coverage for the variation of capacity of the receiver in Keetmanshoop, Namibia.

The sensitivity analysis on TES capacity shows that the increase in the size of the TES implies a decrease in the coverage gap but also reflects an increase in the LCOE (see Fig. 6 and 7).

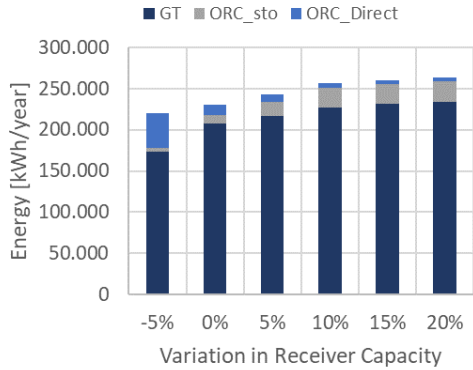


**FIGURE 6.** Electricity production for different TES capacities in Keetmanshoop, Namibia.

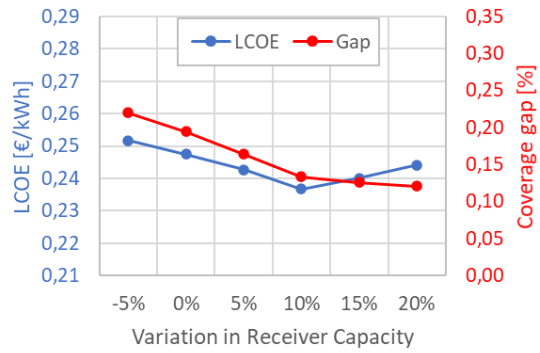


**FIGURE 7.** LCOE and Gap in the coverage for the variation of capacity of the TES in Keetmanshoop, Namibia.

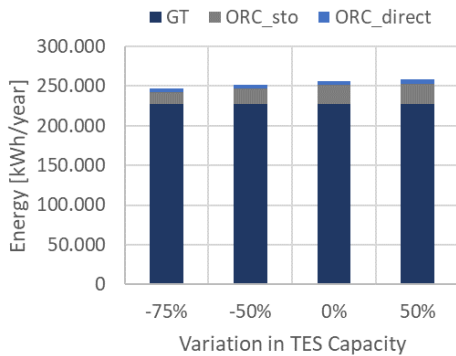
Unlike the Keetmanshoop results, the results for Antofagasta show that a 10% increase in the capacity of the solar receiver (and the heliostat field) reaches the economic optimum (see Fig. 8 and 9). The behavior of the LCOE versus the change in TES capacity maintains the same trend as the Keetmanshoop results despite simulating different operating strategies Fig 10 and 11.



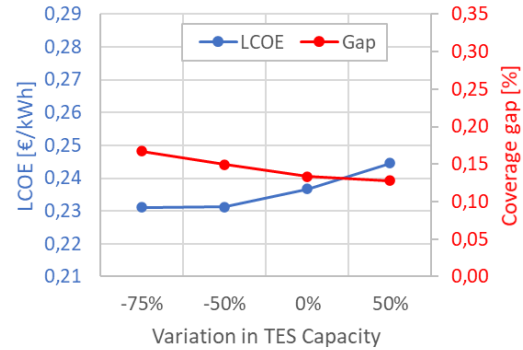
**FIGURE 8.** Electricity production for different receiver capacities in Antofagasta, Chile.



**FIGURE 9.** LCOE and Gap in the coverage for the variation of capacity of the receiver in Antofagasta, Chile.

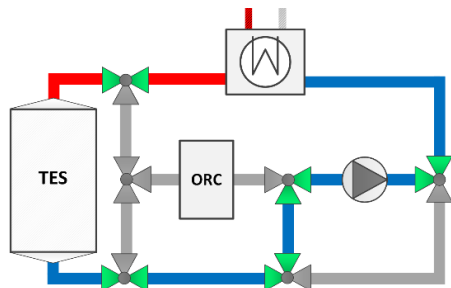


**FIGURE 10.** Electricity production for different TES capacities in Antofagasta, Chile.

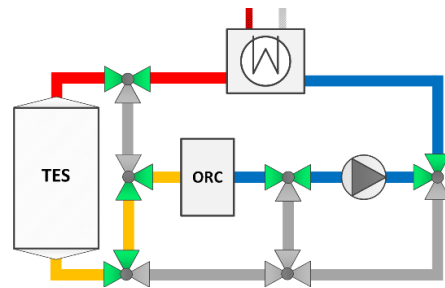


**FIGURE 11.** LCOE and Gap in the coverage for the variation of capacity of the TES in Antofagasta, Chile

On the other hand, the results showed a limitation in the utilization of recovered heat. The variation in the size of the TES highlights that the thermocline reaches the lower level of the tank during the loading process. This implies that the outlet temperature rises enough to activate the ORC unit. This function is possible without altering the original POLYPHEM design and can be easily implemented in the operation (see Fig. 12 and 13). For testing this, an additional operation mode called "Thermocline management" was implemented. In this mode, when the thermocline layer reaches the outlet of the TES in the charging process, the oil is redirected to the ORC to utilize the thermal energy stored in the thermocline. Additionally, this mode also prevents the oil from entering the heat exchanger with a mass flow rate above the pump operating capacity. Redirecting the oil that starts to become hotter through the ORC ensures a temperature decrease that keeps the mass flow within the pump operating capacity limits.

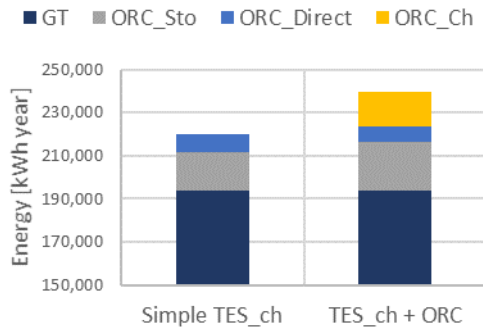


**FIGURE 12.** Simple charge of the TES process.

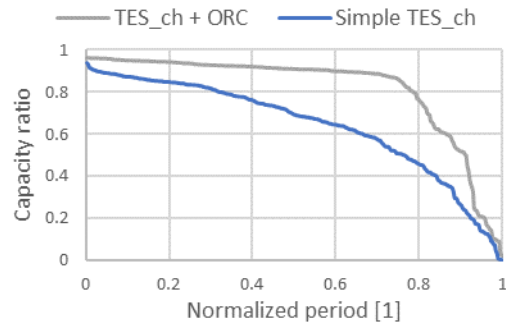


**FIGURE 13.** Charge of the TES and simultaneous operation of the ORC.

The results show that this new strategy increases the electricity production by 11% and improves the utilization of the TES by increasing the maximum daily load level as shown in Fig. 14 and 15.

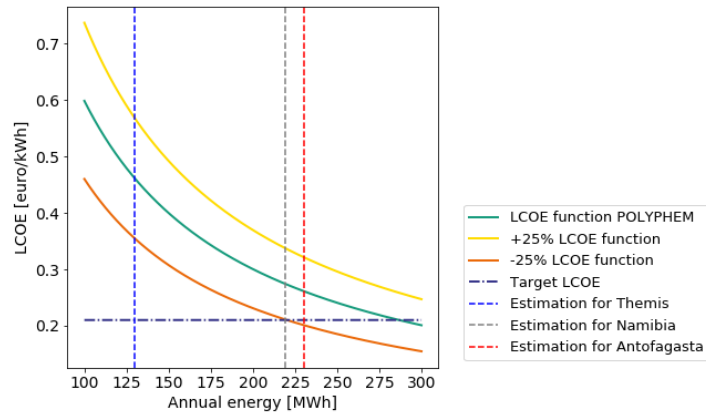


**FIGURE 14.** Electricity production for different Operation Strategies in Antofagasta, Chile.

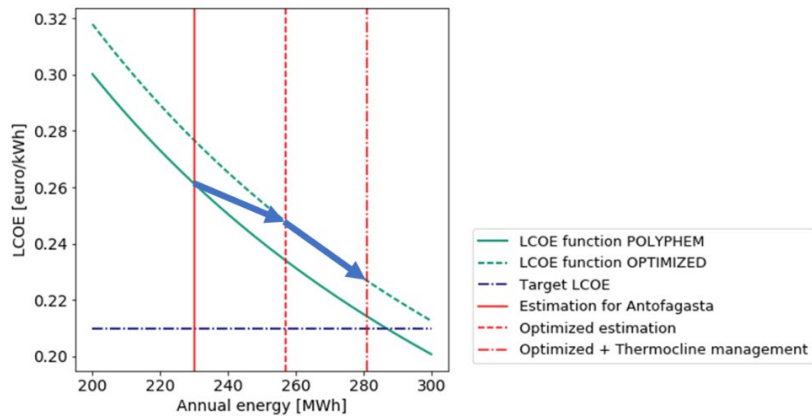


**FIGURE 15.** Utilization of the TES for different Operation Strategies in Antofagasta, Chile.

Fig. 16 shows the estimated LCOE for the studied locations and the comparison with the results for Themis plant in Odeillo, France, place where the POLYPHEM demonstration plant will be tested. Three scenarios for the initial investment cost are considered (original target +25% and -25%). Fig. 17 shows the estimated LCOE for the simulations of Antofagasta, Chile. The results before and after the optimization and the results with the Thermocline Management strategy are compared.



**FIGURE 16.** LCOE comparison for studied locations.



**FIGURE 17.** Variation in the LCOE for Antofagasta, Chile, after optimization in the design and operation strategy.

## CONCLUSION

The OPTIPHEM tool presents representative advantages for the design, simulation, and optimization of CSP plants. The variability of parameters for the execution of transient simulations allows finding operation strategies that optimize production.

The target LCOE established in the POLYPHEM Project can be achieved in locations with a DNI greater than 2900 kWh/m<sup>2</sup> per year if component costs are reduced by 25%.

The advantages of using this storage are the possibility of producing electricity when there is no solar radiation, increasing the coverage of the demand. Operational strategies such as thermocline management allow greater usability of the TES. For the case of Antofagasta, this strategy increases around 11% the electricity production. If this strategy is combined with the CSP Plant design optimization, the annual yield increases around 21%.

## ACKNOWLEDGEMENTS

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