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Analysis and Simulation of CSP and Hybridized Systems

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Hybrid CSP-PV System for Sustainable Energy in a Chilean Mine: A Case Analysis

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Abstract. Chile, a global leader in copper production, faces increasing energy demands in its mining sector, particularly in the northern regions, where the country's major mining operations are located alongside its vast solar potential. Reliable and continuous power supply is critical for these operations. In alignment with the country's ambitious target to decarbonize its energy sector by 2050, innovative renewable energy solutions are required. This study examines the design and feasibility of a hybrid Concentrated Solar Power (CSP) and photovoltaic (PV) system, intended to deliver 150 MW of base-load electricity to a mining operation near La Serena, Chile. The proposed system integrates a parabolic trough CSP plant with molten salt thermal storage and a bifacial PV array equipped with 1-axis tracking. A custom simulation model based on PySAM is used to assess the technical and economic performance of the hybrid system, focusing on the use of HELISOL XLP® as the heat transfer fluid in the CSP component. The results demonstrate that the hybrid system achieves a 70% capacity factor and a levelized cost of energy (LCOE) of 84.39 USD/MWh, outperforming standalone CSP plants. Furthermore, the hybrid configuration enhances energy dispatch efficiency and reduces the overall LCOE, positioning it as a competitive solution for meeting industrial energy demands in Chile. The findings underscore the potential of hybrid CSP-PV systems to significantly lower energy costs while ensuring a stable power supply. This study contributes to Chile's renewable energy transition and provides valuable insights into the role of hybrid systems in supporting the decarbonization of energy-intensive industries, offering a scalable model for global applications and for further optimization and cost reduction of this kind of energy supply.

Keywords: CSP, PV, Hybrid, Parabolic Trough, HELISOL, Mining, PySAM

1. Introduction

Chile, known as a leading global producer of copper, plays a pivotal role in the mining sector, which is the substantial consumer of energy. The country's mining operations, particularly in the north, are crucial for the global copper supply and are energy-intensive, necessitating reliable and continuous energy sources to maintain productivity. This need for constant power is challenging to meet with variable renewable resources like solar photovoltaic (PV) systems, which cannot consistently provide power around the clock. Therefore, the development of sustainable and reliable energy solutions is critical for the continuity and expansion of mining activities, which are essential to both the national economy and global markets. Chilean mining industry needs to be decarbonized finally by 2050 and most of the mines are working on this subject already.

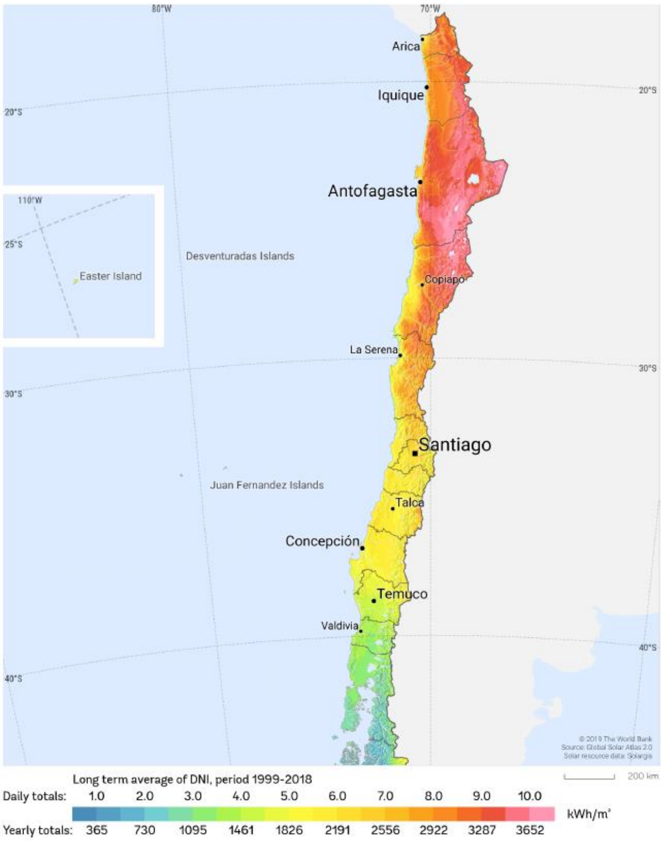

Figure 1. *Direct normal irradiation resource in Chile [1].*

Given Chile's advantageous geographic and climatic conditions, particularly its high Direct Normal Irradiation (DNI) which exceeds any location in Europe, it emerges as an ideal setting for Concentrated Solar Power (CSP) technologies. The analysis of Starke et al. [2] highlights that hybridizing a CSP plant with a PV system in northern Chile can increase the overall plant capacity factor and help achieving a fully dispatchable solar electricity production system. Santiago, for instance, relies on a DNI of 2200 kWh/m² per annum, while regions north of the capital experience even higher levels, exceeding 3300 kWh/m² per annum, as shown in *Fig. 1*. These conditions are predestinated for decarbonization of Chile's energy sector, motivating industrial clients, including those in the mining industry, to reduce their CO_2 emissions through the adoption of renewable energies for both electricity and heat production.

This study investigates a hybrid solar power system that integrates a parabolic trough CSP plant with a PV plant, producing 150 MW base load electricity to meet the 24/7 electricity demand of the mining company. The hybrid plant uses CSP for continuous power generation and PV during peak sunlight hours, thereby illustrating a scalable model for sustainable industrial energy solutions in Chile.

Similar studies of hybrid CSP-PV systems for constant power have performed by Pan & Dinter [3], directly utilizing SAM for the CSP simulations by setting the Dispatch Control schedule matrix for a typical day of each month, to obtain a CSP dispatch profile as complementary as possible to the PV production. It was proven that a hybrid CSP-PV plant can reach lower LCOEs and use smaller solar fields, in contrast with a standalone CSP plant with a constant dispatch scheme. Another is the case of Moraga et al. [4], who proposed a hybrid CSP-PV plant for green H_2 production, such that the electrolyzers can achieve higher capacity factors, therefore decreasing the $LCOH_2$. In this case, the Dispatch Control schedule matrix feature in PySAM was exploited by running a simulation representative of each day of the year according to an individual dispatch profile. While its computational cost of this scheme increases substantially, it provides a more accurate annual simulation for the hybrid system. Both studies considered a Solar Tower plant or Central Receiver System (CRS) as the CSP subsystem. Hybrid CSP-PV systems with linear concentration technologies have not been studied as much.

2. Methodology

The methodology of this study involves the development and simulation of a hybrid solar power system designed to meet the 150 MW base load demand of a mining operation located in North of La Serena, Chile. The system integrates a parabolic trough CSP plant with molten salt storage and a 150 MW_n PV plant with bifacial modules and a 1-axis tracking system, using an in-house developed computational model. The model is initially based on the PySAM framework developed by the National Renewable Energy Laboratory (NREL), specifically the *Physical Trough* and *PVWatts* models, which are adapted for the specific energy production and meteorological conditions of the site, characterized by a DNI of approximately 2900 kWh/m² per annum.

The customized modelling approach includes significant modifications to the dispatch logic of the CSP plant to optimize both the cost and stability of the power supply. This involves an intricate simulation of energy output and storage efficiency to ensure the CSP and PV integration can reliably support continuous mining operations. Additionally, the economic feasibility of the proposed system will be evaluated by comparing the calculated costs against the marginal costs recorded in the spot market of the National Electric System. This comparative analysis aims to underscore the cost-effectiveness and market competitiveness of a hybrid solar system.

Lastly, this study also aims to evaluate the use of a novel silicon oil as heat transfer fluid (HELISOL XLP® from Wacker Chemie AG) [5], in comparison with benchmark DPO/BP heat transfer oils (e.g., Therminol VP-1). The former's stable thermal performance up to 430°C allows for a smaller solar field and storage system sizes for the same thermal output, as well as a slightly higher power-block conversion efficiency [6].

2.1. System modelling

As a first step, the PV subsystem was programmed as a function of the PV-to-CSP design capacity ratio PV_{ratio}, a measure of its relative sizing. The rest of the PV subsystem parameters (see *Table 1*) were taken from a previous detailed evaluation of a pure PV system performance on site. The PV generation is clipped at 150 MW by the inverter, as it is being assumed that additional power generation has zero value.

Table 1. *PV model inputs.*

Model parameter	Value
Module type	Bifacial monocrystalline
Array type	1-axis tracking (north-south horizontal axis)
Bifaciality factor	0.7
Maximum tracking angle	55°
Ground coverage ratio (*GCR*)	0.383
Albedo (annual mean value)	0.166
DC losses	9.22%
Inverter efficiency	95.12%

The CSP subsystem design and setup was done directly in SAM, which allows exporting the model configuration to PySAM. The general model parameters considered are specified in

Table 2 and *Table 3*. All parameters not specified remain at its default values in SAM. The dispatch control is given to the model as a turbine output fraction time series, based on the difference between the simulated hourly PV generation profile and a constant 150 MW output.

Table 2. *General CSP model inputs.*

Model parameter	Value
Design DNI	900 W/m^2
PV design capacity ratio	1.0 – 1.5
Solar multiple (*SM*)	1.0 – 2.5
Hours of storage at design point (TES_h)	10 – 16
Collector name	EuroTrough ET150
Receiver name	Rioglass PTR70
Number of SCAs per loop	4
Condenser type	Air-cooled
Design ambient temperature (for power-block operation)	13°C
ITD at design point	30°C
Cooling system part-load levels	4
TES fluid	Solar Salt

The loop outlet HTF temperature for Therminol VP-1 is a typical value used in PTC plants, whereas for HELISOL XLP, the highest proven working value was used [6]. The number of SCAs per loop was chosen based on a general optimization, observing that the flow rate for HELISOL XLP should be a little lower due to its higher outlet temperature. In both cases, the loop inlet HTF temperature at design was selected around the temperature of 293°C. Lastly, given the higher outlet temperature of HELISOL XLP, the power-block thermal efficiency is expected to slightly increase [6] as well.

Table 3. *HTF-specific model inputs.*

Model parameter	Therminol VP-1	HELISOL XLP
Loop inlet HTF temperature	289°C	283°C
Loop outlet HTF temperature	393°C	430°C
Freeze protection temperature	150°C	No freeze protection
Cycle design thermal efficiency	37.7%	39.2%

In computing the levelized cost of energy and performing system optimization on the hybrid system, the cost shown in *Table 4* were considered. PV costs and yearly energy production degradation factors of both subsystems were taken from a previous detailed study on site. The specific CSP installation costs are taken primarily from the current SAM default values for PTC systems [7], based on data up to 2019 [8]. Economy of scale considerations were taken from Starke et al. [2], cost differences between the use of Therminol VP-1 and HELISOL XLP from Jung et al. [6], and a general cost reduction factor from 2019 to 2024 is used for the CSP subsystem, based on extrapolation of the data in the IRENA 2023 renewable cost report [9].

Table 4. *Hybrid CSP-PV system costs (as of 2019).*

Parameter	Value
PV CAPEX per unit capacity	690,812.90 USD/MW
PV annual OPEX per unit capacity	12,350.90 USD/MW
PV annual energy production degradation	0.7%
CSP site improvements cost per unit aperture area	25 USD/m^2
CSP solar field cost per unit aperture area	150 USD/m^2
CSP HTF system cost per unit aperture area	60 USD/m^2
CSP storage system cost per unit energy capacity	15.5 + 93.0/TES_h USD/kWh_t (Therminol VP-1) 12.8 + 76.7/TES_h USD/kWh_t (HELISOL XLP)
CSP power-block cost per unit gross turbine output	654.29 USD/kW_e
CSP balance of plant cost per unit gross turbine output	90 USD/kW_e
CSP contingency as % of installation cost	5%
CSP EPC cost as % of installation cost	11%
CSP cost reduction factor (C_{2024}/C_{2019})	77.2%
CSP OPEX per unit energy production	22 USD/MWh
CSP annual energy production degradation	0.2%

2.2. Evaluation metrics

Based on the annual energy production of the CSP and PV subsystems, the capacity factor of the hybrid system is calculated as

$$CF = CF_{CSP} + PV_{ratio} CF_{PV} \tag{1}$$

where the LCOE of an individual subsystem is calculated as

$$LCOE = \frac{CAPEX + \sum_{t=1}^{N} \frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E(1-d)^t}{(1+r)^t}} \tag{2}$$

Where $N = 25$ is the project lifespan, d is the annual energy production degradation rate and r is the discount rate, assumed as 8% in accordance with typical Chilean stock market returns.

The hybrid system LCOE can be shown to be equal to the weighed mean of the LCOE of both subsystems, as

$$LCOE = \frac{LCOE_{CSP} \cdot E_{CSP} + LCOE_{PV} \cdot E_{PV}}{E_{CSP} + E_{PV}} \tag{3}$$

where E_{CSP} and E_{PV} are the annual energy production of the CSP and PV subsystems.

3. Results

Figure 2 shows how the capacity factor and the LCOE of the hybrid system vary as a function of the PV capacity ratio, the solar multiple and the hours of thermal storage. For typical design values, the capacity factor results in values around 70% while the LCOE can get as low as around 75 USD/MWh.

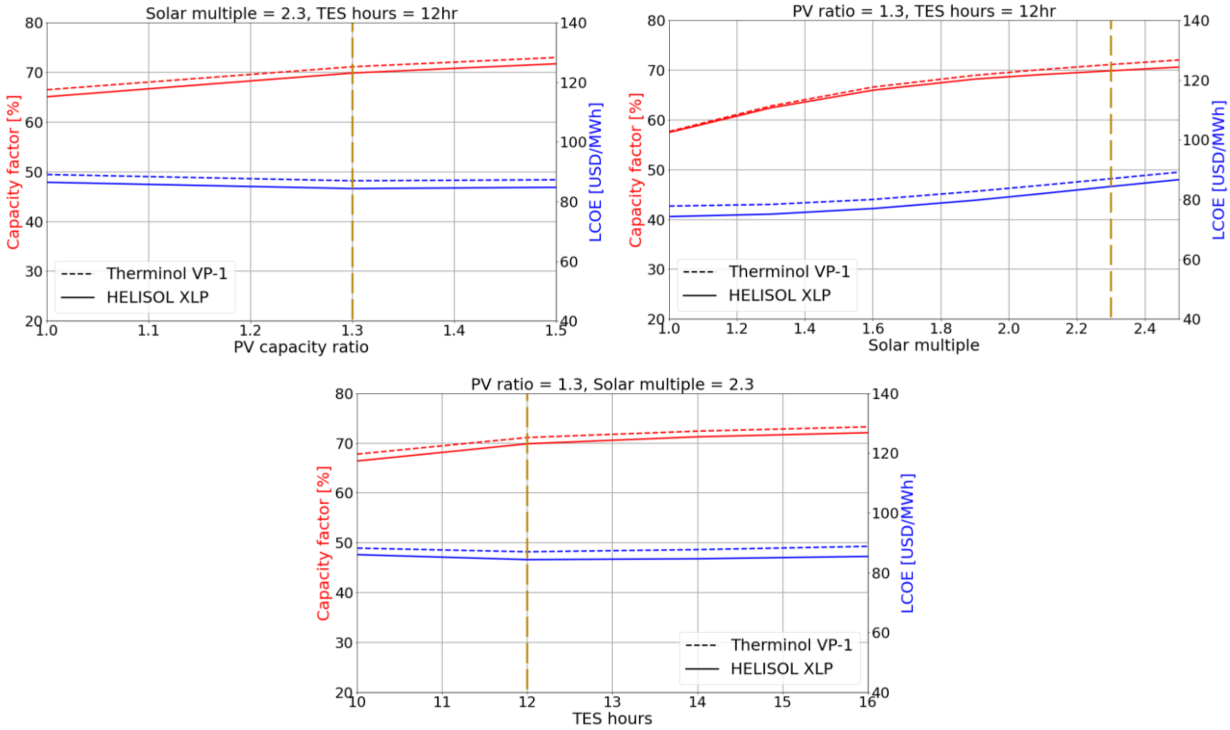

__Figure 2.__ Capacity factor, LCOE and overall cost of energy as a function of the PV capacity ratio, the solar multiple and the thermal storage capacity. In a golden dashed line is the optimal design for HELISOL XLP.

While the simulated plant performance yields almost identical results between the use of both heat transfer fluids, a very slight decrease in the capacity factor is observed with HELISOL XLP, effect that logically increases with the size of the field, represented by the solar multiple. This tiny difference may be almost negligible, being the result of a complex simulation with a highly variable dispatch scheme in a generic PTC model as SAM is. In practice, the plant design should be optimized in detail in terms of the operation requirements.

On the other hand, as a consequence of the higher outlet temperature of HELISOL XLP for the same design thermal load, the required solar field size is smaller, thereby lowering the costs. As a first result, the LCOE drops by approximately 3% by using HELISOL TVP-1 instead of DPO/BP heat transfer oils.

Since the levelized cost of PV production is lower than CSP, the hybrid LCOE will always decrease with respect to the CSP solar multiple, but this substantially lowers the capacity factor as well. Therefore, a restricted optimization approach is proposed in which the LCOE is minimized in terms of the PV capacity ratio, the solar multiple and the thermal storage hours, such that the capacity factor is at least 70%. The optimization was performed on the system using HELISOL XLP, with results in *Table 5*, where the corresponding results with the same design parameters for Therminol VP-1 are also included for comparison. It should be noted that the optimization procedure was performed with a low parametric resolution.

Table 5. *Proposed hybrid CSP-PV system design.*

Design parameter	Therminol VP-1	HELISOL XLP	Relative change TVP-1 → HELISOL
PV capacity ratio	1.3	1.3	0%
PV capacity factor	26.6%	26.6%	-
CSP Solar multiple	2.3	2.3	0%
CSP capacity factor	36.5%	35.3%	-3.3%
TES capacity	12 hours	12 hours	0%
Hybrid capacity factor	71.1%	70.0%	-1.5%
CSP subsystem LCOE	133.66 USD/MWh	130.26 USD/MWh	-2.5%
PV subsystem LCOE	35.23 USD/MWh	35.23 USD/MWh	-
Hybrid system LCOE	87.00 USD/MWh	84.39 USD/MWh	-3.0%

As shown by these results, a parabolic trough CSP plant using the novel silicon oil HELISOL XLP as heat transfer fluid can lower its standalone CSP LCOE by 2.5% and its hybridized LCOE by 3.0%, with respect to a benchmark DPO/BP oil parabolic trough plant, with only 1.2% less capacity factor. Nonetheless, this small difference in capacity factor is to be taken with care, resulting from a conceptual stage simulation from a physical model with a complex plant control algorithm.

A similar study was performed by Starke et al. [2] for a hybrid CSP-PV plant in the Atacama Desert, with annual DNI values of around 3500 kWh/m^2 under consistently clear skies. The LCOE was optimized with the restriction of the capacity factor being over 80%, yielding similar values for the design parameters, particularly a PV capacity ratio of 1.0, a solar multiple of 2.0 and 14 hours of storage. The big difference lies in the lower PV capacity ratio compared to this study and of course in the much higher DNI in the Atacama Desert.

The proposed hybrid CSP-PV plant design is able to dispatch a baseload 150 MW with a solid 70% capacity ratio in a location where, despite the intense annual DNI of around 2900 kWh/m^2, the presence of clouds during the day is rather common, being not far from the coast. Moreover, the levelized cost of the energy produced by this hybrid system for the mine is 84.39 USD/MWh, which is lower than the PPA average cost of the grid energy of 91 USD/MWh, therefore not only feeding the mine's various processes mostly by clean and renewable energy, but also lowering its overall operating expenses.

4. Conclusions

The results of this study highlight the potential of a parabolic trough CSP plant to deliver baseload renewable energy in the northern regions of Chile. To date, there are no parabolic trough CSP plants for utility-scale power generation, despite this technology having been proven reliable for decades in many regions of the planet. However, the very low LCOE of PV plants put CSP systems in a competitive disadvantage during daytime, particularly in Chile when overloading of the electrical is issued by capacity restrictions. This is where hybrid CPS-PV systems emerge as an ideal solution which can dispatch energy on demand at any time of the day thanks to the thermal energy of CSP systems, while at the same time seizing the low costs of PV technology to produce energy at a lower LCOE than stand-alone CSP plants.

The concept of hybrid CSP-PV systems has a great applicability in all countries that benefit from high direct solar radiation, such that a clean and renewable energy mix with lower cost can be developed, which could help countries like Spain, currently struggling with high electricity prices for consumers, and particularly Chile, which has the solar irradiance potential to cover many times its entire energy demand. Moreover, as demonstrated by Moraga et al. [4], hybrid CSP-PV plants also have the potential to produce green hydrogen, by powering electrolyzers by pure solar energy with high capacity factors. This concept is urged to be studied in more detail in the future, with deeper analysis and system performance or cost optimization depending on the particular application.

Data availability statement

The Python code developed for the simulation of a hybrid CSP-PV plant is available upon reasonable request, from the corresponding author.

Author contributions

Frank Dinter: Conceptualization, Investigation, Methodology, Resources, Supervision, Writing – review & editing. **Juan Manuel González:** Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Carlos Felbol:** Conceptualization, Supervision, Writing – review & editing. **Francisco Moraga:** Supervision, Writing – review & editing.

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