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Abstract. This paper focuses on the technology mix proposed for the Diego de Almagro "Solar Technology District" (DTS), intended to be built at the south of the Atacama Desert in Chile, which combines Concentrated Solar Power (CSP) with Photovoltaic (PV) plants to take advantage of both systems attributes: easy installation and low levelized cost of electricity (LCOE) of PV and dispatchability and low cost for storing energy of CSP. Thermal energy storage systems as well as batteries are considered. Local conditions such as solar irradiation, water cost and availability and energy demand profile in Chile are noteworthy and important to be discussed. The methodology followed to optimize the power plant configurations focused on minimizing the LCOE and also considered the available land and the water consumption. Additionally, a rather new PV technology was investigated and selected for the solar park: Bifacial PV modules.The results obtained are useful to project developers seeking for combinations of PV and CSP to satisfy specific electricity demand in an economic, clean and reliable way.

INTRODUCTION

This paper is based on a study contracted by CODESSER, Managing Agent for the Solar Committee of the Chilean Economic Development Agency "CORFO". The objective of the study, was to determine the optimal technological mix and technical characteristics of a "Solar District" or "DTS" for its acronym in Spanish (*Distrito Tecnológico Solar*) proposed to be developed in the area of "Diego de Almagro" located in the Atacama Desert. Particularly, the objective was to define which solar technologies, capacities, configurations and entrance year for each plant, configures an optimal development plant from a private point of view.

This study allowed the Solar Committee to better design public policy strategies in order to promote the deployment of a local solar industry by enhancing the development of local technological solutions with exportation perspectives to the international market and to strengthen the preparation of high quality human resources to be part of the solar industry therefore easing the possibilities of Chile to benefit in an integral manner of the extremely suitable conditions of the Atacama Desert for the development of solar energy projects. A better perspective of

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which the technologies that might be optimal to develop in the region are will also allow CORFO and the local communities to be better prepared to participate in the value chain of future solar energy projects.

The area of study was strategically selected by the Solar Committee considering (i) the extremely high solar radiation monitored in the zone, (ii) the intensive copper mining activity that is developed in the region which in time is highly demanding on baseload energy and (iii) that CORFO owns vast extensions of land which by decree are reserved to the development of solar projects only.

The Chilean market and the specific location considered imposes specific boundary conditions such as solar irradiation, water cost and availability, energy demand profile in Chile and the centralized pool market framework are noteworthy and important to be discussed.

The outcome presented includes the methodology applied for optimizing the technology mix as well as the key techno-economic results and a proposed plant layout.

Because hybridization between PV and CSP is considered, the results obtained are also useful to project developers seeking to satisfy specific electricity demand in an economic, clean and reliable way.

BOUNDARY CONDITIONS

The selected site is located in the Atacama Region, Chañaral province in the Diego de Almagro commune (coordinates: -26.223143°, -69.927646°). The land area is 5,262 ha and belongs to a 26,744 ha site that the ministry on National Assets reserved for the development of electricity generation projects that consider different capacities and technologies and where large scale solar projects coexist. The land area and the irregular shape of the perimeter represents a boundary condition to the capacity of the projects that can be deployed.

The Atacama Desert is known for being the driest no-polar region of the Earth. Official figures estimate a regional water offer of 1.9 m^3/s in the Atacama Region (Ministerio del Interior y Seguridad Pública, 2015). The current regional water demand (16.7 m^3/s) exceeds water supply significantly with a deficit of 14.8 m^3/s (Ministerio del Interior y Seguridad Pública, 2015). It is expected that regional water demand will rise to 22 m^3/s in the upcoming 15 years increasing the pressure on the water system. Neighbor regions to the Atacama Regions show similar water deficits. It is expected that the water consumption of the DTS could not be satisfied with the current water offer in the region. In addition, it is desirable that the water pressure on the system is not increased further. Hence, water costs for the DTS consider the development and construction of a desalination plant at the sea coast. The calculation assumes the investment and running costs of a state-of-the-art reverse osmosis (RO) desalination plant constructed at the pacific ocean close to Chañaral plus the costs of energy to pump water up to the solar park. The calculations done by the project team lead to a water price of 10,50 USD/m^3. Due to its high price, the water quantity consumed by the CSP plants was an important factor for the technology mix selection.

The DTS site is characterized by an outstanding solar resource with a global horizontal irradiation (GHI) of 2,467 kWh/m^2/year and direct normal irradiation (DNI) of 3,541 kWh/m^2/year. The meteorological data for simulations was obtained from the Solar Explorer [1].

The option to import electricity from the grid at spot market prices was included in the simulation, but the possibility to install hybrid systems of solar and conventional technologies at the side was excluded.

The DTS shall provide electricity to the mining sector in the north of Chile through Power Purchase Agreements (PPAs). Mining companies in the north of Chile operate continuously, hence, base load (24/7) was chosen as demand profile for the modelling.

Connection point of the DTS will be the substation “Cumbres 500” which would require a 500 kV transmission line of 2.5 km in length from the district substation. As it is up to the investors to negotiate contracts with the mining companies, it is unknown to which substation the clients will be connected. The Solar Committee chose two extraction/import points for the study on behalf of a proper analysis of spot market price projections based on data provided by Systep [2]. These points are: “Cumbres 500” representing a case where spot market prices of the connection point equal those of the extraction point and “Pan de Azúcar” representing a case where spot market prices between the connection point and extraction point tend to be different (“decouple”) over the year. Additionally, due to the dependence of the spot market prices with the hydrology in Chile (energy prices increase for dry seasons due to reduction of generation from hydraulic power plants and vice versa) two hydrology cases were considered during the optimization, leading in total to four cases to be considered (see Table 1).

TABLE 1. Cases selected for the plant design optimization

	Hydrology Dry	Hydrology Wet
Import from Cumbres 500 S/E	**Case 1**	**Case 3**
Import from Pan de Azúcar 220 S/E	**Case 2**	**Case 4**

The DTS was divided into three separate blocks with their hypothetical starts of operation set to 2021, 2023 and 2025. The nominal capacities of the hybrid PV-CSP plants was set at 100 MWe net power; for this reason the yearly import energy by the client at the consumption point is fixed to 876 GWhel/y per unit plant.

METHODOLOGY

After the local boundary conditions were set, the next step was to define the solar technologies to be considered. Once the power plant types and main components were selected, all parameters needed for the techno-economic simulation were collected, mainly based on previous experience of the participating partners.

In order to search for the optimal power plants for the DTS, two main axes were defined:

- Attraction for private investment: The development, construction and operation of solar plants at the DTS shall be attractive for investors and developers. This corresponds to minimizing the LCOE.
- Quality of supply: To be able to sell the electrical energy produced, developers have to meet the requirements of potential clients. The methodology to define the optimal technology mix is designed to meet 24/7 load profiles at any time of the year. Security of supply is assured through grid connection and power imports.

Operation Strategy Selected for Hybrid CPS-PV Plants

In this study, the main assumption with regard to the plant dispatch is that PV has the feed-in priority in front of CSP. While during PV feed-in peaks the heat collected by the solar field is partially stored in the thermal energy storage and the CSP turbine operates in partial load (or does not operate for PV output above 100 MWe). This choice is justified by the dispatchability of CSP systems, by the relative low cost of the thermal energy storage in comparison to battery storage and by the lower LCOE of PV. This situation may change in the future (probably 2030 onwards, depending on cost developments) as battery storages increase their economic competitiveness. Further studies should detail on the optimal dispatch of CSP-PV plants, e.g. considering transient operation, forecasting systems, equipment-safe operation, etc.

Technologies Selected

On a first stage of the study, the technologies summarized on the Table 2 were assessed and compared.

TABLE 2. Cases selected for the plant design optimization

No.	Technology	Configuration
1	CSP	Parabolic Trough, Thermal oil HTF
2		Parabolic Trough, Solar salt HTF
3		Solar Tower, Solar salt HTF
4	PV & Li-Ion Battery	PV fix & Battery
5		PV single axis tracked & Battery

In the case of the CSP technologies, a thermal energy storage system (TES) with molten salt medium was considered. The PV systems consisted of polycrystalline silicon modules and Lithium-Ion batteries. The systems selected were all state-of-the-art technologies and are therefore not explained in this paper.

Based on a first analysis, not presented here as it is not the focus of this paper, solar tower plants with molten salt and PV single-axis tracked systems without batteries were pre-selected.

During the course of the study, it was determined that bifacial PV systems are very relevant for this kind of application. Therefore they were first compared to monofacial PV systems in order to select a PV technology and continue the design optimization. Bifacial modules have the advantage of capturing sunlight from front as well as from rear surfaces, and therefore, they are able to produce larger amounts of energy, compared with standard (monofacial) modules. However, their performance depends on the spatial distribution of the irradiance incident on the rear module surface, which is strongly affected by several site-specific conditions, such as albedo, reflective surface size, module elevation, and tilt angle [3]. In the framework of this study, ISC-Konstanz simulated bifacial installations with their owned program MoBiDiG (Modeling of Bifacial Distributed Gain). 72 cells bifacial glass-glass n-type PERT (passivated emitter rear totally diffused) "BiSoN" modules were selected for the simulations of fixed tilt and tracked "BiSoN Farms". Details about BiSoN technology can be found under [4]. As a result, compared to a monofacial reference system, for the fixed tilt bifacial PV system an energy yield increase of around 12% is predicted, and for the bifacial system with single axis tracking the calculated energy yield increase is expected to be 15 %. The results of the comparison between monofacial and bifacial PV lead to the decision to consider only single axis tracked bifacial PV systems due to the considerable advantage in terms of simplified LCOE, approximately 11% lower than PV monofacial. The analysis was done based on the cost break-up presented by NREL [5] and the costs and performance data provided by ISC Konstanz.

The search for the optimal combinations of solar tower CSP and bifacial PV is the focus of the rest of this paper.

Techno-Economic Assessment

The assessment of the key design parameters as well as of the annual yield values has been performed with the simulation tool INSEL [6]. The Table 3 shows the parametric variations over the four key design parameters of CSP and PV systems carried out. The solar multiple (SM) is defined as the ratio between the thermal power of the solar field under design conditions and the nominal power block input. The unit of the storage is full load hours of operation at 100 MW_{el}.

TABLE 3. Variation range of key design parameters

	Minimum	**Maximum**	**Incremental Step**
Solar Multiple [-]	1.00	2.50	0.25
TES capacity [h]	2.5	15.0	2.5
PV cap. [MWp]	0.0	152.0	12.7/25.7
Battery capacity [h]	0.0	0.5	0.5

The incremental steps selected were considered small enough to identify relevant techno-economic optima. Additionally, on previous simulations done, the range was wider and the steps for storage capacity smaller.

Based on previous steps in the study the option to use batteries in the DTS seems not to be competitive, therefore, only to verify this, battery capacity of 0 and 50 MWh (or 0 and 0,5 full load hours) per configuration were selected.

The LCOE can be understood as an indicator of competitiveness for energy projects. It represents the minimum price at which, in average, the energy of a project must be sold to obtain at least a net present value (NPV) equal to zero. From a private point of view, it can allow to compare the profitability of different projects. However, as it is a yearly average price, it does not include the market performance of different dispatch profiles and therefore fails to deliver a useful comparison between expected profitability of projects with different dispatch curves in markets with highly differentiated prices within the day and within the grid.

This is the case of the Chilean energy market, where due to a high integration of PV generation among others, the hourly prices at the spot market vary strongly. This implies that the conventional LCOE is not sufficient to compare the competitiveness among two or more solar projects of different configuration.

Moreover, the Chilean market is a so called "centralized pool market with financial PPAs" where the generation park is operated by the central Independent System Operator which dispatches the system in order to achieve the technically feasible minimal operational cost for the system. On one side, generators are paid for their generation at the spot price in the injection node, while on the other side, consumers are obligated to buy energy from generation companies through PPAs at a given consumption node. The generators that own PPAs are obligated to buy energy from the spot market in the consumption node at spot price and to sell it to the client at the negotiated PPA price. This implies that the PPA market is only financial and does not affect operation as generators are not allowed to adjust their own dispatch to optimize revenue.

In this paper, a modified version of the LCOE is proposed to make it useful for a more accurate comparison of competitiveness between projects in Chile by accounting for expected spot market revenue and the risk of price decoupling between injection and consumption nodes.

The LCOE is defined as the total life-cycle cost (TLCC) of a power-generating asset [in chosen currency] divided by the total electricity output of the asset [in kWh] over its lifetime (N). The TLCC consist of the sum of annual costs for installing and operating the system over the years discounted to a base year using present value analysis and a defined discount rate.

In this special case, LCOE considers the spot market (SM) calculating export revenues (ExR) and import expenditures (ImE) from the interference of the DTS and the grid. The solar power plants will inject electricity into the grid, in the amount of their net electricity generation (NEG), at the "Cumbres" substation and obtain incomes according to the marginal costs (MC) at the spot market at that hour (h) and year (n).To serve their Power Purchase Agreement (PPAs) the solar plants will need to retire energy from the spot market at marginal costs at the consumption point of their clients. The annual power imports (API) are set constant here since the client requires base load power 24/7. All revenues and expenditures are discounted to a base year. In order to obtain the LCOE of the hybrid CSP-PV plants with spot market interaction ImE are added and ExR extracted from the TLCCs of the plants.

$$ExR = \sum_{n=1}^{N} \frac{\sum_{=1}^{8760} MC_{h,n} * NEG_{h,n}}{(1+d)^n} \tag{1}$$

$$ImE = \sum_{n=1}^{N} \frac{MC_n * API}{(1+d)^n} \tag{2}$$

$$LCOE_{with\ SM} = \frac{TLCC_{CSP} + TLCC_{PV} + ImE - ExR}{\sum_{n=1}^{N} \frac{API_n}{(1+d)^n}} \tag{3}$$

This indicator allows having a powerful single variable of comparison that contains the information of the conventional LCOE such as plant factor and CAPEX but also account for the particularities of the Chilean market.

After the technical inputs are defined, an automatic parametric study is carried out by means of a batch scripts.

1. Standardized result output files provide hourly values of all relevant parameters for each technology.
2. A python script interacts with the INSEL model and the key design parameters are changed iteratively.
3. An economic model calculates the LCOE under consideration of the INSEL technical results as well as the economic and financial assumptions.

RESULTS

As explained above, the plan of the DTS was formulated in three phases or blocks with a total net electrical output between 750 and 1000 MWe. For simplification, this paper details the configuration, inputs and outputs for the first block only, hypothesized to be commissioned by 2021.

The Figure 1 shows the results for combinations of PV and CSP plants which present the lowest LCOE for different PV capacities. Each bar on the diagram correspond to a combination PV-CSP, where each area represents the relative net electrical output of CSP, PV and taken from the grid. On the bottom of each bar the main parameters are written, being SM: solar multiple of CSP, TES: full-load hours of thermal storage, PV: nominal capacity DC and Bat: battery capacity. Four curves are shown for the LCOE depending on the sub-station where the energy from the grid is taken and the hydrology scenario selected (Pan de Azúcar 220 or Cumbres 500); the sub-station where the energy generated by the DTS plant is exported to is always fixed to Cumbres 550, changing only the hydrology scenario. An additional curve is shown (dashed) for the LCOE in case that the costs of energy import and export are not considered, in order to examine the impact of the spot market prices on the optimal configuration.

The difference between the LCOE curves is related to the expected electricity spot market prices. For example, the lowest LCOE (curve with large squared marker) is obtained for the dry hydrology case if the non-generated energy is imported from Pan de Azucar 220, because the energy price at Pan de Azucar 220 is expected to be lower that the price at Cumbres 500 on the dry scenario from 2021 to 2056, according to a separate study provided by Corfo. On the other side, the energy price at Pan de Azucar 220 is expected to be higher than Cumbres 500 on the wet scenario, therefore the highest LCOE values are obtained if the imported energy comes from Pan de Azucar in a wet scenario.

This difference in spot market prices creates the so-called "decoupling risk" for the DTS owner. Nevertheless, as shown in Figure 1, the LCOE curves after a certain amount of installed PV (>25 MW) are practically parallel to each other, meaning that the optimal configuration would be similar regardless of which sub-station is used to calculate the cost of energy import. This is confirmed by the curve w/o power import and export costs (dashed). It is also important to notice that the difference in LCOE from one configuration to the next, before reaching 100 MW installed PV, is very low. If we add to this the uncertainty of the results, it can be concluded that there is no clear favorite configuration regarding LCOE. For this reason, also the land and water amount required were considered for the final selection of the configuration.

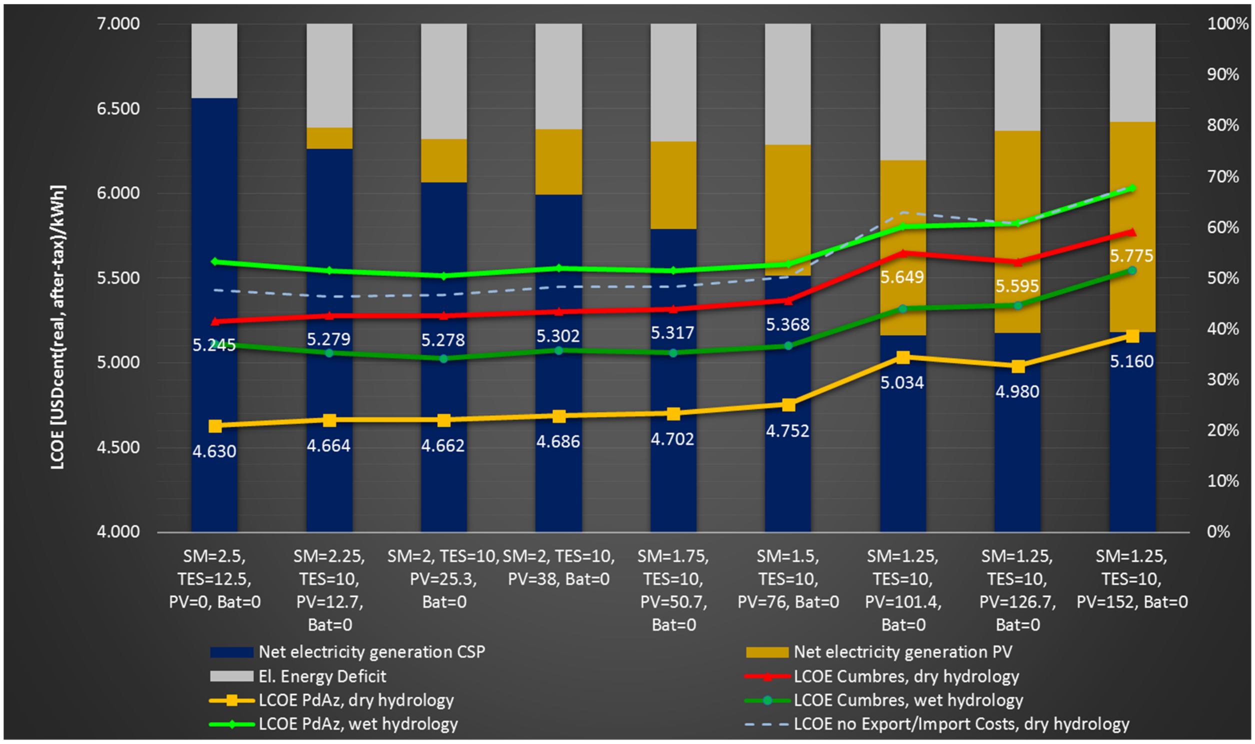

FIGURE 1. Comparison of different CSP-PV configurations

Based on the optimization process, one configuration that combines CSP and PV for each of the three blocks of DTS was selected, and in order to reach the total net electrical output of the park, two configurations per block are required. This has been concluded after verifying the number of plants fitting into the land area reserved for the park, including their auxiliaries, such as transformers and transmission lines. The proposed layout is shown below.

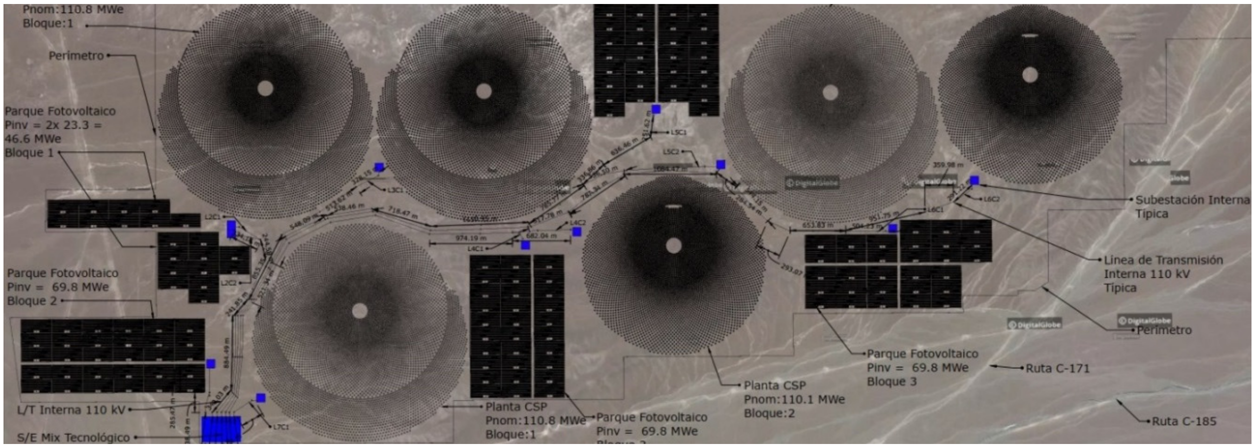

FIGURE 2. Complete DTS park layout proposed as result of the study

The main technical results of the economically optimized configurations are presented below. Table 4 summarizes the design parameters of the selected plants, Table 5 presents the main results of the annual yield simulations for the 1st year, without plant degradation.

TABLE 4. Key design parameters of the Block 1 configuration

Design Parameters	Unit	Block 1	Design Parameters	Unit	Block 1
CSP			**PV**		
Nominal Cap. (gross)	MW_{el}	110.8	Nominal Capacity (DC)	MW_p	25.3
Nominal Net Output	MW_{el}	100.0	Inverter Capacity (AC)	MW_p	23.3
Turbine Efficiency	%	42.8%	Module area	m²	122,798
Total Mirror Area	m²	992,079	Solar Multiple	-	1.09
Solar Multiple	-	2.00	Land Use PV	km²	0.55
TES Capacity	MWh_{th}	2,588	**Battery**		
Receiver Capacity	MW_{th}	584.2	Storage Capacity	MWh_{el}	0.0
Tower Height	m	229.8	Power (AC/DC)	MW_{el}	0.0
Land Use CSP	km²	4.34			
TES FLH	h	10.0			

TABLE 5. Annual performance results for the Block 1 configuration

Results	Unit	Block 1	Results	Unit	Block 1
CSP			**PV**		
Gross Electricity Generation	GWh_{el}/y	687.9	Gross Electricity Generation	GWh_{el}/y	81.8
Net Electricity Generation	GWh_{el}/y	630.4	Net Electricity Gen. (AC)	GWh_{el}/y	77.6
Own Electricity Consumption	GWh_{el}/y	57.6	Specific Energy Production	kWh / kW_p	3068.6
Off-line Electricity Consumption (import)	GWh_{el}/y	12.4	Annual System Efficiency	%	19.2%
Fuel Consumption (aux. heater) - LHV	GWh_{th}/y	0.0	Curtailment	GWh_{el}/y	0.0
Water Consumption CSP[1]	m³/y	164446	Water Consumption PV	m³/y	0.0
Thermal Power delivered by Solar Field	GWh_{th}/y	1629.9	**Battery**		
Dumped Solar Heat	GWh_{th}/y	60.6	Cycles per year	-	0.0
Thermal Power from TES	GWh_{th}/y	798.6			
Total Plant Output					
Net Electricity Generation	GWh_{el}/y	708.0			
Total Fuel Consumption	GWh_{th}/y	0.0			
Energy Balance					
Deficit (Import – Export)	GWh/y	168.5			
Output Share[2]	%	80.8%			
Capacity Factor[3]	%	65.5%			

[1]for CSP dry cooling is assumed; [2] relation energy from solar plants to total imported energy; [3] relation energy from solar plants to net capacity if operated continuously

The LCOE results are presented on Table 6 considering the reduction in output of the solar plants due to degradation; the cases shown correspond to those presented on Table 1 above.

TABLE 6. LCOE results. All unit in [USDcent/kWh]

	Case 1	Case 2	Case 3	Case 4
Total LCOE	5.28	4.66	5.03	5.51
Partial LCOE CSP	5.66			
Partial LCOE PV	3.36			
Grid deficit[4]	4.83	1.98	3.75	6.00

[4]The value "Grid deficit" has been calculated as the difference of the import expenditures minus export revenues divided by the energy deficit (i.e. the energy not covered by the solar plants). These values are not to be confused with the average spot market prices.

CONCLUSIONS

Although this paper focuses on an specific case study, the results shown can be useful for the Chilean and international solar industry mainly for two reasons: first as an example of the possibilities being analyzed for the development of large scale solar power plants in Chile in relation to the local conditions that affect the optimization of the plant design parameters, and second to learn about the benefits of combining CSP plants with PV systems for markets with a strong limitation on the demand side, especially with regard to base load energy supply generated from the sun.

Since the hybridization of CSP and PV is relatively new and gaining much attention, it is recommended to study in detail how to optimize the operation of the different subsystems, since there may still be a large LCOE reduction potential. It has been noticed, that many of the tools used to simulate CSP and PV plants still do not offer the option to simulate both plants together, making it difficult to give the priority to generate electricity with PV during the day while storing the heat from CSP for generation during the night.

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