Assessing the performance of Hybrid CSP+PV plants in Northern Chile

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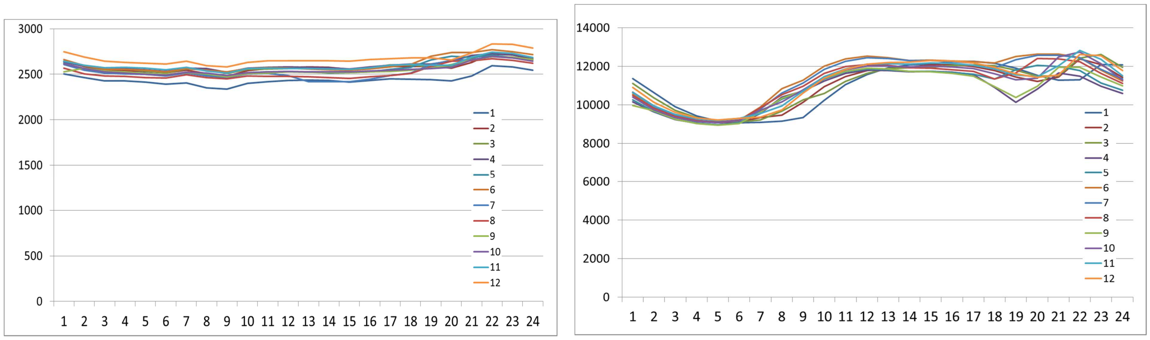
Abstract. The electricity systems in Chile are characterized by a variable hourly demand in the central grid and an almost constant demand in the northern grid, which require different operation strategies for solar power plants depending on their location. Hybridizing a CSP plant with a PV plant can increase the whole plant capacity factor by allowing thermal energy to be stored while the PV plant is in production and thus help to achieve a fully dispatchable solar electricity production system. A thermal and economic analysis of hybrid CSP+PV plants is conducted considering a range of plant capacities based on a parabolic trough plant with the addition of a PV plant for the environmental conditions of Crucero in Northern Chile, which is a hotspot for solar energy development in the country. The study considers a parametric analysis and optimization of the storage and power block sizes for the CSP plant in terms of the levelized cost of energy (LCOE) for varying PV plant nominal capacity. The annual production of the plants are calculated by using the Transient System Simulation program (TRNSYS), which uses a new component library developed for that purpose. The results show good agreement with other software packages as well as with actual data from currently operating CSP plants. The adopted approach helps the proper assessment of the integration of different technologies, since it uses the well-kwon modular structure of the TRNSYS. Regarding the potential for the hybrid solar-solar plants in the Atacama Desert, the high level of irradiation available in Chile can provide a competitive electricity cost, allowing to investors the access to PPA contracts with mining companies in northern Chile. Additionally, the optimization analysis shows that the northern regions of Chile present an outstanding potential for the deployment of such projects.

INTRODUCTION

Chile is a developing market for renewable energy in general and solar energy in particular with legislations that mandate a renewable energy quota of up to 10% of the electrical energy generated, which must be met by 2024, with public announcements already being made that would modify this goal in order to achieve 20% of power generation by 2020 from renewable energy [1]. Solar energy is currently at the initial stages of market penetration, with several projects being developed including PV, CSP, and industrial heat supply plants. Even as the country is endowed with an exceptional solar potential, the contribution of solar energy to the energy mix in Chile is still small. As of June 2015, only 537 MW of PV plants have been deployed and are currently operating with 1,849 MW being built and 8,990 MW approved for construction in the environmental evaluation system. There are 110 MW of CSP plants under construction with another 870 approved. In terms of energy contribution, statistics from the government indicate that during 2014 a total of 458 GWh were produced accounting for 0.66% of the total Chilean electricity consumption, and that from January to May 2015 the contribution amounted to 484 GWh, or 1.65% of the national total for that period [2].

The electricity system in Chile is composed of two main interconnected systems, the northern one known as *Sistema Interconectado del Norte Grande* SING and the central known as *Sistema Interconectado Central* SIC.

The SING has an installed capacity of 4,149 MW with a maximum demand during 2015 of 2,384 MW, while the SIC has an installed capacity of 15,738 MW with a maximum demand during 2015 of over 13,000 MW [3]. Figure 1 shows the typical hourly demands of SING and SIC for 2014.



(a) (b)

FIGURE 1. Hourly power demand (in MW) in the Chilean electricity systems for each month (in colors): SING (a) and SIC (b).

For the largest system, SIC, it can be seen that the lowest demand ranges from 8,500 and 9,000 MW depending on the month approximately from 3 to 5 am, increasing steadily until the afternoon peak from about 11,750 to 13,000 at noon to 5 pm with also nightly peaks up to 13,000 MW occurring around 9 pm. This profile responds to the geographical zone that the SIC grid serves, that concentrates the largest fraction of population including Santiago with more than 6 million people; it shows combined demands from industry and a strong presence of the residential and commercial sectors. In contrast, the Northern Chile Interconnected System (SING) displays demand with low hourly variations. The demand profile is almost flat during the day and fluctuates during the year only 10% of the maximum demand. This system is smaller than the SIC, with demand peaks slightly over 2,500 MW. Most of its demand according to [3] corresponds to the mining industry, which requires a flat 24/7 power supply. This characteristic demand makes it difficult for the PV industry to offer their production to mining companies by PPAs as such a contract would offer only a fraction of the power and energy required due to its low capacity factors that in Chile can reach 25-30%. However, CSP solutions with thermal storage can increase this capacity factor although at a much higher cost due to the larger storage capacity and solar multiple needed to guarantee baseload production throughout the year.

Industry has already reacted to this situation in Chile by proposing concepts of hybrid CSP+PV plants. The Abengoa Cerro Dominador project currently under construction includes a 110 MW molten salt tower with a 100 MW PV plant [4], and the SolarReserve Carrera Pinto Project considers a 110 MW molten salt tower with a 60 MW PV plant, notably tilted at 45° in order to maximize winter production of the PV plant [5]. In these plants, the hypothesis is that the CSP plant dispatches responding to the PV output, which can enable a lower cost solution for a specific design capacity factor than what would have been obtained by a stand-alone CSP plant. This concept works well when the objective is to generate with a high capacity factor as it is required in the SING, and can be adapted to operation in the variable-demand SIC.

Solar Radiation in Chile

Figure 2 shows a map of daily irradiation in yearly average, obtained from GeoModel Solar free maps service. It can be observed that yearly totals over 3,000 kWh/m^2 of DNI are present in most of the country from Santiago to the north, where the maximum levels reach over 3,500 kWh/m^2 for DNI in the Atacama Desert. The highest values for DNI are found in northern Chile as the region shows low cloud cover presence and low aerosol contents in the intermediate depression and even higher in the Andes mountains, with a small decrease with latitude. Due to this it can be concluded that most of the country is suitable for CSP solutions, which make it necessary to study how best to integrate the technology to the grid considering the production and demand profiles of its two main systems SIC and SING. It can also be observed that there is a large influence of the coastal cloud covers as the solar radiation is much lower in the coast than in the intermediate depression, which in practice means that the technology options for coastal and interior northern Chile will be very different.

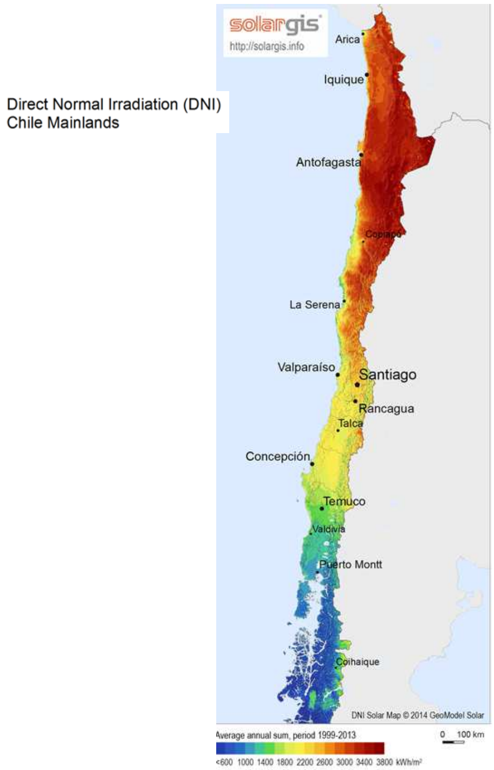


FIGURE 2. Average annual sum of DNI for Chile. From GeoModel Solar free maps service.

The data used in this study corresponds to hourly averages of direct measurements of DNI taken in the vicinity of Crucero with a Rotating ShadowBand Irradiometer of the RSBR 2x model manufactured by Irradiance. A description of the procedures utilized in the measurement campaign can be found in [6].

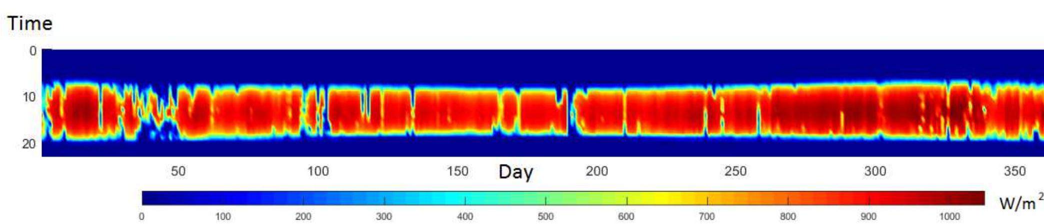


FIGURE 3. Hourly DNI available in Crucero for measurements taken in 2012. From [6].

Figure 3 shows hourly totals of DNI at Crucero (22°2S, 69°5W), which is a large desertic plain located in extremely arid conditions that has seen interest from both the PV and CSP industries. This location has been selected as it is representative of the conditions present in northern and central Chile in a place of relevance in terms of energy demand for the mining industry, and in fact is at a short distance from the location of the Cerro Dominador project.

With a yearly total of 2,571 kWh/m^2 for GHI and 3,389 kWh/m^2 for DNI in 2012, Crucero is one of the top worldwide sites for solar radiation. Most of northern Chile shares this high radiation endowment [6]. The seasonality for DNI is apparent, with shorter days and lower values for the winter season. During summer, daily maximums reach 1,200 W/m^2 of DNI, while during wintertime the maximums only reach between 900 and 950 W/m^2 of DNI. However, during February there are episodes of persistent cloud covers resulting from moisture coming from the Amazon basin in what is known as altiplanic winter. Even then, more than 300 days of clear skies are available each year.

System description

As a first approach, and aiming to analyze the effect of the plant configuration on the LCOE the system considered herein considers a hybrid scheme composed by a parabolic trough plant (PTC) and a PV field, as illustrated in Figure 4. The configuration of the PTC plant is considered in a configuration analogous to the observed in an actual plant located in South Spain, Andasol 1 [7]. Hence, the model considers EuroTrough ET150 solar collectors and UVA3 Schott PTR70 receivers. Additionally, the heat transfer fluid Therminol VP-1 is considered, where the design temperature of 393 ºC. The rated efficiency of the cycle is 38.1 %. The design cycle pressure is 100 bar and the cycle gross output is 50 MW. In addition, a molten salt mixture of 60% $NaNO_3$/40% KNO_3 was considered for the two tank indirect thermal storage, finally, in order to address a suitable solution for Chilean conditions, the plant were simulated considering a dry cooling system.

The PTC plant is integrated to a PV field, which is considered fixed (without tracking system) and tilted in an angle equivalent to the local latitude. In order to address the performance of the field in actual conditions, an actual data performance for the module is considered: the SunPower 128-Cell Module and the Siemens SINVERT PVS1401 inverter [8]. The effect of the total capacity of the PV array (in MWdc) on the LCOE of the hybrid plant is investigated by scaling the rated capacity with respect to the PTC cycle gross output (50 MW). This procedure allows determining the proper size of the PV field, showing the existence of an optimal hybrid capacity, as evidenced in the following sections. However, as demonstrated for the SolarReserve project [5] it is also possible to analyze the effect of the PV plant tilt angle, which will be examined in future communications by our group.

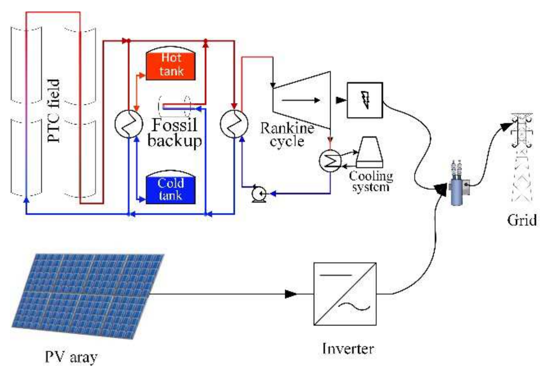


FIGURE 4. Schematic diagram of the system including a PTC CSP plant hybridized with a PV plant.

METHODOLOGY

The annual performance of the hybrid plant was determined by a simulation model, which considers an hourly resolution meteorological database. For that purpose, the Transient System Simulation Program (TRNSYS) [9] was selected, due to its modularity and open-source structure. The open access mathematical model [10] developed by the U.S National Renewable Energy Laboratory (NREL) for the System Advisor Model (SAM) [8] software were compiled as an add-on library compatible with TRNSYS software, as described in [11]. Therefore, in order to model the parabolic trough plant, the physical trough model available in SAM was employed [12]. On the other hand, the PV system was modelled using the Sandia Photovoltaic Array Performance Model [13], alongside with the Sandia performance model for grid-connected photovoltaic inverters [14].

The PTC and PV systems are simulated in a unique TRNSYS deck, where PTC dispatch power is controlled as a response to the output from the PV array; allowing a production of a baseload output, composed by both the PTC and PV productions combined, which is close to the nameplate capacity of the CSP power block. This coupling is done by modifying the turbine output fraction at each time-step of the simulation, which is calculated as a function of the PV power generation. This methodology allows a more complex control strategy, with the possibility of using up to nine different control/policy for the turbine output fraction, which is done by the dispatch period schedule. It is worth to mention that the standard mathematical models (used in SAM) do not allow the update of the turbine output fraction at each time-step. Therefore, the original codes were modified to allow this procedure and enable the simulation of the hybrid plant.

The main objective of the CSP+PV hybrid plant is provide a lower-cost solution for a solar-only high capacity factor plant. In this context, in order to address the economic performance of the solution the Levelized Cost of Electricity (LCOE) is used as a figure of merit. The LCOE is defined as,

$$LCOE = \frac{I_0 + \sum_{t=1}^{n}\left(A_t/(1+i)^t\right)}{\sum_{t=1}^{n} M_{t,el}/(1+i)^t} \tag{1}$$

where I_0 is the initial investment (in this case PV + PTC plants) and A_t are the annual costs considering O&M and insurance. Finally, $M_{t,el}$ is the annual electricity delivered by the system, which in this case can be either considering only the baseload electricity or the total electricity delivered by the hybrid system.

Considering the particular features of the plant, the LCOE for the baseload production was optimized in terms of the thermal storage size and solar multiple. Therefore, it allows determining the minimum LCOE value, depending on the PV plant scale factor and installation prices. In addition, a constraint for baseload capacity factor was established in the objective function (LCOE). This constrained optimization problem was solved using a penalty method. (i.e. capacity factor penalty function was added in the LCOE objective function). Thus, the minimal energy cost is obtained, ensuring a constrained capacity factor, which allows to the hybrid plant to compete in PPA tendering offers. Therefore, the optimization problem can be defined as follows,

$$\begin{aligned} &\min_{\vec{x}}\left\{f(\vec{x}) = LCOE_{baseload}(\vec{x}) + 1000P(\vec{x})\right\} \\ &subject\ to \\ &\vec{x} \in S \\ &P(\vec{x}) = \begin{cases} 0, & if \quad CF_{baseload}(\vec{x}) \geq CF_{target} \\ 1, & otherwise \end{cases} \end{aligned} \tag{2}$$

where S is the feasible region defined by the solar multiple and TES size, $P(x)$ is the penalty function, CF_{target} is the minimum allowable value of the capacity factor, $LCOE_{baseload}$ and $CF_{baseloand}$ are the levelized cost of energy and capacity factor considering only the values of power production at baseload. For the evaluation of the LCOE, the definition adopted by [15,16] was used. Considering the definitions descrived above, the optimization problem was solved by the Generic Optimization Program (GENOPT), which can be easily coupled with TRNSYS. Since the problem consist of a multi-dimensional optimization with continuous variables the GPS implementation of the Hooke-Jeeves algorithm, with multiple starting point, was adopted as recommended by [17].

Economics

The main economic parameters of the PTC plant are listed in Table 1, which is based in the information reported in [19-21]. In addition, an interest rate of 8% and a plant availability of 96 and 100 % was defined for the PTC plant and PV system, respectively. The project lifetime was established in 25 year and no subsidies were considered, since such incentives does not yet exist in Chile. For the PV system, due to the large variation in the costs reported for each component, different scenarios of total installed cost per capacity were considered, namely, 1.30, 1.50, 1.93 and 2.55 US$/Wdc. In addition, a cost of 20 US$/kW/year was adopted for the operation and maintenance cost of the PV system and an insurance rate of 0.5 % of the total cost.

Table 1. Economic parameters considered for the CSP plant.

Direct costs		*Indirect Costs*	
Site improvements (US$/m^2)	15	Land cost (US$/acre)	10000
Solar field (US$/m^2)	270	EPC and owner cost (as % of Direct cost)	11
Heat Transfer Fluid (US$/m^2)	80	Sale tax (%)	0
TES (US$/kWh$_{th}$)	30		
Fossil backup (US$/kWe)	0	*Operation and maintenance*	
Power block (US$/kWe)	850	O&M fixed (US$/kWe-year of a nameplate power)	65
Reference power block (MWe)	55	O&M variable (US$/MWh of the annual electrical output)	3
Balance of plant (US$/kWe)	105	Est. gross to net conv. Factor (%)	90

Contingency (as % total equipment cost)	7

RESULTS AND DISCUSSION

The two dispatch models are depicted in Figure 5. On the left figure, as the PV power output increases, the PTC power output decreases keeping the PTC+PV power production near constant and equal to the baseload power production that is required. On the other hand, the figure on the right shows a peak on the total power production, caused by the increase in the PTC power output; this situation is allowed only in case of the thermal storage is fully charged and therefore extra solar heat can be converted to electricity and dispatched. The alternative in this case is to defocus part of the solar field and reject the extra heat available. Instead of dumping the energy excess, the plant can produce additional electricity and sell it on the spot market. It is worth mention that baseload production is monitored in order to keep track on the amount of energy produced under this condition.

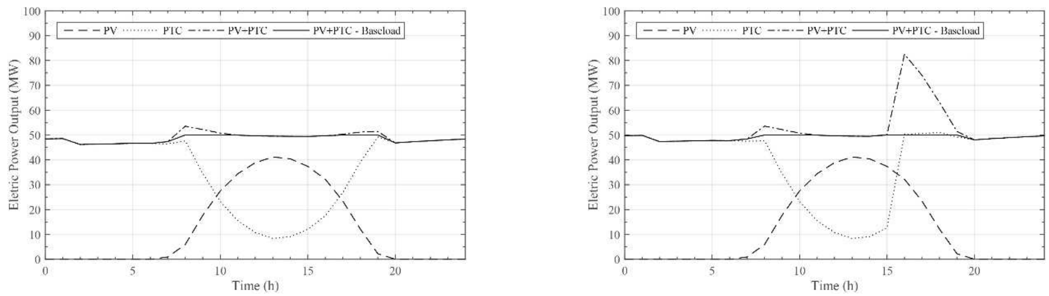


FIGURE 5. Dispatch modes of power production of the PV-PTC hybrid plant.

In order to understand the effects of the main design parameters in the LCOE, a parametric study was carried out in terms of the LCOE and capacity factor of the baseload production. For that purpose, the TES size (in hours), the solar multiple and the PV scale factor were considered independent variables. Figure 6 shows contour plot of these two figure of merits, considering a PV cost of 1.50 US$/Wdc. It can be noted that when increasing the PV scale factor, the location of the minimal LCOE is shifted to the left, to the region of lower solar multiple. In addition, the value of the minimal LCOE varies with the PV scale factor, depicting the existence of an optimal PV scale factor. In turn, increasing the size of the PV system also increases the domain of solutions with high capacity factor, and therefore a plant with smaller PTC solar field can archive capacity factors of up to 80% and more.

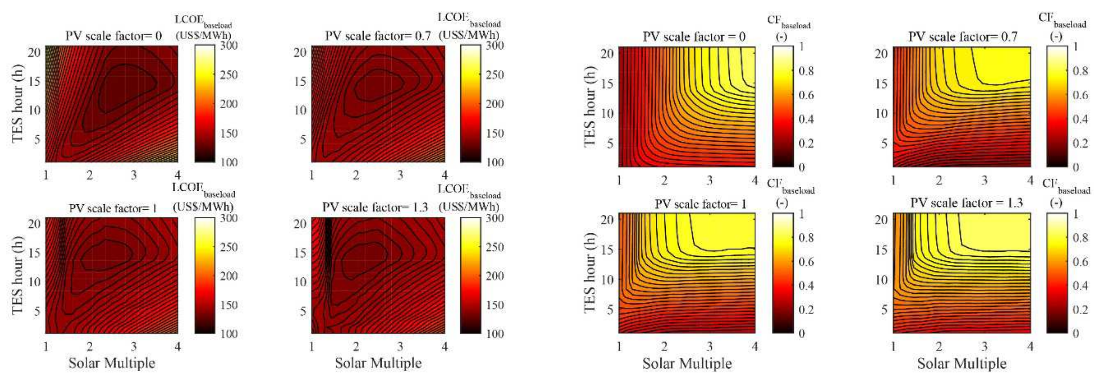
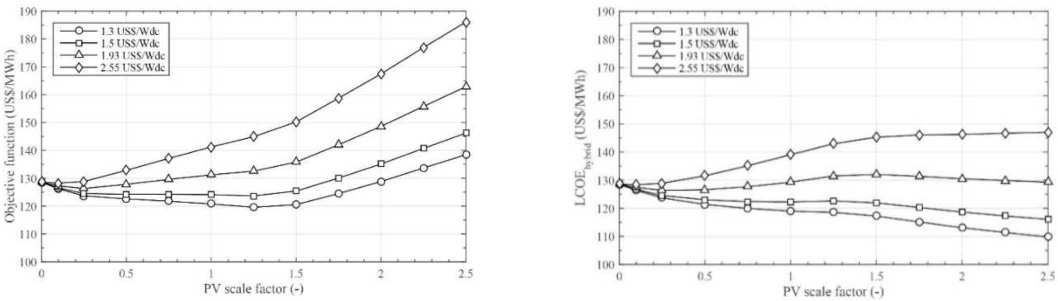


FIGURE 6. Levelized cost of energy and capacity factor for the baseload power production for different sola multiple and TES size, for a PV cost of 1.50 US$/Wdc.

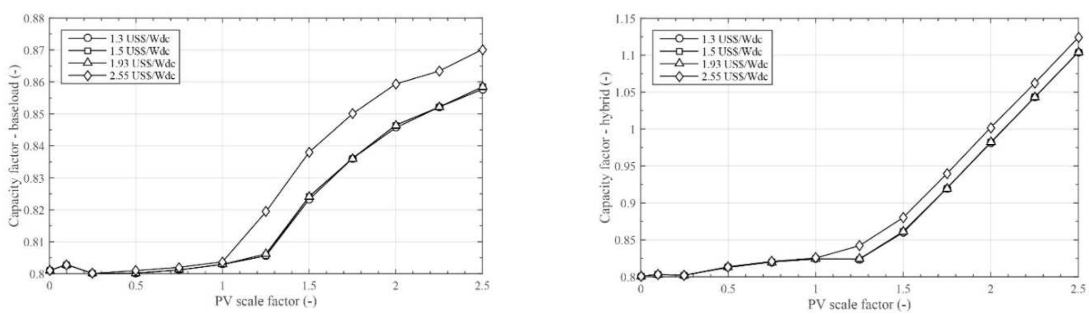
The results of the optimization process are presented in Figure 7. For each PV scale factor and costs, the optimization problem defined by Equation 2 is solved using the Genopt program. It can be seen on the left figure, that for each PV cost, there is a value of the PV scale factor that minimizes the baseload LCOE (objective function). In the scenarios considering high PV installation costs, the optimum scale factor tends to zero, meaning that the PTC-only plant is economically more attractive. Therefore, in scenarios where the PV installation costs are between 2.55 and 1.93 US$/Wdc, the optimal scale factor are around 10 and 25 %, respectively; and these values provide a reduction of only 0.2 and 1.8 % in the baseload LCOE, when compared with the PTC only plant. However, in the scenario of low PV cost, i.e. 1.5 and 1.3 US$/Wdc, the optimal scale factor is around 125%, and provides a reduction of 3.8 and 7% in the baseload LCOE, respectively. In addition, it can be seen that increasing the PV scale factor to values higher than the optimal, the baseload LCOE increases linearly with the scale factor. These effects shows the existence of a size limit for integrating PV and PTC plants, and that after the optimal value the additional energy production does not compensate the cost of the additional capacity in the PV field. As some of the optimal configurations deliver both baseload and peak energy to the grid, if all of the power generated by the plant is considered, the figure changes as observed in Figure 7b.



(a) (b)

FIGURE 7. Optimal LCOE for the baseload power production (a) and for the complete hybrid scheme (b).

Figure 8 shows the capacity factor achieved by the optimal solutions obtained from the optimization routine described above. For lower values of the PV scale factor the capacity factor of the baseload generation tends to the value defined as a constraint, which in this case is 80%. It means that for lower PV scale factors the system can achieve lower LCOE values if the capacity factor is not constrained. However, if all of the energy delivered is considered for determining the capacity factor, it can achieve higher values as evidenced in Figure 8b. Finally, Figure 9 shows the optimized solar multiple derived from the optimization process, where the size of the solar field is reduced as the PV capacity grows, achieving a stable value for scale factors higher than 1.5. For all of the simulated scenarios the size of the TES system was also optimized, however the optimal value is always close to 14 hours of thermal storage which is in good agreement with the projects currently under construction or development in Chile.



(a) (b)

FIGURE 8. Optimized capacity factor of the baseload generation (a) and for the complete hybrid system (b)

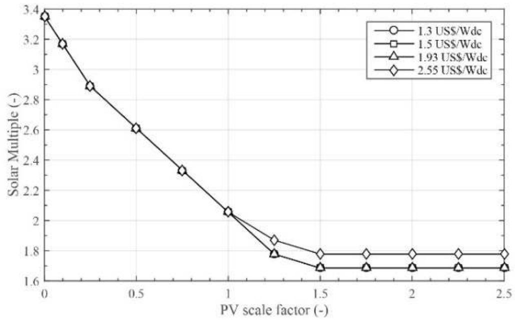


FIGURE 9. Optimized solar multiple of the PTC plant as function of the PV scale factor

CONCLUSIONS

Chile is endowed with perhaps the highest solar resource in the world, with availability of high DNI levels throughout the year for most of the country. This condition has sparked interest for both PV and CSP development, with a market in the initial stages of large-scale penetration of solar technologies for power generation. However, the two main interconnected systems in Chile display a markedly different demand curve, which is almost flat for the northern system SING and with larger variability for the central system SIC. Due to this, it has been proposed that a solar-solar hybrid CSP+PV plant can generate with a profile closer to a baseload plant, thus facilitation its integration to the grid by reduced variability of the solar power generation, as well as facilitation the adoption of solar PPAs for the interesting clients such as mining operations.

This work presented the performance evaluation of a hybrid CSP+PV plant in northern Chile (Crucero) in terms of the LCOE, considering a constraint on the capacity factor for supplying baseload energy to the electricity grid. The study was carried out using a new TRNSYS library, built using the mathematical models developed by NREL. The adopted approach helps the proper assessment of the integration of different technologies, since it uses the well-kwon modular structure of the TRNSYS. Regarding the potential for the hybrid solar-solar plants in the Atacama Desert, the high level of irradiation available in Chile can provide a competitive electricity cost, allowing to investors the access to PPA contracts with mining companies in northern Chile. Additionally, the optimization analysis shows that the northern regions of Chile present an outstanding potential for the deployment of such projects.

Ongoing and future work by the group includes the analysis of hybridization with other CSP technologies such as towers and Fresnel, as well as the optimal tilt angle for the PV panel or even the utilization of tracking systems for the PV field.

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