



CSP + PV hybrid solar plants for power and water cogeneration in northern Chile



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ABSTRACT

The integration between solar energy and seawater desalination is an interesting option in northern Chile due to a high solar potential in the Atacama Desert, where most of the mining operations are located. This industry is intensive in electricity and water consumption; therefore, there is an ideal market opportunity. The CSP + PV plant has the benefits of reduce costs, increase capacity factor and offer high dispatchability, while the integration of a MED plant presents the advantage of using the waste heat. A CSP + PV + MED plant model was performed in TRNSYS implementing a dispatch strategy that prioritize PV output and minimize the turbine shutdowns. The results show that a CSP + PV + MED plant presents a capacity factor 7.6% lower than CSP + PV plant. Regarding the operation of the turbine and the MED plant, the configurations that maximize the operating hours also maximize the performance at partial load, obtaining different PV capacities for the maximum operation hours of the turbine and MED plant. For the CSP + PV + MED plant, different CSP and PV plant configuration between optimal or suboptimal were found to minimize the LCOE and LWC. Also, the best combination between LCOE and LWC is achieved with a CSP close to optimal configuration and suboptimal PV.

1. Introduction

One of the global challenges for humanity in the next years is to reduce greenhouse gas (GHG) emissions with the aim of limiting the global temperature rise (United Nations, 2015). This concern has led in the last decade to rapid growth in renewable energies, which have surpassed coal last year to become the largest source of installed power capacity in the world (IEA, 2016). Solar energy has also followed a noticeable upward trend, e.g., between 2010 and 2014 global solar installed capacity grew 4.5 times (IEA, 2015). Particularly in Chile, the PV capacity increased from 2 MW operating at the end of 2012, to 1,524 MW operating in May 2017. An additional 820 MW are under construction, and 14,840 MW are approved for construction in the environmental evaluation system (CNE, 2017). Investors have seen an opportunity in the country due to an exceptional solar potential, e.g., some places in the Atacama Desert can reach a yearly total about 3,500 kWh/m² of DNI (Direct Normal Irradiation) and more than 300 days of clear skies each year (Escobar et al., 2015).

Another future global challenge is related to water scarcity (United Nations, 2016). Several factors such as increased population, industrial expansion, tourism, and agriculture development have led to increase the water demand in the world. For this reason, some countries mainly

in water-stressed or arid regions are augmenting their freshwater supply with the development of seawater desalination technologies (Ghaffour et al., 2013). Chile, as well as many regions of the planet, is undergoing changes in rainfall that is altering hydrological systems, then this impacts water resources in terms of quantity and quality (Stehr et al., 2010). In addition, the economic development of the country is based on mining, an industry with high water consumption, which makes necessary the search for new water supplies, mainly in the northern region.

Desalination processes require significant quantities of energy (Kalogirou, 2005). Given the global goal of reducing GHG emissions, the latest research efforts are devoted to the implementation of energy minimization strategies and cleaner energy supplies in desalination units (Eltawil et al., 2009; Subramani et al., 2011; Sharon and Reddy, 2015). In particular, the integration between solar energy and seawater desalination is an interesting option in Chile since the lack of freshwater resources occurs near the Atacama Desert, where most of the mining operations are located; therefore, there is an ideal market opportunity to sell electricity and water which requires the design and performance evaluation of solar energy system capable of producing both utilities.

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Nomenclature

CF	Capacity Factor
CNE	Comisión Nacional de Energía
CRS	Central Receiver System
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiation
FF	Forward Feed
GHG	Greenhouse Gas
GOR	Gain Output Ratio
IEA	International Energy Agency
LCOE	Levelized Cost of Electricity

LWC	Levelized Water Cost
MED	Multi-Effect Distillation
MSF	Multi-Stage Flash
NREL	National Renewable Energy Laboratories
PV	Photovoltaic
PTC	Parabolic Trough Collector
RO	Reverse Osmosis
SAM	System Advisor Model
SM	Solar Multiple
SWCC	Seawater Cooling Circuit
TES	Thermal Storage System
TRNSYS	Transient System Simulation Program

1.1. Hybrid CSP + PV solar power plants

Owing to its intermittent nature, there is a mismatch between most renewable energy supplies and user demand (Liu et al., 2016). In solar energy, thermal energy storage (TES) is an important research field that follow the aim of overcoming the variability of solar resource. Several TES technologies integrated to concentrating solar power (CSP) plants have been developed in recent years (Gil et al., 2010; Singh et al., 2010). Molten Salt has been indicated as the most feasible and commercial option, but it is still expensive while there is not a significant market penetration of CSP (IEA, 2014). On the other hand, photovoltaic (PV) modules are the cheaper technology today. Moreover, additional cost reductions of 30–50% in PV will lead to global installed capacity of 1,000 GW by 2040 (IEA, 2015). However, PV produce a variable output during the day, developing low capacity factors, e.g., PV solar plants installed in northern Chile have implemented one-axis-tracking in order to increase the capacity factor up to 30% (CIFES, 2016).

CSP + PV hybrid schemes can match PV low costs with high capacity factor (CF), dispatchability and night generation that offer CSP with TES. The CSP + PV concept has been proposed and analyzed through different approaches. Platzer (Platzer, 2014) carried out a study of the performance of a hybrid plant using data for Daggett, California. He analyzed whether the combination of solar thermal power with cheaper photovoltaic systems may present lower levelized cost of electricity (LCOE), and higher dispatchability than either photovoltaics or solar thermal stand-alone power plants. In fact, CSP + PV plants may provide more economical power generation than CSP-only power plants. In addition, using the opportunity to supply electricity during daytime by the PV modules and prioritizing the charging process of the storage (and discharging in low radiation periods), the number of hours dispatching electricity at nominal capacity increased almost 3 times. Another study was done by Green et al. (2015) who assessed the hourly performance of a hybrid plant in Chile through the use of Solar Reserve's SmartDispatch software, where priority levels of plant power output were assigned. This study found that is feasible to achieve capacity factors higher than those achieved by CSP-only plants. Moreover, a PV tilt angle optimized for winter was proposed in order to reduce the seasonality effects.

Parrado et al. (2016) performed an economic study where the LCOE of a hybrid plant in the Atacama Desert by 2050 was calculated. Two scenario projections (Blue Map and Roadmap) made by the International Energy Agency (IEA) were used. The first approach calculated the LCOE for current PV and CSP technologies. The second approach calculated the LCOE for a hybrid plant composed by 20 MW PV and 30 MW CSP. Moreover, economic parameters were projected to estimate the LCOE in 2050. It was found that the LCOE of a hybrid plant tends to LCOE of CSP-only plant or PV-only plant depending on the scenario evaluated and values between 80 and 90 USD/MWh will be achieved by 2050. The last study was developed by Starke et al. (2016) who analyzed the performance of hybrid CSP + PV plants in northern Chile in terms of the LCOE and considering parabolic trough collectors

and central receiver systems. This study concluded that the main advantage of the hybridization of a CSP plant with a PV array is reducing the size of the CSP solar field, achieving CF higher than 80%, and consequently lowering the LCOE.

1.2. CSP + MED integration

Although reverse osmosis (RO) is the most common desalination technology worldwide (Al-Karaghoul and Kazmerski, 2013), thermal desalination technologies are very attractive for combined power and desalination plants. Within thermal technologies, multi-effect distillation (MED) offers the advantages of utilizing low temperature steam as heat source, lower energy consumption compared to multi-stage flash (MSF) and is, so far, the only commercially proven technology that can be operated in part load conditions (Frantz and Seifert, 2015). Regarding CSP integration with desalination, Palenzuela et al. (2011) showed that the integration of a MED plant reduces the cooling requirements of a CSP power plant, but the CSP + RO combination is slightly more efficient. Nevertheless, considering additional factors as environmental constraints and possible limitations of the use of RO, CSP + MED can offer a suitable solution.

Casimiro et al. (2014) carried out a study using a new tool developed in the Transient System Simulation Program (TRNSYS) to simulate the cogeneration of water and electricity, considering a CSP and a forward feed (FF) MED plant. A seawater cooling circuit (SWCC) in parallel to the MED plant was proposed, aiming to operate the MED plant under nominal conditions most of the time, even with a variable heat load output from the steam turbine. It was concluded that coupling CSP + MED/SWCC plants is technically feasible and have the potential to be economically interesting. The electrical performance of the CSP + MED/SWCC is only 5% lower than the CSP alone plant. Palenzuela et al. (2015) presented another study comparing several CSP schemes integrated to MED and RO plants in two locations: Almeria and Abu-Dhabi. Economic parameters as efficiency, LCOE and levelized water cost (LWC) were evaluated. For Abu-Dhabi it was found that CSP + MED presents better performance than CSP + RO, both thermodynamically and economically. In Almeria instead, it was found that CSP + RO is more suitable. Regarding costs, CSP + RO presents a slightly lower LWC, but a higher LCOE than CSP + MED.

Ortega-Delgado et al. (2016) also presented a comparative techno-economic study between MED and RO in Almeria, in order to find the best coupling strategy for a 5 MWe CSP plant. In that context, the best coupling option is with the RO unit connected to the local electric grid, which produces the lower LWC. Finally, Mata-Torres et al. (2017) performed a techno-economic analysis of a CSP parabolic-trough collector (PTC) coupled with a MED plant, in transient conditions, analyzing two configurations and two locations: Venezuela and northern Chile. The results show that the proposed scheme is feasible, and a reduction of 15% of installed cost for northern Chile is observed and 25% for Venezuela. Also, the sensitivity analysis shows that an optimal water cost can be achieved by changing the capacity of the

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