Research Article
Assessment of Climate Change Impacts and Water Restrictions on Solar Tower Plants

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Climate projections under the high-emission representative concentration pathway “RCP-8.5” scenario are used to show the effects of global warming on the energy production of two similar concentrated solar tower power plants in Spain and Chile from 2025 to 2060. Results show a reduction of the annual energy production of almost 1.8% for Chile and an increase of almost 6% in the Spanish plant, but an increase of 10% water consumption due to both the increase in dry- and wet-bulb temperatures and changes in the direct normal irradiation caused by climate change. When the effect of water restrictions is included in the model caused by the foreseen reduction in water availability in Spain, the increase of the annual energy production is only 2%. Finally, the levelized cost of energy (LCOE) calculated during the whole power plant lifetime (35 years) with respect to the LCOE obtained at the beginning of the project is increased by 1.1% in the Chilean plant, whereas in the Spanish plant, it can be reduced more than 2.5% if there are no water restrictions, while a reduction of 0.4% is expected in a scenario with water restrictions. Results show that careful consideration of climate projections should be considered to properly estimate the economic viability of solar tower plants.

1. Introduction

Climate change can affect the performance of thermoelectric plants due to the increase of the temperature of the cooling fluid [1] or decrease of the water availability [2, 3]. Some of these plants such as the concentrating solar power plants can also be affected by changes in the solar radiation [4]. Most of the investigations published on the impact of climate change on thermoelectric plants concern fossil fuel plants [1, 5, 6] including coal, gas, and nuclear power plants. The majority of thermoelectric power plants are variants of vapor power plants that use water as the working fluid. The efficiency of the power cycle of these plants decreases if the cooling capacity of the condensing system is reduced. The main types of condensing systems are as follows: (i) once-through cooling systems that use water that is disposed after refrigerating the condenser, (ii) recirculating water cooling systems that use wet towers to refrigerate the water stream, and (iii) dry cooling systems that use air as the cooling fluid. The climatic parameters that have a major impact on the cooling capacity are the water temperature in once-through systems, the wet-bulb air temperature in recirculating systems, and the dry-bulb air temperature in dry cooling systems. On the other hand, some water is consumed in recirculating systems since it is evaporated or discharged as blow-down in the refrigeration towers while much larger volumes of water are consumed and directly discharged in once-through systems. Meng and Sanders [7] developed regression models fed with data from over one thousand coal and natural gas power plants in the US to conclude that for every 1°C increase in ambient temperature, plants using dry cooling systems can see a reduction in efficiency of up to 0.2%. Bartos and Chester [8] studied the impact of climate change on the western United States generation capacity, predicting average summertime losses in the 2040-2060 period relative to the historical period of 1.4-3.5% for combustion turbines and 7.4-9.5% for steam turbines. Behrens et al. [9] studied the effect of changes in water availability, temperature, and sectoral water use on thermoelectric generation in the EU, and the findings indicated that power
availability could be reduced as a result of water stress, with the majority of the vulnerable regions located in the Mediterranean region.

The effect of climate change on the performance of renewable energy generation systems has been investigated to a lesser extent [10–12], particularly as it relates to solar energy. Crook et al. [13] analyzed the behavior of PV and CSP systems in the face of climate change. They concluded that in Europe and China, PV energy output is expected to increase by a few percent from 2010 to 2080, while little change is anticipated in Algeria and Australia. In contrast, PV energy output is projected to decrease by a few percent in the western USA and Saudi Arabia. For CSP systems, an increase of more than 10% in energy output is likely in Europe, with several percent increases expected in China and a few percent increases anticipated in Algeria and Australia. However, like PV, CSP energy output is also projected to decrease by a few percent in the western USA and Saudi Arabia. However, a further analysis is needed including the effect of the air temperature on the condensing system of the CSP plant since it has a substantial impact on the calculated energy output.

The problem of water scarcity is getting worse due to the intensification of floods and droughts and changes in the precipitation patterns due to the climate change. This could lead to water consumption constraints that force to reduce the water use in power plants. Carvalho and Carneiro [14] evaluated future electricity generation scenarios to study the effects of different sets of power plants on the water-energy nexus, and they concluded that CSP plants with wet or hybrid cooling systems would represent 92% of the water consumption by 2050 for the scenario where the 100% of the electricity is produced by renewable energies (combining solar and wind plants). Therefore, dry cooling should be considered as an alternative to wet cooling for CSP plants to reduce the water consumption.

Solar power tower (SPT) plants with thermal energy storage (TES) are considered one of the most promising commercial CSP plants [15]. SPT plants consist of a solar field, where direct solar radiation is concentrated to heat a fluid that circulates in the receiver. This fluid is then used to generate the vapor needed in the Rankine power block. Recently, the possibility of combining SPT and parabolic trough plants in the same power block is being investigated [16, 17]. Arnaoutakis et al. [18] showed that the capacity factor for the combined SPT and parabolic plant increases by 2% compared to that for a standalone plant based on parabolic trough collectors. Solar radiation change should be considered when analyzing the climate change impact on CSP energy output and efficiency, since anthropogenic air pollution and associated accumulation of aerosols in the atmosphere may have substantially contributed to the variations in surface solar radiation [19–21]. In addition, the air temperature has a strong effect on the behavior of the condensing system and hence on the performance of the plant. Once-through cooling systems are not typically available for a solar power plant. Contrarily, because CSP facilities are frequently located in areas with water constraint, dry cooling is being employed as a substitute for wet cooling to reduce water use [22]. Uzgoren and Timur [23] studied the use of dry or wet cooling systems in terms of overall energy output and water consumption for a small-scale parabolic trough plant located in Cyprus, and they concluded that a dry cooling unit can save 18.7 tons of water per MWh while producing 27% less energy than a wet cooling unit. The lower electricity production and higher cost of dry cooling system in comparison with wet cooling have led to the adoption of a hybrid cooling system, combining dry and wet units, in certain CSP plants. Moreover, most CSP plants with wet units include evaporation ponds, where the blowdown water from the cooling tower is discharged. On the other hand, the source of raw water is usually ground or surface water from rivers, lakes, wells, or other reservoirs and must be treated to remove organic content and solids to achieve the quality requested by the different consumers in the plant, one of them being the make-up water of the cooling tower that recovers the evaporated and blown-down water [24]. Fernández-Torrijos et al. [25] studied the impact of dry and hybrid condensing systems on the energy and economical performance of CSP plants and proposed a method to choose the operation strategy of the condensing system that maximizes the power plant revenues depending on the water price. The methodology developed by Fernández-Torrijos et al. [25] is applied here to select the optimal configuration and operation strategy of a CSP plant’s cooling system in a climate change scenario. To the best of our knowledge, this study is the first to quantify the impacts of climate change on SPT plants by modeling the influence of changing meteorological conditions in the different systems of the SPT plants. Besides, previous studies on the climate change impact on CSP plants only considered solar radiation and dry air temperature changes in the solar field output. However, there is a lack of studies including the effect of the air temperature evolution on the condensing system of the CSP plant while it has a substantial impact on the calculated energy output. In addition, previous works neglected the projections of water scarcity that limit water availability for power generation in forthcoming years.

The present work quantifies the influence of climate change and water availability on energy production and cost of energy of SPT plants placed at two different countries with different climate conditions where commercial CSP plants are already located and CSP contributes significantly to the energy mix: Chile and Spain. Moreover, dry and hybrid cooling alternatives are evaluated for both locations.

Hence, the methodology proposed and the results provided help with the design of solar tower plants that are better adapted to climate change. Furthermore, it provides useful tools for the energy planning since a substantial increase of the cost of electricity systems is foreseen if climate change impacts are not anticipated [26].

2. Data and Method

To model the future performance of the SPT plants, the climate data from Meteonorm [27] has been used. This software generates data that reliably describe present and future climate conditions [28]: Meteonorm uses 10 global
climate models based on Coupled Model Intercomparison Project Phase 5 (CMIP5) to calculate the parameters of temperature, precipitation, and solar radiation for any period between 2020 and 2100 under RCP 8.5 scenario. Meteonorm’s database 1961-1990 for temperature and 1981-1990 for solar radiation is used together with interpolation algorithms and a downscaling stochastic model to generate the future data. The data generated by the software are validated against the data available from years 1996 to 2005 [27].

The different subsystems of the CSP plant have been modeled using a MATLAB code which was previously validated with the experimental data provided by the Solar Two experimental campaign [29–31], the results of experimental tests of steam turbine-generator units conducted in commercial power plants [32, 33], and following the methodology developed by Conradie and Kröger for dry-cooling systems [34] and wet cooling towers [35, 36] to model the condensing subsystem [25].

2.1. Climate Data. CSP production is susceptible to vary with climate change, as this technology strongly depends on weather conditions. As a result of the climate change, the solar radiation can be affected due to changes in clouds, atmospheric aerosols, or dust. Besides, the variations of both dry-bulb and wet-bulb temperatures as a result of the climate change need to be considered, as they indirectly affect the efficiency of the power plants.

The Köppen-Geiger system [37] distinguishes five main classes of climate, namely A, B, C, D, and E. Each class is divided into 6 subclasses, and in each subclass, there are subgroups depending on the temperature. The solar tower plant of Atacama is located in a BWk climatic region (B: arid, W: desert, and k: cold) while Seville is in a Cs a region (C: warm temperate, s: summer dry, and a: hot summer).

The meteorological data for the two locations in 2020 can be seen in Figures 1(a)–1(c) and 2(a)–2(c). It can be easily noticed that because they are located in South and North hemisphere, the radiation is maximum in the first and last months of the year for the Atacama plant, while for the Spanish plant, it is in the central months. Furthermore, it is evident that the Chilean location is preferable for CSP production, since there is higher irradiation and lower temperatures: based on the Meteonorm data [27] in 2020, the total annual direct normal irradiation (DNI) in Atacama was 3.33 MWh/m² and in Seville was 2.02 MWh/m². According to the Meteonorm documentation [27], the overall uncertainties of the measured DNI are in the range of 6-17%. For the American plant, the dry-bulb temperature ranges from 6.5°C to 22.9°C, and its annual average temperature is 16.9°C (Figure 1(b)). The wet-bulb temperature for 2020 varies from -0.8°C to 14.5°C (see Figure 1(c)), and the average relative humidity is 27.2%, which can be calculated knowing both dry- and wet-bulb temperatures and ambient pressure of the site. For the Mediterranean plant, the annual average temperature is 18.5°C, and it ranges from -0.3°C to 33.6°C (Figure 2(b)). The average relative humidity for 2020 is 63.09%, and the wet-bulb temperature varies from -0.9°C to 23.4°C (see Figure 2(c)).

To analyze the effect of the climate change in the CSP plants studied in this work, the climate projections from 2030 to 2060 for both Spanish and Chilean locations were obtained from Meteonorm software [27] for a scenario of representative concentration pathway (RCP) 8.5 defined by the Intergovernmental Panel on Climate Change (IPCC). Future data from this software is obtained from 10 global climate models based on the project CMIP5 (Coupled Model Intercomparison Project Phase 5), and the Meteonorm tool is able to generate future typical meteorological years (TMY).

TMY data is useful for comparing the performance of solar energy systems located in different sites. It must be noticed that TMY data generated does not represent extreme conditions such as heat waves, droughts, or fires. Besides, it must be considered that the modeled projections of regional temperature and radiation have large uncertainties [38].

Figure 3 shows the projected evolution of the total DNI, average dry-bulb ambient temperature, $T_{amb}$, and average wet-bulb temperature, $T_{wb}$, with years. It can be noticed that the projections show an increase in the dry-bulb and wet-bulb temperature in both locations, while the annual direct radiation decreases in the South American location and increases in the South European location. On the one hand, the projection in Chile predicts that the mean dry-bulb temperature will increase an average of 0.55°C/decade, and the maximum and minimum temperatures will increase in average 0.45°C/decade and 0.6°C/decade, respectively. Moreover, the annual irradiation is expected to decay from 3.33 MWh/m² in 2020 to 3.27 MWh/m² in 2060. On the other hand, the annual irradiation predicted for Seville will increase from 2.02 MWh/m² in 2020 to 2.15 MWh/m² in 2060. Moreover, the projections show an increase of the mean dry-bulb temperature 0.67°C/decade in average and in the minimum and maximum dry-bulb temperature of 0.82°C/decade and 0.84°C/decade, respectively. It is important to notice that the changes in DNI will directly affect the number of working hours of the CSP plant, as the heat rate transferred to the fluid in the receiver strongly depends on solar radiation. Furthermore, the efficiency of the power block will be affected by changes in both dry- and wet-bulb temperatures, as they have an impact in both dry and wet condensing systems.

2.2. CSP Model. Solar tower plants are composed of the solar system (including the sun-tracking mirror field, the tower receiver, and storage system), the power block (made up of the evaporation train and the turbine), and the cooling system [33]. A standard reheated and regenerative Rankine cycle has been considered for this work. Furthermore, two different cooling systems have been studied: a dry cooling system and a hybrid cooling system that consists of air-cooled condensers and wet mechanically driven cooling towers. In Figure 4, the different fluid flows and subsystems of the CSP plant are shown. In this article, two similar CSP tower plants located in Spain and Chile have been studied. The details of solar power plants modeled can be found in Table 1.
Figure 1: Distribution of (a) direct normal irradiation (DNI), (b) dry-bulb temperature \((T_{\text{dry}})\), and (c) wet-bulb temperature \((T_{\text{wb}})\), based on the data from Atacama (Chile) in TMY of 2020 [27].
Figure 2: Distribution of (a) direct normal irradiation (DNI), (b) dry-bulb temperature ($T_{\text{dry}}$), and (c) wet-bulb temperature ($T_{\text{wb}}$), based on the data from Seville (Spain) in TMY of 2020 [27].
2.3. Solar System. The solar system encompasses the heliostat field, the solar tower, and the thermal storage subsystem. The heliostat field consists of thousands of two-axis tracking mirrors that concentrate the solar radiation on a 360° tubular external receiver located at the top of the tower. The heat transfer fluid (molten salt) enters the receiver at 290°C, and it is heated to 565°C and sent to the hot tank. The incident heat rate on the receiver ($Q_{rec}$) (see Eq. (1)) is a function of the solar field efficiency ($\eta_{op}$), the number of heliostats ($N_{hel}$), the area of each mirror ($A_{hel}$), and the hourly data of direct irradiation (DNI) of a typical meteorological year obtained from Meteonorm data.

$$Q_{rec} = \eta_{op} N_{hel} A_{hel} \text{DNI}. \quad (1)$$

![Figure 3: Climate change projections for (a) Atacama and (b) Seville of dry-bulb temperature (red), wet-bulb temperature (blue), and annual direct radiation (black stars). The average dry-bulb temperature values are plotted with red circles, and average wet-bulb temperature is plotted with blue boxes: range bars encompass the lowest and highest values of the dry-bulb and wet-bulb temperatures.](image)

![Figure 4: Operation scheme of the CSP plant with hybrid cooling system. Orange line: molten salt; red line: steam; blue line: liquid water. CT: cold salt storage tank; HT: hot salt storage tank; RH: reheater; SH: superheater; SG: steam generator; PH: preheater; HPT: high-pressure turbine; LPT: low-pressure turbine; ACC: air-cooled condenser; WT: wet tower.](image)

<table>
<thead>
<tr>
<th>Table 1: Plant design parameters of the studied power plants.</th>
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<tbody>
<tr>
<td><strong>Latitude</strong></td>
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<tr>
<td><strong>Longitude</strong></td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
</tr>
<tr>
<td><strong>Storage system</strong></td>
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<tr>
<td><strong>Cycle design net power output (MW)</strong></td>
</tr>
<tr>
<td><strong>Cycle design thermal input, $Q_{in,nom}$ (MW)</strong></td>
</tr>
<tr>
<td><strong>Cooling system</strong></td>
</tr>
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</table>

2.3. Solar System. The solar system encompasses the heliostat field, the solar tower, and the thermal storage subsystem. The heliostat field consists of thousands of two-axis tracking mirrors that concentrate the solar radiation on a 360° tubular external receiver located at the top of the tower. The heat transfer fluid (molten salt) enters the receiver at 290°C, and it is heated to 565°C and sent to the hot tank. The incident heat rate on the receiver ($Q_{rec}$) (see Eq. (1)) is a function of the solar field efficiency ($\eta_{op}$), the number of heliostats ($N_{hel}$), the area of each mirror ($A_{hel}$), and the hourly data of direct irradiation (DNI) of a typical meteorological year obtained from Meteonorm data.

$$Q_{rec} = \eta_{op} N_{hel} A_{hel} \text{DNI}. \quad (1)$$
The efficiency of the solar field, $\eta_{\text{wp}}$, is the average of each heliostat efficiency, which depends on the height of the receiver, the position of the mirror, the time of the year, and the optical properties of the mirror and atmosphere. The location of the heliostats of the solar fields was obtained from the software FluxSPT [39]. Both solar fields are symmetrical; the tower of the Chilean plant is displaced to the north, while in the Spanish plant, it is displaced to the south (see Figure 5). SolarPILOT software [40] has been used to calculate the solar field efficiency. The hourly average efficiency of each solar field, $\eta_{\text{wp}, i}$, is calculated using the following assumptions:

(i) Atmospheric Conditions. Cloudless year, visual range of 40 km, limb-darkened sun model, and flat land

(ii) Flux Simulation Model. Hermite simulation with $25 \times 25$ grid resolution

(iii) Receiver. Maximum allowable peak flux 1500 kW/m²

Figure 5 shows the efficiency of the heliostats and incident heat flux distribution on the receiver at both locations at solar noon on the 21st of March for a DNI = 1000 W/m². This incident heat rate, $Q_{\text{inc}}$, is partly lost by convection and radiation and partly absorbed by the molten salts which flow through the tubes of the receiver $Q_{\text{salt}} = \eta_{\text{rec}} Q_{\text{inc}}$, where $\eta_{\text{rec}} = 0.8$ is the thermal efficiency of the receiver [33]. The operational limits of the receiver, that is, minimum allowable mass flow rate of the molten salts of 20% of the nominal conditions under low irradiation, turbulent regime in the tubes, and maximum flux of 480 MW, have been taken into account [41]. The main design parameters of the solar system can be seen in Table 2.

When the heat absorbed by the fluid in the receiver, $Q_{\text{salt}}$, exceeds the minimum heat rate required to generate the steam for the power block, $Q_{\text{in}}$, the heated salts can be stored and later used when there is no sun radiation. Consequently, power production can be decoupled from solar energy. As in most of the solar tower plants, a two-tank molten salt storage system has been considered. For both plants, storage capacity of 10 hours ($n_{\text{st}} = 10$ h) has been selected. The change in the energy stored during a time, $\Delta t$, can be calculated using

$$Q_{\text{stor}} = (Q_{\text{salt}} - Q_{\text{in}}) \Delta t.$$  \hspace{1cm} \text{(2)}

2.4. Power Block System. In this work, a conventional reheated and regenerative power block has been considered with four high-pressure and two low-pressure feedwater heaters, and a deaerator, commonly used in CSP plants, has been simulated. A comprehensive description of the power block is detailed in Marugán-Cruz et al. [33].

Under nominal conditions at the inlet of the high-pressure turbine (exit of the superheater), the steam mass flow rate is 87.46 kg/s at 550°C and 126 bar, while the mass flow rate of the steam through the condenser is $\dot{m}_c = 61.07$ kg/s at 44.7°C and 0.095 bar, and the thermal efficiency of the power block is $\eta_{\text{nom}} = 44.1\%$. When the condensing temperature is not the nominal condensing temperature (44.7°C), the power block efficiency is affected (see Eq. (3)). The method of Spencer et al. [32] has been used to calculate the power block efficiency at different condensing temperatures

$$\eta_{\text{PB}} = \eta_{\text{nom}} - \frac{\dot{m}_c \Delta h_c}{Q_{\text{in}}},$$  \hspace{1cm} \text{(3)}

where $\Delta h_c$ is the enthalpy change at the condenser due to the variations in the condenser temperature.

2.5. Condensing System. The impact of the condensing system on the amount and cost of the energy produced in the power plant considering the global warming from 2020 to 2060 is studied for the two different locations (Spain and Chile). With this aim, the performance of both hybrid and dry condensing systems is studied and compared. The hybrid cooling system features a parallel condensing arrangement, where the condensing steam is divided among several air-cooled condenser cells and a steam condenser. This steam condenser cools the circulating water within one or more wet cooling towers, also operating in parallel. Conversely, the dry condensing system is composed of several air-cooled condensers operating in parallel.

In our assessment of both dry and hybrid condensing systems, we conducted separate modeling for the air-cooled condenser and the subsystem comprising the steam condenser and wet cooling tower, to evaluate the condensing heat, parasitic consumption, and water usage across a range of operating parameters, including ambient temperature. Following this analysis, we initiated an optimization process to select the cooling system’s operational parameters that maximize the revenue generated by the power plant. These parameters encompassed the selection of the number of both air-cooled condenser units and the wet cooling towers in operation, condensing temperature, fan and pump rotational speeds, and cooling water temperature as a function of the ambient temperature. To conduct the optimization of the operational parameters, the revenue generated by the power plant was calculated as follows:

$$B = P_e P_{\text{net}} - P_w n_{\text{WT}} V_{\text{water}} + V_{\text{water}}.$$  \hspace{1cm} \text{(4)}

where $B$ is the hourly revenue, $P_e$ is the price of electricity, $P_w$ is the price of water, $n_{\text{WT}}$ is the number of wet towers working, and $V_{\text{water}}$ is the makeup water of each tower. Please note that the hourly net energy is calculated as the energy generated by the power block minus the energy consumed by the air-cooled and cooling tower fans, steam condenser, and air-cooled pumps. Both the electricity and water prices are considered in the optimization of the operating parameters. The calculation procedure for the different
subsystems is summarized here, and further details can be found in the supplementary material of this paper and in Fernández-Torrijos et al. [25].

2.5.1. Dry Cooling System. The proposed dry system in this study comprises multiple air-cooled condenser cells (ACCs) working in parallel. The air outlet temperature and

**Figure 5:** Heliostat hourly average efficiency at solar noon on the 21st of March (a) and heat flux distribution on the receiver (b).
Table 2: Solar system main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Optical height of the tower, $H_{tower}$ (m)</td>
<td>180</td>
</tr>
<tr>
<td>Diameter of the receiver, $D_{rec}$ (m)</td>
<td>17.6</td>
</tr>
<tr>
<td>Receiver height, $H_{rec}$ (m)</td>
<td>21.6</td>
</tr>
<tr>
<td>Boundary radius of the solar field (m)</td>
<td>1380</td>
</tr>
<tr>
<td>North/south shift of the boundary (m)</td>
<td>240</td>
</tr>
<tr>
<td>Number of heliostats, $N_{hel}$</td>
<td>10,300</td>
</tr>
<tr>
<td>Heliostat area, $A_{hel}$ (m²)</td>
<td>110.25</td>
</tr>
<tr>
<td>Nominal mass flow rate, $m_{nom,salt}$ (kg/s)</td>
<td>586.2</td>
</tr>
<tr>
<td>Storage time, $n_t$ (h)</td>
<td>10</td>
</tr>
</tbody>
</table>

Condensate flow rate along tube rows are obtained by applying the effectiveness-NTU method [42, 43]: an iterative process is applied to solve the energy equation, assuming that the air mass flow rate is known. Afterwards, the draft equation of the air-cooled condenser is solved to check the value assumed for the air mass flow rate.

2.5.2. Wet Cooling System. The hybrid cooling system divides the condensing flow in two subsystems operating in parallel: the dry cooling subsystem, where the condensing steam flow is distributed among multiple ACC units connected in parallel, and the wet cooling subsystem formed by a surface steam condenser, where the circulating water is cooled in one or more wet cooling towers (WTs) also connected in parallel.

For the analysis of the wet cooling system, separate modeling for the surface steam condenser and the wet cooling tower was accomplished. First, the steam condenser is studied: to determine the cooling water mass flow rate circulating through the steam condenser, the draft equation assuming the water outlet temperature is solved. Subsequently, the effectiveness-NTU method is employed to verify the assumed value for the cooling water outlet temperature.

The cooling water outlet temperature and mass flow rate obtained from the surface condenser model serve as inputs for the wet tower model, where the air outlet temperature is obtained using the effectiveness-NTU method for evaporative systems [42, 43]: the energy equation is solved using an iterative procedure to calculate the air mass flow rate and the temperature of the saturated air at the tower inlet. Then, the amount of makeup water consumed by the tower is determined considering both the water lost due to evaporation and the water that needs to be discharged as blowdown to control the concentration of dissolved solids in the cooling water.

2.6. Solution Procedure. Figure 6 shows the different steps and models used in this work. The input parameters for conducting the optimization of the CSP operation are the wet-bulb and dry-bulb temperatures and DNI obtained from Meteonorm, the solar field optical efficiency provided by SolarPILOT, and the electricity and water prices. The CSP model developed in MATLAB provides the condensing temperature, the net power required by the power block, and water consumption for every hour. Performing an annual analysis, the energy production and water consumption are obtained, and knowing the investment costs and also the operational and maintenance costs of the plant, the economic model determines the levelized cost of electricity for the designed plant.

3. Results

In this work, the effects of global warming on the energy production and water consumption of two similar concentrated solar tower power plants in Spain and Chile were analyzed.

First, a comprehensive investigation was conducted involving various cooling systems, including both dry and hybrid configurations, each featuring a varying number of air-cooled condensers and wet towers. The objective was to determine their operational parameters with the aim of maximizing the plant’s revenue. This optimization process was carried out for every possible pairing of dry- and wet-bulb air temperatures. Then, the selection of the condensing system was conducted for each location (Spain and Chile) to determine the number of ACC units and wet towers that minimize the simplified LCOE of the plant, assuming that the meteorological data of 2020 will remain constant along the life of the plant (2025-2060). Afterwards, the LCOE of the CSP plants with different cooling system configurations studied are calculated considering the variation in the energy output and water consumption due to the climate change, and they are compared to the simplified LCOE previously obtained without considering the influence of the global warming. Finally, once the condensing system of the plant is selected based on the LCOE results, the evolution of the energy output and water consumption is studied along the life of the plant considering the variation of temperatures and DNI due to global warming, considering two scenarios: no water restrictions and water restrictions.

3.1. Base Case Scenario. To design the condensing system, the TMY data from 2020 has been employed to evaluate and compare the performance of the various cooling systems under investigation: (i) dry cooling system featuring either 16, 20, or 24 ACC cells and (ii) hybrid system comprising 16, 20, or 24 ACC condensers and 1, 2, or 3 wet towers. Changing the condensing system configuration leads to variations in power output due to fluctuations in the condensing temperature. However, it is important to note that the number of operating hours remains the same, as the steam mass flow rate at the turbine inlet remains constant throughout the study (see Section 2.4).

Table 3 shows the working hours, the annual energy production, and water consumption, for the different condensing systems. The annual energy production and water consumption for the different cases studied are also shown in Figure 7 to expose more clearly the results. For the calculations presented in Figure 7 and in Table 3, the energy output has been calculated using the meteorological data of TMY 2020 and the electricity price and the water costs of that year. The electricity price used for the Chilean solar
The water price depends on natural and social factors that are affected by precipitation, ambient temperature, population growth, and gross domestic product. The water price for the Atacama power plant was taken as 4.9 $/m³ [46], while the water at Seville was considered free, since according to [47], the plant has a pond providing an annual amount of 0.5 hm³ of water.

It is remarkable the difference between the results of the two locations: it can be easily noticed that, independently of the condensation system, the total number of working hours per year is 6514 and 4159 for the Chilean and Spanish plants, respectively. The lifetime energy production of the Spanish plant, calculated as the hourly energy production from 2025 to 2060, varies from 15·10³ GWh to 15.52·10³ GWh depending on the cooling system employed, while for the Chilean plant, the lifetime energy production varies from 23.9·10³ GWh to 24.27·10³ GWh.

For the Chilean plant, it can be seen that, when the cooling system has more than 16 ACC units, the wet cooling towers would not be necessary since the wet towers would not come into operation. Furthermore, in case the hybrid system was designed with only 16 ACC units, only a single wet tower would work during 781 hours while the ACC system would be able to provide the cooling needed during 5733 hours. The increase of the energy output due to the operation of the wet tower is very small in the American plant. Due to this, cases 2-4 actually have the same configuration of the cooling system and hence the same results, as observed in Figure 7(a)), and the same is true for cases 5-8 and cases 9-12. On the other hand, in the Spanish plant, the wet cooling towers would come into operation independently of the number of ACC units considered, and the energy output increase is considerable in all cases. Observing Figure 7(b)), we can conclude that adding more ACC units and WT has a substantial effect on increasing energy output. However, as the LCOE results will show, this is not always economically advantageous.

Table 4 shows the simplified levelized cost of energy (sLCOE), which measures the cost per unit of energy yield for the different cooling system configurations studied. The configuration that yields the minimum simplified levelized cost of energy (sLCOE) is considered as the optimum one. Assuming a constant energy output and fixed operation and maintenance (O&M) costs, without considering financing expenses, the sLCOE can be calculated as follows:

$$s\text{LCOE} = \frac{C_{\text{inv}} \cdot (f_{\text{ins}} + f_{\text{cr}}) + C_{\text{OM}}}{E_{\text{yr}}}$$

where $C_{\text{inv}}$ are the investment costs, $C_{\text{OM}}$ are the operation and maintenance costs (O&M) costs, $f_{\text{ins}} = 0.5\%$ are the insurance costs [48, 49], $f_{\text{cr}} = 8.58\%$ is the capital recovery factor, and $E_{\text{yr}}$ is the annual energy output. Notice that estimating investment and operational costs for power
Table 3: Summary of simulation results for different condensation systems for the base case scenario in Atacama (Chile) and Seville (Spain) for year 2020.

<table>
<thead>
<tr>
<th>Case</th>
<th>ACC</th>
<th>WT</th>
<th>ACC work. hours (h)</th>
<th>WT1 work. hours (h)</th>
<th>WT2 work. hours (h)</th>
<th>WT3 work. hours (h)</th>
<th>TTotal hours (h)</th>
<th>Energy prod. (GWh/yr)</th>
<th>Water (10^5 m^3/yr)</th>
<th>ACC work. hours (h)</th>
<th>WT1 work. hours (h)</th>
<th>WT2 work. hours (h)</th>
<th>WT3 work. hours (h)</th>
<th>Total hours (h)</th>
<th>Energy prod. (GWh/yr)</th>
<th>Water (10^5 m^3/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
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<td>6514</td>
<td>—</td>
<td>—</td>
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<td>428.4</td>
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</tr>
<tr>
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<td>781</td>
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<td>62</td>
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<td>4159</td>
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</tr>
<tr>
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<td>0.3</td>
<td>0</td>
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<td>6514</td>
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<td>690.2</td>
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<td>0</td>
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<td>3</td>
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<td>0</td>
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<td>693.5</td>
<td>0</td>
<td>4159</td>
<td>—</td>
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<td>437.4</td>
<td>0.00</td>
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<td>440.0</td>
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<td>0</td>
<td>0</td>
<td>—</td>
<td>6514</td>
<td>693.5</td>
<td>0</td>
<td>0</td>
<td>12</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>4159</td>
<td>4159</td>
<td>443.4</td>
<td>4.09</td>
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</table>
generation systems can be challenging, as these costs can vary significantly based on several factors, including the location (country), the level of technological maturity, and specific project conditions, and they are rarely published [48, 50–52]. This simplified LCOE expression provides a metric for comparing the combination of capital costs, O&M costs (including water costs), and performance. This metric is useful for a preliminary study to compare the various cooling system configurations for the two plants under consideration. The full expression of the LCOE, which takes into account varying energy output and O&M costs over the plant’s entire life, will be used later for comparison to the results obtained from this preliminary analysis.

The equipment costs of a solar tower plant, \( C_{\text{equip}} \), encompass those of the solar subsystem, (solar field, solar mirrors, tower and receiver, thermal storage system, and auxiliary systems), the conventional power-block components (turbine, feed water heaters, generator, and grid connector), and the cooling system. The costs of the CSP plants with the different cooling systems can be seen in Table 5. Thus, the investment costs are calculated as follows:

\[
C_{\text{inv}} = C_{\text{equip}} \left( 1 + f_{\text{cont}} \right) \left( 1 + f_{\text{ind}} \right), \tag{6}
\]

where \( f_{\text{ind}} \) refers to the indirect costs and \( f_{\text{cont}} \) refers to the comprehend contingency of the investment costs. The O&M costs, \( C_{\text{OM}} \), include the maintenance of the equipment, \( C_{\text{m}} = C_{\text{inv}} f_{\text{OM}} \), the labor costs, \( C_{\text{lab}} \), and the water costs, \( C_{\text{w}} = V_{\text{w}} P_{\text{w}} \), where \( V_{\text{w}} \) is the total water consumption and \( P_{\text{w}} \) is the water price.

From the results shown in Table 4, it can be noticed firstly that the average cost of electricity for the Chilean CSP plant is substantially smaller than for the Spanish, which is mainly due to the higher irradiation in Chile (see Figures 1 and 2), and secondly that the optimum configuration of the cooling

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**Table 4:** sLCOE (c$/kWhe) for different condensation systems for the base case scenario in Atacama (Chile) and Seville (Spain) for year 2020. For each location, the minimum is indicated in bold text.

<table>
<thead>
<tr>
<th>ACC</th>
<th>Atacama</th>
<th>Seville</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>9.08</td>
<td>9.08</td>
</tr>
<tr>
<td>20</td>
<td>9.04</td>
<td>9.04</td>
</tr>
<tr>
<td>24</td>
<td>9.05</td>
<td>9.05</td>
</tr>
</tbody>
</table>

**Table 5:** CSP plant costs. Detailed costs of the plant for 16 ACC units. Sources: 0Fernandez-Torrijos et al. [25], 1NREL [48], 2Turci et al. [49], 3Ling-zhi et al. [56], 4Turci and Heath [57], 5Carapellucci and Giordano [58], 6Glatzmaier et al. [59], 7EIA [8, 52], Li et al. [60]. Prices have been updated to 2022 prices in dollars. The details of the calculation of investment costs are detailed in Fernandez-Torrijos et al. [25].

<table>
<thead>
<tr>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP dry Cooling System, ( C_{\text{inv}} ) (M$)</td>
<td>589.73[0]</td>
</tr>
<tr>
<td>CSP hybrid cooling (1 wet tower), ( C_{\text{inv}} ) (M$)</td>
<td>590.45[0]</td>
</tr>
<tr>
<td>CSP hybrid cooling (2 wet towers), ( C_{\text{inv}} ) (M$)</td>
<td>591.10[0]</td>
</tr>
<tr>
<td>CSP hybrid cooling (3 wet towers), ( C_{\text{inv}} ) (M$)</td>
<td>591.74[0]</td>
</tr>
<tr>
<td>Labor costs, ( C_{\text{lab}} ) (M$/year)</td>
<td>2.56[1-4]</td>
</tr>
<tr>
<td>O&amp;M operations, ( f_{\text{OM}} ) (%)</td>
<td>1[1]</td>
</tr>
<tr>
<td>Annual insurance cost, ( f_{\text{ins}} ) (%)</td>
<td>0.5[1-3]</td>
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<tr>
<td>Contingency cost, ( f_{\text{cont}} ) (%)</td>
<td>7[6]</td>
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<tr>
<td>Indirect cost, ( f_{\text{ind}} ) (%)</td>
<td>11[7]</td>
</tr>
<tr>
<td>Debt interest rate, ( d_{\text{rate}} ) (%)</td>
<td>8[1-2]</td>
</tr>
<tr>
<td>Inflation rate, ( f_{\text{inf}} ) (%)</td>
<td>3[8]</td>
</tr>
<tr>
<td>Lifetime, ( n_{\text{yr}} ) (years)</td>
<td>35[1,3]</td>
</tr>
</tbody>
</table>

---

**Figure 7:** Annual energy production (blue circles) and annual water consumption (magenta diamonds) in the (a) Atacama and (b) Seville power plants for different cooling system cases enumerated in Table 3.
system is different for the two plants: for the Chilean plant, the optimum corresponds to a dry system with 20 ACC units (sLCOE = 9.04 c$/kWhe), and for the Spanish, the smallest sLCOE (sLCOE = 14.07 c$/kWhe) is that with a hybrid system of 16 ACC and 3 wet towers. The difference in water costs has a significant impact on this result. The water price in Atacama is very high due to the region’s limited access to freshwater sources such as rivers, lakes, or aquifers, as well as the fact that it is an arid region with frequent water scarcity due to low rainfall. These areas may have to rely on costly water transportation or desalination processes to meet their water needs. Seville’s plant, on the other hand, relies on its own pond for water and will face less water stress than Atacama in 2020 [53]. Thus, for each solar power plant location, a different cooling system was selected to study the influence of the climate change in the annual energy yield and water consumption.

3.2. Power Plant Future Projections. The power generation of the CSP plants will be affected by the variations in ambient dry-bulb and wet-bulb temperatures and radiation due to climate change. The condensation temperature of the cycle and therefore the efficiency and energy output are affected by fluctuations in dry- and wet-bulb temperatures, whereas the heat power absorbed by the molten salts and the working hours of the solar plant are affected by the available DNI.

It is important to notice that the climatic projections predict DNI changes that vary depending on the region: although a reduction is expected in southern South America, other regions of the world, such as the North of South America, South-East of North America, wide parts of Europe, South Africa, China, and Australia, could experience all-sky radiation rises by about 0.03 W/m²/year [19]. Despite the predictions concerning the evolution of the solar radiation show an increasing tendency in certain regions of the world while a decreasing tendency in others, the temperature will increase all over the world. Therefore, the simulation of the plant along its lifetime is recommended to study if a tentative increase in solar radiation at the plant location is enough to compensate for the energy generation decrease caused by the negative effect of the ambient temperature on the performance of the condensing system.

3.2.1. Life Cost Analysis. In this section, an economical analysis along the life of the CSP plant (2025-2060) has been conducted using the TMY projections for Seville and Atacama. The LCOE is an economic metric that calculates the average unit energy cost over the entire operational lifetime of a power plant or energy project [54]. For a project with a varying energy output, variable operation and maintenance (O&M) costs, and no financing, the LCOE can be calculated as follows:

\[
LCOE = \frac{\sum_{yr=0}^{n_{yr}} \left( (C_{yr} + C_{OM, yr})/(1 + d_{rate})^{yr} \right)}{\sum_{yr=1}^{n_{yr}} (E_{yr})(1 + d_{rate})^{yr}},
\]

where \(n_{yr}\) is the lifetime in years and \(C_{yr}\) is the capital cost in period \(yr\), which has been calculated as the overnight capital cost, which is the total cost during the construction of a project (excluding financing costs); therefore, \(C_{yr=0} = C_{inv}\) (see Table 5) and \(C_{yr} = 0\) otherwise. \(C_{OM, yr}\) are the operations and maintenance costs in the year, \(d_{rate}\) is the discount rate and \(E_{yr}\) is the annual energy output. The \(C_{OM, yr}\) considers the water price and the increasingly water consumption over the years, and \(E_{yr}\) considers the variable energy generation of the plant during its lifetime. Therefore, the difference between the simplified LCOE calculated with Eq. (5) and the LCOE calculated with Eq. (7) is that the latter considers the variation of the O&M cost and energy output along the project life. For comparison, Figure 8 shows the simplified LCOE and the LCOE considering the variation in the climatic conditions under RCP 8.5 scenario in the Atacama.

![Figure 8: Simplified LCOE for TMY 2020 and LCOE considering the variation in the climatic conditions under RCP 8.5 scenario in the (a) Atacama and (b) Seville power plants for different cooling system cases enumerated in Table 3.](image)
and Seville power plants for different cooling system configurations (cases 1 to 12 depicted in Table 3). As shown, the LCOE for the Chilean plant is higher than the simplified LCOE obtained when only the TMY of 2020 is used for all the cooling system configurations, mainly due to the fact that the radiation in Atacama is expected to decrease along the years. This means that, considering the effects of climate change, the costs to produce electricity will increase for the Chilean plant. The contrary trend is observed for the Spanish plant: the LCOE is lower than the value of the simplified LCOE obtained when only the TMY of 2020 is used for all the cooling system configurations, which means that hybrid cooling is a cost-effective configuration, despite the increasing water consumption, due to the increasing radiation in the Seville region predicted by the meteorological model. Additionally, Figure 8 shows that the optimal cooling system configuration chosen based on both the sLCOE and LCOE results remains unchanged: for the Chilean plant, a dry system with 20 ACC units, and for the Spanish plant, a hybrid system with 16 ACC and 3 wet towers. For these optimal cooling system configurations, the LCOE calculated during the whole power plant lifetime (35 years) with respect to the LCOE obtained at the beginning of the project (sLCOE) is increased by 1.1% in the Chilean plant, whereas the Spanish plant can be reduced more than 2.5%. Therefore, careful consideration of climate projections should be

Figure 9: Projection of the annual working hours (red stars) and annual energy generation (blue circles) in the (a) Atacama and (b) Seville power plants from 2025 to 2055.

Figure 10: Projection of the energy generation in (a) Atacama and (b) Seville. Solid lines represent the monthly energy yield (GWh), and dashed lines represent the average year production.
considered to properly estimate the economic viability of solar tower plants.

3.2.2. Performance of the Optimum Configurations. The life cost analysis performed in the previous section confirms that the configurations with the lowest LCOE (calculated taking climate change into account) were also the configurations with the lowest sLCOE (calculated for the year 2020): a dry system with 20 ACC units for the Chilean plant and a hybrid system with 16 ACC and three WT for the Spanish plant. As a result, the generation forecasts of the most cost-effective configurations for both locations are shown in this section. The contrast between the future projections of the number of working hours (h) and annual energy yield (GWh) in the two locations studied can be easily noticed in Figure 9.

For the Atacama plant, the annual energy production reduces during most of the period studied due to two effects: on the one side, the DNI is reduced during most of the period, which results in lower incident power on the receiver and lower number of working hours (from 6514 hours in 2020 to 6419 in 2050); on the other hand, both dry- and wet-bulb temperatures increase along the period, which results in lower efficiency of the power block. Comparing Figures 3(a) and 9(a), it is shown that the energy yield results (or number of working hours) correlate well with the DNI trend: the peculiarity of large decay of the DNI in the first decade and a small recovery in the next decade can be seen also in the energy yield results and number of working hours. On the contrary, the Spanish plant increases its annual energy production due to the increasing DNI caused by the reduction of the clouds due to the climate change (see Figure 3). In the case of the Seville plant, the projection shows also a raise in the availability (number of working hours per year) of the plant. The lifetime energy production
of the Spanish plant, calculated as the hourly energy production from 2025 to 2060, is 16.07·10^3 GWh which is 3.9% larger than the predicted energy production using the 2020 TMY.

Figure 10 shows the monthly energy yield for 2020 to 2060. The same pattern can be observed in all years for both locations: the months with lower energy output correspond to the months with lower irradiation (see Figures 1 and 2). In the case of the southern hemisphere plant, the months with higher energy production are from January to March and from October to December while for the northern hemisphere CSP plant, it is from mid-March to mid-October where the energy output increases because in those months, the DNI is considerably higher. As shown, the energy output decreases along the years in the Chilean plant, whereas the opposite trend is observed for the Spanish plant, which is easily explained by the opposite trend in the DNI evolution due to the climate change for both locations studied in this work.

Figure 11(a) shows the monthly water consumption for TMY during the lifetime of the Spanish plant. It can be seen that the water consumption is maximum in the central months of the year due to the higher dry- and wet-bulb temperatures (depicted in Figure 11(b)) that lead to the increasing use of the wet towers to reduce the condensing temperature during those months. It is interesting to notice that the increasing water consumption with time caused by the higher average dry and wet temperatures lead to more than 6% increase in the lifetime of the plant: the total water consumption of the plant from 2025 to 2060 would be 17.25·10^6 m³, which is 1·10^6 m³ more than predicted using the 2020 TMY values.

3.2.3. Sensitivity to Water Resources. The use of water could become limited in the next years due to problems related to its availability, growing demand, and price. Climate change exacerbates the issue by amplifying floods and droughts, changing precipitation patterns, and disrupting water supplies, especially in arid regions. This may lead to water consumption constraints that force to restrain the use of the wet condensing system, which will result in a decrease of the energy output of the power plant. According to [53], Atacama is in a region designated as high (3-4) overall water risk, arid, and with low water use. This is the reason why the condensing system of the power plant in Atacama has a unique dry cooling system. On the other hand, Seville is located in a region also designated as high (3-4) overall water risk but with extremely high water stress, meaning that the ratio of total water withdrawals to available renewable surface and groundwater supplies is >80%. This means that a scenario of water restrictions is very likely to occur in this region in the near future, forcing the power plant to operate solely with the dry units of its condensing system. With the aim of studying this scenario, a simulation of the performance of the Spanish plant operating with 16 dry cells and 3 wet towers until 2030 is accomplished, while only 16 dry cells are available from 2030 due to the water unavailability, as the water stress is predicted to be >100% according to [53]. For the Atacama plant, the condensing system is composed of 20 dry cells for the whole period, so water restrictions are not studied.

Figure 12 shows the monthly energy reduction for years 2030 to 2050 for a scenario with no available water compared to that with no water restrictions. It can be seen that the lack of use of wet towers affects only slightly the monthly power generation in the cold months (January to April and October to December) while during the hotter months, the power generation decreases sharply when no wet towers are used, as the condensing temperature is increased, which results in the reduction of the efficiency of the power block.
In case of no available water, the annual decrease in the energy yield is 14.81 GWh/yr in the 2030 decade, 15.18 GWh/yr in the 2040s, and 16.5 GWh/yr in the 2050s.

The LCOE has been calculated for the Spanish plant under a water restriction scenario, and the results are presented in Table 6 together with the values under no water restrictions. If water constraints are anticipated, restricting the functioning of the wet component of the condensing system from 2030 onward, the LCOE would increase due to the lower yield energy revenue. However, a hybrid condensing system with three WT would still be the best option, but 20 instead of 16 ACC units would be required.

According to these results, climate change and water availability should be taken into account at the plant design stage. For instance, national legislation [55] requires, in some cases, to guarantee a minimum amount of energy produced by the plant in a certain period, penalizing the plants that do not reach this amount.

4. Conclusions

In this work, the influence of global warming on the energy production and water consumption in solar tower plants has been investigated. Two representative locations, Atacama (Chile) and Seville (Spain), have been selected to perform the analysis. The design of the CSP plants has been optimized to select the condensing system configuration with the best economical performance for each location in the base case scenario (TMY 2020). As a result, the cooling system selected was different due to the different climatic conditions and electricity and water prices (a dry system formed by 20 ACCs was considered optimal for the Chilean plant, and hybrid system formed by 16 ACCs and 3 wet towers was selected for the Spanish plant). The influence of the climate change on the energy performance during the expected life of the SPT plants (from 2025 to 2060) was studied.

The climate data projections from 2020 to 2060 obtained for an IPCC scenario of RCP 8.5 have been used to calculate the hourly performance of the solar power plants. Under this scenario, both dry- and wet-bulb temperatures are expected to rise in both locations, while the DNI is expected to decrease for the Chilean CSP plant and to increase for the Spanish plant. Therefore, the future annual energy production of the CSP plants is affected differently: during its lifetime, the Chilean energy output is reduced by more than 330 GWh while the Spanish plant is expected to produce more than 600 GWh of additional energy output if there are no water restrictions or almost 140 GWh in case of water unavailability.

Finally, the LCOE of the plants will be affected when the climate change is considered. For the optimum Chilean plant, the LCOE calculated from 2025 to 2060 considering the climate change increases 1.1% compared to the simplified LCOE calculated for TMY 2020, due mainly to the reduction expected in the DNI, which causes a decrease in the energy production. On the other hand, the LCOE for the Spanish plant considering the climate change decreases more than 2.5% compared to the simplified LCOE obtained for TMY 2020. In the latter case, the lower efficiency of the condensing system due to the higher temperatures (especially during summer months) is compensated by the higher DNI expected, so the energy produced is higher. Besides, when both climate change and water restrictions starting in 2030 are contemplated for the Spanish plant, the LCOE would increase in comparison with the no restriction scenario, and a hybrid system with a higher number of ACC units would be recommended.

Our results suggest that climate change will affect the capacity and utilization hours of CSP plants, especially during the summer season. A careful study in other regions is needed, particularly where CSP plants represent a bigger share of the electricity production.

Notations

Acronyms

ACC: Air-cooled condenser
CMIP5: Coupled Model Intercomparison Project Phase 5
CSP: Concentrating solar energy
CT: Cold salt storage tank
DNI: Direct normal irradiation
HT: Hot salt storage tank
HPT: High-pressure turbine
LCOE: Levelized cost of energy (c$/kWh$_e$)
LPT: Low-pressure turbine
O&M: Operation and maintenance
RH: Reheater
RCP: Representative concentration pathway
SC: Surface condenser
SG: Steam generator
sLCOE: Simplified levelized cost of energy (c$/kWh$_e$)
The authors declare that they have no conflicts of interest.

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Supplementary Materials

In the supplementary material, a detailed description of the dry and wet cooling system, as well as the operating restrictions and equations used to calculate the power consumption and heat transfer, can be found. (Supplementary Materials)

References


