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Optimal annual operation of the dry cooling system of a concentrated solar energy plant in the south of Spain

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ABSTRACT

This work presents the optimization of the operation of a concentrated solar power plant with dry cooling over a year, evaluating the molten salts storage, the power block and the air cooling system as a function of the climate and atmospheric conditions. We locate the plant in the south of Europe, Almería (Spain), due to the high solar irradiation and for comparison purposes with a wet cooling based facility. The optimization of the system is formulated as a multiperiod MINLP (mixed integer non-linear programming problem) that is solved for the optimal production of electricity over a year defining the main operating variables of the thermal cycles and the cooling system. The power produced ranges from 9.5 MW in winter to 25 MW in summer, where 5% of this power is consumed by the air cooling system. The annual production cost of electricity is 0.16 €/kWh and the investment required is 265 M€, both slightly higher than when wet cooling is used, but with negligible water consumption. For the selected location, the wet based technology generates slightly less CO_2 than the air cooled facility.

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1. Introduction

Energy and water consumption are major concerns nowadays. While pursuing energy efficiency has become a natural trend, water savings have not received the same attention until very recently. Lately some reports claim that two thirds of the planet will suffer water stress in the next decade [1]. The link between energy production and water consumption is well established when using fossil fuels. However, social pressure towards cleaner energy production and lower environmental impact are leading to develop alternative technologies and use renewable energy sources whose water consumption is still under evaluation. Considering solar energy, it is important to note that the solar energy that reaches the surface of the Earth is more than enough to cover the mankind needs [2]. However, the solar energy received at the surface is only a few kWh/m^2/day. To achieve higher intensities and high operating temperatures CSP (concentrated solar power) technologies are used. They are based on the concentration of solar radiation to heat up a fluid that is used to generate steam and ultimately power. CSP plants consist of three parts: solar field, steam turbine and cooling unit. Over the last years, demonstration solar plants are being built across the globe [3–5]. For the continuous operation of these plants during the night and in overcast days, thermal energy from the heat tank and/or an additional source of energy are typically used [3]. The thermodynamic cycle selected is a Rankine one with regeneration since they provide efficiency advantages [6]. Finally, like any other power plant, the cooling system is a challenge because energy production has associated a certain water consumption. Mainly we can use wet cooling or dry cooling. However, the low price for water results in less attention paid to its consumption and availability. Therefore, wet cooling is widely used in the power industry but it has as a drawback, the consumption of water. Water is lost by evaporation in the cooling towers [7]. In case of a solar based power plant, it is important to highlight that typically regions where the solar incidence is high correspond with those where the availability of water is low. Thus, indirect and direct dry cooling can be implemented. Indirect dry coolers use water to condensate the steam from the low pressure turbine. An air cooler cools down the water in a closed cycle. Direct dry cooling typically uses either an A-frame configuration so that air is used directly as cooling agent to condensate the steam or by means of natural convection, where a design similar to wet cooling towers is provided so that the air moves driven by density gradient. A-frame are the most common air cooled condensers.

Over the last years, a number of simulation based studies have compared the use of wet and dry cooling technologies in power

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plants, conventional or CSP. Kelly and Price [8] published a report comparing wet, forced or mechanical draft, and dry heat rejection for a Rankine Cycle using the GateCycle Program. They presented that the efficiency of the cycle increases for higher inlet pressure and temperature at the turbine and decreasing temperature and pressure at the outlet. The exhaust pressure and temperature have an important effect on the cooling. The low prices of freshwater revealed that the levelized cost of energy was lower in the case of the wet system while the capital investment cost was 5% lower too. The penalty in the energy production cost was at least 8% for dry cooling facilities. Finally, they found that the production cost of the wet cooling plant reached that of the dry cooling based one when the cooling water reached the value of $14.8 per 1000 gal. Turchi et al. [9] presented a report that evaluated the efficiency and impact of dry and wet cooling technologies in parabolic trough CSP plants. They used the SAM (solar advisor model) from the NREL. The switch from wet to dry cooling increases from 3 to 8% the cost of electricity, reducing the water consumption by more than 90%. The water consumed is due to steam cycle maintenance and mirror washing. The investment of the dry cooled facilities was 2% higher. Zhai and Rubin [10] compared the performance of wet induced draft cooling tower and dry A-framed cooling technologies for coal power plants. The models were implemented in the IECM package [11]. The results showed that the dry cooling system was more than twice as expensive per kW of cooling, resulting in an investment cost 8.5% higher when using the dry cooling system, and the efficiency of the plant got reduced 2%. The advantage was the null water consumption versus the 2.46 t of water per MWh produced required by the wet cooling system. Blanco-Marigorta et al. [12] and Habl et al. [13] compared a forced draft wet cooling tower with an A-frame air cooler for the operation of the Andasol 1 power plant following a process simulation approach. This plant uses a Rankine cycle and concentrated solar technology as source of energy. Apart from comparing the effect of the exhaust pressure on the energy output, the dry cooling technology plant showed a reduced energy output in the summer months due to the enhanced need for cooling as a result of the higher ambient temperature. No results on actual water consumption are reported. The electricity production cost in the zone around the Andalucian Granada are 15.27 ct/kWh when using wet cooling and 16.08 ct/kWh in case of dry cooling. Barigozzi et al. [14] performed a sensitivity based optimization study to compare a forced wet cooling condensation system and an A-frame air cooler condenser for cogeneration plants. They modeled the plant using the Thermoflex software to evaluate the effect of the exhaust pressure of the turbine and the air humidity on the power output. The air cooled condenser resulted the best way to reject heat if the ambient temperature is lower than 15 °C. However, no consideration on water consumption was presented. Another interesting comparison was presented in the use of concentrated solar power for water desalinization. Liqreina [15] presented the operation of dry cooled based plants, in particular Andasol in Spain and Ma'an in Jordan, and compared the use of dry cooling with wet cooling over a year long using also a simulation based approach, Greenius software. The dry cooled facility presented regularly 4–8% lower energy production. The LCOE tuned out to be 0.1284 €/kWhe with an investment of 248 M€, while the dry cooled based plant showed a cost of 0.1491 €/kWh with an investment of 289 M€ for a production facility of 50 MW. The water consumption of the wet cooled was 1.6 L/kWh, while the dry cooled was 0.095 L/kWh, computed using SAM software. Palenzuela et al. [16] used a simulation based approach using EES (engineering equation solver) software assuming a steady state operation. The efficiency of the dry cooling based plant was 2% lower than the evaporative water cooling system, while the levelized energy cost of the dry cooling was 0.249 €/kWh vs. the 0.241 €/kWh of the wet system.

The problem with the use of modular commercial simulation software is that it is not that easy to see how cost estimations are implemented nor the detailed design of the cooling systems, which are the key issues for the energy and water consumption associated. Furthermore, only sensitivity based studies were carried out to evaluate and optimize the effect of some operating parameters. On the other hand, the advantage is that rigorous thermodynamics are solved. Lately, Martín & Martín [17] optimized a concentrated solar plant operating over a year using a mathematical programming approach and later it was coupled with a biomass polygeneration system to provide for the energy when solar is not enough [18]. The process consisted of a regenerative Rankine cycle using wet cooling technology. Apart from determining the optimal pressures and temperatures using an equation based optimization approach, the authors showed that an average of 2.1 L of water per kWh produced was consumed over a year of operation.

In this paper we use mathematical programming techniques for the conceptual optimal design and operation of a concentrated solar power plant using an A-frame air cooling system over a year. Our aim is to evaluate the cooling system that, while reducing water consumption compared to the wet cooling based facility [17], requires energy for the operation of the A-frame. The facility is located in Almería (Spain), a region with one of the highest solar radiations in Europe, the same region selected for the previous work [17]. The paper is organized as follows. Section 2 describes the modeling features and the atmospheric conditions of the selected location. In Section 3 we present the optimization procedure. Next, in Section 4 the main results are discussed such as the major operating conditions, the power consumed by the cooling system and the units of the A-frame needed, followed by an economic evaluation and a comparison between dry and wet cooling facilities based on CO_2 savings. Finally, in Section 5 we draw some conclusions.

2. Modeling

2.1. Modeling assumptions

The plant consists of three parts, the heliostat field including the collector and the molten salts storage tanks, the steam turbine and the air cooler steam condenser. Fig. 1 presents the flowsheet for the process where the heliostat field has not been included. For the detailed information on the modeling features of the heliostat field and the steam turbine, we refer to the supplementary material and to previous work [17,18]. Our process is based on the use of a tower to collect the solar energy and a regenerative Rankine cycle. The steam is generated in a system of three heat exchangers where water is heated up to saturation and then evaporated using the total flow of molten salts. However, only a fraction of the flow of salts is used to superheat the steam before it is fed to the first body of the turbine. The rest is used to reheat up the steam before it is fed to the second body. In the second body of the turbine, part of the steam is extracted at a medium pressure and it is used to heat up the condensate. The rest of the steam is finally expanded to an exhaust pressure, condensed and recycled. In the model, we consider conservative average efficiencies for the heliostat field and the turbine efficiency based on rules of thumb for the conceptual design of the facility over a year, using a time period of a month, for comparison purposes with previous work [17]. Refs. [19–21] can be used to include the operation of the solar field into this formulation accounting for the decrease in the efficiency of the turbine as function of the load and the efficiency of the solar field as a function of the direct normal irradiation. In Refs. [19,20] we see that the efficiency

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