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Thermodynamic Performance and Water Consumption of Hybrid Cooling System Configurations for Concentrated Solar Power Plants

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Abstract: The use of wet cooling in Concentrated Solar Power (CSP) plants tends to be an unfavourable option in regions where water is scarce due to the high water requirements of the method. Dry-cooling systems allow a water consumption reduction of up to 80% but at the expense of lower electricity production. A hybrid cooling system (the combination of dry and wet cooling) offers the advantages of each process in terms of lower water consumption and higher electricity production. A model of a CSP plant which integrates a hybrid cooling system has been implemented in Thermoflex software. The water consumption and the net power generation have been evaluated for different configurations of the hybrid cooling system: series, parallel, series-parallel and parallel-series. It was found that the most favourable configuration in terms of water saving was series-parallel, in which a water reduction of up to 50% is possible compared to the only-wet cooling option, whereas an increase of 2.5% in the power generation is possible compared to the only-dry cooling option. The parallel configuration was the best in terms of power generation with an increase of 3.2% when compared with the only-dry cooling option, and a reduction of 30% water consumption compared to the only-wet cooling option.

Keywords: hybrid cooling systems; concentrated solar power; power block; water consumption

1. Introduction

Concentrated Solar Power (CSP) plants are gaining global acceptance due to their potential to efficiently use and store solar thermal energy, making this renewable energy source more dispatchable and avoiding the use of fossil fuels to produce electricity. To achieve higher efficiency and longer operation periods, CSP plants are best located in areas with high Direct Normal Irradiance (DNI). These locations, however, are typically arid and often preclude the use of substantial quantities of water by wet cooling systems to condense the exhaust steam from the power block. Although wet cooling towers are more effective than dry coolers as the cooling depends on the wet bulb temperature, they consume large quantities of water due to evaporation (mainly), blowdown, drift and leakages, which require a continuous supply of makeup water to cope with such water losses. For instance, for a 100 MW_e plant with a wet-cooling system in place and operating at base load, water consumption is around 1.4×10^6 m^3/year, out of which 94% is due to water losses through evaporation [1]. It is also important to highlight that the water requirements of a Parabolic Trough (PT) CSP plant have been found to be higher than for Solar Tower (ST) CSP plants, in comparison 3 m^3/MWh and 1.5 m^3/MWh, respectively [2]. Air-Cooled Condensers (ACC) could be used to enable the plant to work without consuming water for cooling. However, as the cooling depends on the dry-bulb temperature, when the ambient temperature reaches its maximal values during the summer, the ACC performance decreases considerably leading to a lower steam turbine efficiency. It becomes more relevant in arid regions where the installation of CSP plants is more suitable. As a matter of fact, it has been published in the literature that an ACC used in PT CSP plants located in arid regions can cause an annual reduction of 7% in electricity production and about 10% increase in the cost of electricity, being the efficiency reduction lower in the case of ST CSP plants [2].

Hybrid cooling systems can provide a solution in order to overcome the disadvantages of either only-dry or only-wet cooled plants. According to Colmenar-santos et al. [3], these systems allow a reduction in water consumption of 60–80% at an expense of 3–5% increase in the capital cost. In addition, these systems also enhance the performance in warm weather compared to dry-cooled plants since they can maintain the turbine performance close to design conditions, even at high ambient temperatures [4,5], and reduce the energy penalty to below that of conventional air coolers [6].

Several research works that evaluate the impact of hybrid coolers on the performance of power plants (both CSP and conventional ones) and the water reduction achieved against conventional cooling systems can be found in the literature. Williams and Rasul [7] evaluated the efficiency of a coal-fired steam power plant using a hybrid cooling system composed of an Air-Cooled Heat Exchanger (ACHE) and an evaporative wet cooling tower that operated in two modes: series and parallel. They found that the parallel operation mode was more efficient from a thermodynamic point of view (i.e., less coal consumption) than the series one, although the latter option led to a lower water consumption. Zhai and Rubin [8] performed a techno-economic assessment of a hybrid cooling system for coal and natural-gas-fired power plants. The hybrid cooling system comprised of a wet-cooled condenser and an ACC connected in parallel. They observed that the total water consumption can be reduced from 1 m^3/MWh to 0.1 m^3/MWh when a hybrid cooling system is used in the natural gas combined power plant, in comparison with an only-wet cooling system. Whereas, in the case of pulverized coal, it was found that the total water consumption was reduced from 2.1 m^3/MWh to 0.2 m^3/MWh. However, the reductions in water consumption come with an increase of 3−5% in overall plant Levelized Cost of Electricity (LCOE) for coal and natural-gas-fired power plants without carbon capture system. They reported that during hot periods (26–28 °C ambient temperatures), the operation of the wet cooling tower at the 30% of the total cooling load would minimise the overall system costs.

Rezaei et al. [9] developed a numerical model of a hybrid cooling system and built a pilot setup to investigate experimentally the water losses considering the series and parallel operation modes in an industrial plant. The hybrid cooling system was composed of an ACHE and an evaporative wet-cooled section which could be either connected in parallel or series configuration. They observed that in the case of a parallel configuration, the hybrid cooling system had lower water losses but it required a larger area for heat transfer in the dry cooler because of a lower thermal efficiency. A reduction in water consumption from 243 m^3/h to 61.2 m^3/h and from 213.8 m^3/h to 57 m^3/h in summer and winter, respectively, was obtained in this configuration, when the dry cooling fraction (i.e., the percentage of cooling water flow rate going to the dry cooler) was varied from 0.2 to 0.8. In the case of series configuration, water consumption decreased from 252.6 m^3/h to 89.6 m^3/h and from 220.8 m^3/h to 77 m^3/h in summer and winter, respectively, when the dry cooling fraction was varied from 0.2 to 0.8. Ashwood and Bharathan [10] investigated the use of hybrid cooling systems to enhance the net power output of an air-cooled geothermal power plant during hot ambient conditions using minimal amounts of water. They considered two schemes of hybrid cooling system: a water-cooled condenser connected in parallel or series with the ACC and a water-cooled condenser connected in parallel with an ACHE. They reported that the overall water consumption of the plant can be restricted to 3.5% of the total water used in a fully wet-cooled power system if the duration of the operation of the wet cooling in the hybrid system is limited to 1000 h during a year.

Benn et al. [11] investigated hybrid cooling systems from a theoretical point of view, for thermoelectric power plants in which a conventional wet cooling tower was connected to a direct dry thermosyphon steam condenser in parallel and a dry indirect thermosyphon cooling tower in parallel and series configurations. They observed that the coefficient of performance was two times higher in the case of hybrid system with direct dry thermosyphon steam condenser when compared to a hybrid system with dry indirect thermosyphon cooling tower in parallel. In addition, the effectiveness was 25% higher in the case of hybrid parallel configuration with direct dry thermosyphon steam condenser compared to a hybrid system with dry indirect thermosyphon cooling tower connected in parallel or series. Bustamante et al. [12] developed a numerical model to evaluate the performance of a conventional steam power plant with a hybrid cooling system composed of a wet cooling tower and an ACC connected in parallel. They found that a water saving of 22–89% was achievable at ambient temperatures of 0–50 °C compared to an only-wet cooling system. Wagner and Kutscher [13] evaluated the performance of a CSP plant with a hybrid cooling system composed of an ACC connected in parallel with a wet-cooled condenser. They considered two designs of the hybrid cooling system with a wet cooling capacity of 15% and 50% and compared the results with the base case of an only-wet cooling system. The results showed that the hybrid cooling system offers a significant reduction in water consumption, 85% and 52% in the case of 15% and 50% wet cooling capacity, respectively. However, this reduction in water consumption took place at the expense of the CSP plant performance, resulting in a reduction of 2.33% and 1.67% in the conversion efficiency in the case of 15% and 50% wet cooling capacity, respectively. Petrakopoulou and Olmeda-Delgado [14] performed simulations of a hybrid cooling system to investigate water consumption in natural gas combined cycle and an integrated solar combined cycle. The hybrid cooling system was comprised of a wet cooling system and an ACC connected in parallel. They reported that the cooling water consumption was reduced by half when a hybrid cooling system was used in comparison to a wet-only cooling system in both cycles. However, water consumption in the case of integrated solar combined cycle was more than two times compared to natural gas combined cycle because of a higher steam mass flow passing through the cooling.

Despite the special need to reduce the water requirements by the cooling system in CSP plants, especially located in arid areas, there are limited research works that provide exhaustive analyses focused on this topic. Under the framework of an European project called 'Water Saving for Concentrated Solar Power' (WASCOP) [15], a hybrid cooling system, consisting of a dry and wet cooling towers has been designed and modelled using the Thermoflex simulation tool and an exhaustive evaluation in terms of water saving and thermal efficiency when integrated into a CSP plant has been carried out. The aim of this study is to identify the best configuration of the hybrid cooling system in terms of power generation and water reduction in a CSP plant. In addition, another objective of this study is to investigate the effect of cooling tower capacities on specific water consumption in a CSP plant. The parabolic trough technology has been selected for the CSP plant, since it covers 60 to 70% of the CSP applications and also because the commercial 50 MW_e PT CSP plant ANDASOL-1, the operating conditions of which are available in the literature, can be taken as reference for input data and model validation.

The present paper is arranged as follows: Section 2 gives a description of the hybrid cooling system, including a detailed explanation of the operation of all analysed configurations. Section 3 deals with the modelling of each component: power block, dry cooling tower and wet cooling tower and provides detail of the general assumptions taken for the simulations. Section 4 is dedicated to the validation of the power-block model in on- and off-design conditions with the data of the commercial CSP plant ANDASOL-1. Section 5 presents the results obtained from a sensitivity study that has been performed to evaluate the performance of several configurations of the hybrid cooling system at variable ambient temperature, wet/dry cooling fraction and relative humidity. Moreover, the cooling capacity of the cooling towers has been varied in the different hybrid cooling configurations in order to evaluate its impact on the specific water consumption at variable ambient conditions. The last section gives some conclusions drawn from the sensitivity analysis and further developments to be considered for future works.

2. Description of the Hybrid Cooling System

A scheme of the CSP plant integrating the hybrid cooler is shown in Figure 1. The CSP plant includes a conventional steam power block and a cooling system, whereas a solar field provides the heat source. A thermal energy storage is integrated into the solar field to store the surplus thermal energy in order to improve the dispatchability during the absence of solar energy. The power block is a regenerative, reheat Rankine cycle that converts the thermal energy from the solar field into electrical energy by the use of several turbines stages. Finally, the condenser removes the 'latent' heat from the discharged steam and enables the resultant condensate to be pressurised and recirculated to the boiler via the feed-water pump. The cooling system rejects the heat removed by the condenser to the environment.

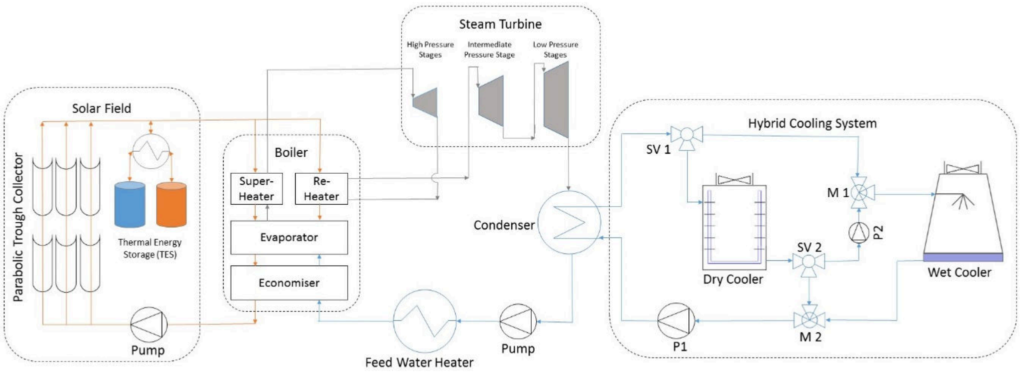

Figure 1. Simplified process flow diagram of a Concentrated Sola Power (CSP) plant with a hybrid cooling system.

The hybrid cooling system investigated in this paper consists of both a wet- and a dry-cooling tower in such a way that the cooling water mass flow rate that goes to each element can be split by control valves (split valves in Figure 1) in any ratio between 0 and 1; 0 being no flow whereas 1 corresponds to 100% flow. Thus, each cooling tower can work at full load, no load or part load. The pressure head losses are overcome by pumps. The hybrid cooler system can be operated in different operation modes: series, parallel or a combination of both, by adjusting the split valves (see Figure 1). It is important to note that the dry cooling system considered in this study is an indirect-dry cooler, ACHE, so the steam is firstly condensed through a conventional wet-cooled condenser (which is shared with the wet cooling tower) and then the water is cooled through the dry cooling tower.

In the series configuration, the cooling water flows firstly through the dry cooling tower by adjusting the split valve (SV1) where its temperature is reduced by rejecting the heat to air at the dry-bulb temperature. Then, the cooling water leaving the dry cooling tower is pumped to the wet cooling tower by adjusting the split valve (SV2) where it is sprayed and evaporation takes place to dissipate the heat of condensation. In this case, as the cooling water temperature is reduced in the dry cooling tower before entering the wet cooling tower, the evaporative water losses are minimised. However, as the whole cooling water circulates through both dry and wet cooling towers, the auxiliary energy consumption due to pumping is higher in this option. In the parallel configuration, the cooling water coming from the condenser is split into two streams by the split valve (SV1), with part of the flow diverted to the dry cooling tower and the remaining flow being sent to the wet cooling tower. Then, the cooling water stream coming out from the dry cooling tower is directed to the mixer (M2) by the split valve (SV2) where it is mixed with the cooling water stream leaving the wet cooling tower and finally sent back to the condenser by the pump (P1).

In the series-parallel configuration, the cooling water coming from the condenser is firstly sent to the dry cooling tower by the split valve (SV1) and then, one part of the cooling water leaving the dry cooler goes to mixer (M2) by the split valve (SV2) and the other part is pumped to the wet cooling tower by pump (P2) to further reduce the temperature through evaporation. The cooling water is then mixed with the outlet of the dry cooling tower in mixer (M2) and finally sent back to the condenser by the pump (P1). In the parallel-series configuration, part of the cooling water coming from the condenser is firstly sent to the dry cooling tower and the rest is sent to the wet cooling tower by the split valve (SV1). Then, the cooling water leaving the dry cooling tower is mixed with the part of the cooling water going to the wet cooling tower by split valve (SV2) being mixed in mixer (M1) before entering the wet cooling tower. Finally, the cooling water collected at the basin of the wet cooling tower is sent back to the condenser.

3. Model Development

The Thermoflex thermodynamic simulation tool was used for the model development. The model was used in design and off-design modes in order to determine the performance both at nominal and partial load conditions. For this purpose, heat and mass balances were firstly performed in a 'thermodynamic design' mode whereby the physical size and characteristics of the plant components were derived and estimated from its nominal operating point. Then, using the in-built mathematical models and other system modelling features, the performance of that system or its components were simulated at other operating conditions in an 'off-design' mode. Notice that the solar field was not modelled, but it was considered that 'Dowtherm A' thermal oil (as the Heat Transfer Fluid (HTF)) is delivered at the designed inlet temperature of 393 °C to the power block. It was also assumed that the HTF is split between the steam generator and the reheater in parallel at 90% and 10%, respectively, in all scenarios.

3.1. Model Assumptions

The following assumptions were considered in the simulations:

- Steady-state conditions.
- Wind speed is an important factor affecting the performance of dry and wet cooling towers. However, in this study the focus has been on the performance comparison of several hybrid cooling configurations and it has not been done for a particular site. Therefore, the effect of wind speed on the performance of the wet or dry cooling tower has not been considered.
- A 100% relative humidity has been assumed for the air leaving the wet section. Although the air leaving the wet cooling tower may not be saturated in some cases, this study follows the Merkel method [16], which assumes that the air leaving the tower is saturated (100% relative humidity). As this study is a comparative one on a like-for-like basis, it has been considered that this value will not have an impact on the conclusions.

In this study, the hybrid cooling configurations have not been optimised based on operating strategies i.e., the ambient conditions and/or economic benefits and annual performance analysis would be required to do so. Although economic benefit is one of the elements when considering a hybrid cooling system, it requires annual performance analysis which is crucial to better understand the trade-off between the cost and performance. Economic analyses are strictly dependent on the location and can vary in different scenarios. As this study has been focused on the comparative performance assessment of different hybrid cooling configurations and the analysis has been carried out for a range of ambient temperatures and relative humidities and not for a specific location or a Typical Meteorological Year data, the economic analysis would not give precise results. Therefore, the economic benefits have not been evaluated in this paper.

3.2. Power Block Model

The power block was modelled considering the Siemens SST-700 steam turbine used at the Andasol 1 CSP plant. The scheme of the power block model developed in Thermoflex simulation tool is shown in Figure 2 and described below. The steam turbine was modelled as seven stage blocks, with two high-pressure stage blocks before the reheater, then one intermediate-pressure and four low-pressure stage blocks. Steam is extracted from the turbine at each stage block to regenerate feed-water in three low-pressure closed feed-water heaters, one open feed-water heater/deaerator and two high pressure closed feed-water heaters. Steam pressure losses between each turbine extraction and its feed-water heater have been accounted for but it has been assumed that thermal losses are negligible. Governing equations behind the proposed cycle and water consumption calculations are shown in Supplementary Materials.

The off-design performance of the steam turbine is calculated using Stodola's ellipse law [17], which allows a turbine to be divided into stage groups between steam extraction points and treats each of these as a single nozzle [18]. Steam pressure, temperature, mass flow rate and the relationship between pressure ratio and enthalpy drop are used to determine the performance of a steam turbine at off-design conditions. The turbine isentropic efficiency (η_i), which is set at each turbine stage based on the steam conditions at the design point, is determined by the following equation.

$$\eta_i = \frac{actual\ stage\ enthalpy\ drop}{isentropic\ stage\ enthalpy\ drop} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{1}$$

where h_{in} and h_{out} are the specific enthalpy at the inlet and outlet, respectively and $h_{out,\,s}$ is the ideal specific enthalpy at the outlet.

On the other hand, the steam generator has been modelled using the standard Thermoflex heat exchanger components for each of the economiser, evaporator and super-heater stages. Similarly, the reheater has been modelled using a standard heat exchanger component block and incorporated in parallel to the entire steam generator. A fixed flow split of the HTF between the steam generator and the reheater has been adopted. Finally, the surface condenser has been modelled as a conventional shell and tube type. The performance of all heat exchangers in off-design conditions have been modelled using the "Thermal Resistance Scaling" method [19].

The principal parameters and input variables used for the model development in Thermoflex are shown in Table 1.

Table 1. Summary of main parameters and input variables used in Thermoflex to match 50 MW_e Andasol 1 CSP plant at base load.

Input Variables/Parameters		Value	Units
HTF outlet temperature from Solar field		393	°C
HTF mass flow		618.1	kg/s
HTF mass flow split to Reheater		10	%
Superheated steam temperature		381	°C
Superheated steam outlet pressure		105	bar(a)
Boiler pinch temperature		1.3	°C
Turbine gross output		55	MW_e
Turbine net output		50	MW_e
Fan power (Dry-cooling tower)		2500	kW_e
Fan power (Wet cooling tower)		500	kW_e
Cooling water pump power		630	kW_e
Condenser pressure		0.065	bar(a)
Feed-water Heater Terminal Temperature Difference		1.7	°C
Feed-water Heater Drain Cooler Approach temperature		5	°C
Cooling water mass flow rate		2502	kg/s
Indicated efficiency of turbine:	HP stage 1	80.59	%
	HP stage 2	89.02	%
	IP stage	76.57	%
	LP stage 1	87.97	%
	LP stage 2	90.66	%
	LP stage 3	92.57	%
	LP stage 4	89.44	%

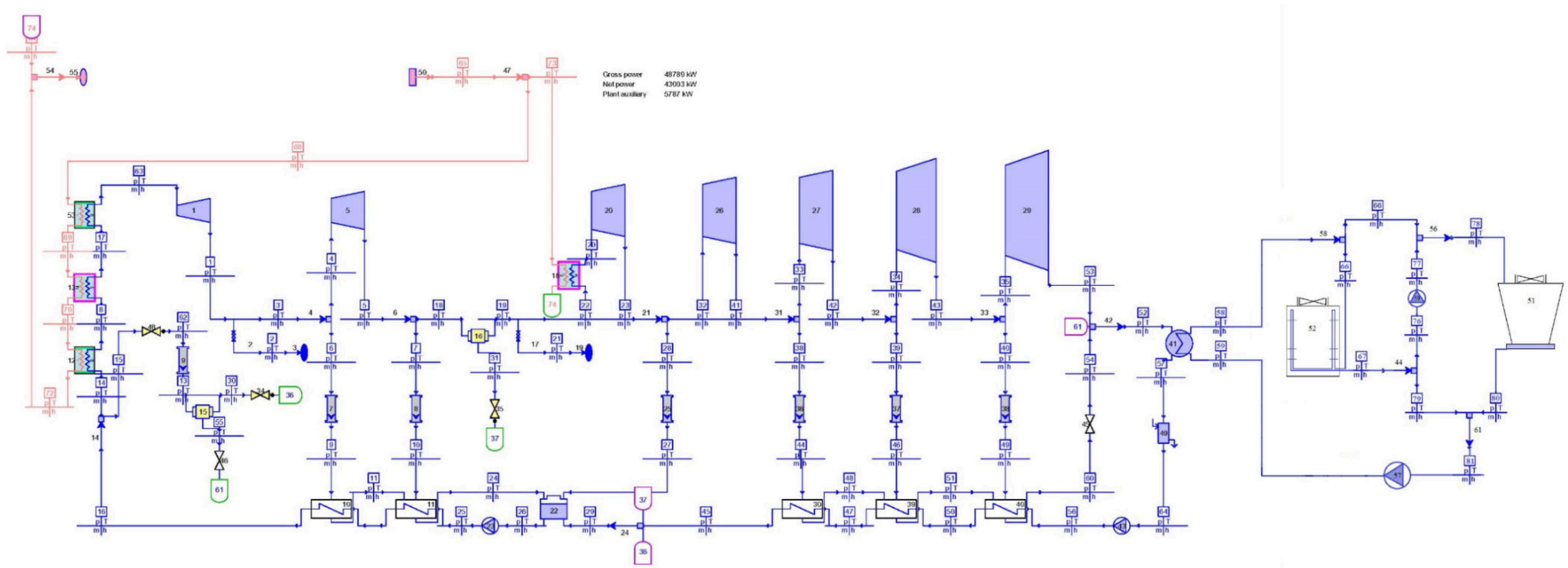

Figure 2. Thermoflex flowsheet of a 50MW$_e$ CSP plant with hybrid cooling system.

3.3. Cooling System Model

The hybrid cooling system has been integrated into the power block so that the impact of different cooling strategies on the power block performance can be directly assessed. In order to model the four configurations in Thermoflex, both the dry cooler and the wet cooler have been firstly modelled independently in the design mode at full-load Maximum Continuous Rating (MCR) (55 MW_e gross output, equating to a 50 MW_e net output at 100% MCR) at their respective design ambient conditions. After designing both coolers, they were then combined using splitters and mixers to achieve the different configurations (series, parallel, series-parallel and parallel-series). Two split valves (SV1 and SV2 in Figure 1) have been used to control the cooling water mass flow rate across each cooling tower. The position of such split valve (split ratio) can be adjusted in Thermoflex in such a way that any of the four hybrid cooling configurations are achievable. In addition, a cooling water circulating pump (P1) and an internal pump (P2) were used to overcome the pressure head losses across the system.

3.3.1. Dry Cooling Tower Model

An ACHE model has been developed in thermodynamic design mode considering that the full load of the total heat is rejected in the condenser. The design parameters of the ACHE are based on the design data provided by the French company Hamon D'Hondt, which are summarised in Table 2. The ACHE designed by Hamon D'Hondt consists of 22 bays, each bay having three fans. At the design point, the ACHE is able to dissipate 84 MW_{th} of heat for a 50 MW_e plant at full load whereas the fan power consumption is estimated to be 37.2 kW_e per fan.

Table 2. Design parameters used for the ACHE system.

Parameters	Value
Design point approach to dry-bulb ambient temperature	6.75 °C
Design point ambient dry-bulb temperature rise in dry section	8.25 °C
Air temperature at design point	20 °C
Fan efficiency	75%
Fan static efficiency	59%
Volumetric air flow rate	151.08 m^3/s
Pressure drops on air side	146.8 Pa
Pressure drops on water side	57.23 kPa
Height of the cooling tower	9 m
Cooling water inlet temperature	35 °C

3.3.2. Wet Cooling Tower Model

As in the case of the dry cooler, the wet cooling tower has been designed in thermodynamic design mode to dissipate the full load of the heat rejected in the condenser. The design parameters of the wet cooling tower have been based on the design data available in the literature [20], summarised in Table 3. At the design point, the wet cooling tower is able to dissipate 84 MW_{th} of heat for a 50 MW_e plant at full load whereas the total fan power consumption is estimated to be 500 kW_e. Thermoflex uses a constant value of outlet air relative humidity in its calculations for cooling tower performance. In this study, a value of 100% relative humidity for the air leaving the wet cooling tower has been considered, equivalent to the Merkel method [16].

Table 3. Design parameters considered for the wet cooling tower.

Parameters	Value
Pressure of the thermodynamic environment	1 bar
Wet bulb temperature of ambient air	20 °C
Relative humidity of ambient air	60%
Cooling tower approach temperature	5 °C
Cooling tower range	10 °C
Air relative humidity leaving the wet section	100%
Concentration factor	3
Fan efficiency	75%
Cooling water inlet temperature	35 °C
Design point air draft loss	1.25 mbar
Height of the cooling tower	9 m

4. Validation Approach

The power block model of the CSP plant has been validated against the 50 MW_e Andasol 1 power block flowsheets at both design and off-design conditions reported in Dias de la Fuente [21]. Notice that these flowsheets do not include a cooling system but indicate the cooling water temperatures at the inlet and outlet of the condenser at several operating conditions (100%, 90%, 75%, 50% and 25% MCR). For the validation of the thermodynamic model at design conditions, the ambient temperature and humidity were not taken into account and the temperature at the inlet of the condenser and the cooling water mass flow rate were established at 27 °C and 2502 kg/s, respectively. Table 4 shows the results from the comparison for the variables: temperatures, pressures, mass flow rates and specific enthalpies of the main streams. Moreover, the heat duties of boiler, reheater and condenser and the gross power generated by the steam turbine have been also compared. As can be seen, the simulation results are in good agreement with the Siemens flowsheet data with a mean absolute percentage error of below 0.52% (see Table 5).

Table 4. Comparison of simulation results with Siemens data [21].

	SIEMENS Andasol 1 Flowsheet				Thermoflex Model			
Stream/Variable	**T (○C)**	**P (bar)**	**h (kJ/kg)**	**$\dot{m}$ (kg/s)**	**T (○C)**	**P (bar)**	**h (kJ/kg)**	**$\dot{m}$ (kg/s)**
Inlet of HP steam turbine	381.0	104.98	3020.2	60.935	381.0	105.0	3023.6	60.767
Outlet of HP steam turbine	214.2	20.72	2728.1	54.880	214.1	20.68	2729.8	54.749
Inlet of LP steam turbine	380.0	18.29	3207.2	49.905	380.0	18.23	3207.4	49.962
Outlet of LP steam turbine	38.0	0.065	2305.9	38.902	38.1	0.067	2313.2	38.727
Outlet of condenser	38.0	0.065	159.3	47.805	38.1	0.067	159.4	47.943
Discharge of LP feed-water pump	39.2	13.00	165.3	47.805	39.6	13.00	167.2	47.943
Outlet of LP feed-water heater 1	73.9	13.00	310.6	47.805	74.1	13.00	311.4	47.943
Outlet of LP feed-water heater 2	104.7	13.00	439.7	47.805	104.9	13.00	440.9	47.943
Outlet of LP feed-water heater 3	144.7	13.00	609.7	47.805	144.9	13.00	610.6	47.943
Outlet of deaerator	180.1	10.04	763.5	61.550	180.1	10.05	763.6	61.381
Discharge of HP feed-water pump	182.5	129.00	780.8	61.550	184.4	129.0	788.6	61.381
Outlet of HP feed-water heater 4	210.9	129.00	905.5	61.550	211.0	129.0	906.5	61.381
Outlet of HP feed-water heater 5	250.4	129.00	1087.5	61.550	250.5	129.0	1088.5	61.381
Cooling water at condenser inlet	27.0			2502	27.0			2495
Cooling water at condenser outlet	35.0			2502	35.0			2495
Boiler heat duty (kW_t)		118,958				118,780		
Reheater heat duty (kW_t)		21,479				21,423		
Condenser heat duty (kW_t)		83,597				83,832		
Gross power (kW_e)		55,000				54,999		

Table 5. Mean absolute percentage errors.

Parameter	Mean Absolute Percentage Error
Temperature	0.26%
Pressure	0.52%
Enthalpy	0.28%
Mass flow rate	0.28%
Boiler heat duty	0.15%
Reheater heat duty	0.26%
Condenser heat duty	0.28%
Gross power	0.00%

For the validation of the power block model at off-design operating conditions, the operation of the plant at 90%, 75%, 50% and 25% of MCR (which corresponds to a variation in the HTF mass flow rate from 61.8 to 618.1 kg/s) was considered. Differences in power output and heat rate (which is the amount of thermal energy required to produce one kilowatt hour of electricity) between the Siemens flowsheets data [21] and Thermoflex model at off-design conditions are shown in Table 6. It can be observed that the Mean Absolute Percentage Error (MAPE) in the gross power generation and heat rate was 0.5% and 1.1%, respectively, proving the accuracy of the model.

Table 6. Comparison of gross power generation and heat rate in the off-design mode.

Nominal %MCR	Gross Power Generation (MW_e)			Heat Rate (kJ/kWh)		
	Siemens Data	Thermoflex Model	Error (%)	Siemens Data	Thermoflex Model	Error (%)
100	55	55	0.0	9114	9099	0.2
90	50	49.54	0.9	9210	9150	0.6
75	41.25	41.21	0.1	9320	9265	0.6
50	27.50	27.41	0.3	9666	9576	0.9
25	13.75	13.58	1.2	10,741	10,413	3.1
MAPE (%)		0.5			1.1	

5. Results and Discussions

As mentioned before, a sensitivity analysis was performed to investigate the effect of relative humidity, the ambient temperature, and the split ratio on the performance of the hybrid cooling system on the basis of the water consumption and net power generated by the power block for all hybridisation configurations (series, parallel, series-parallel, parallel-series). Moreover, the specific water consumption (m^3/MWh), which is the water consumption per unit power generation, has been considered as the performance indicator for the hybrid cooling system performance at different ambient temperatures and split ratios. Notice that the split ratio is the wet fraction in the case of parallel and series-parallel configurations and the dry fraction in the case of parallel-series configuration.

The sensitivity study was performed firstly taking into account cooling towers with 100% cooling capacity and then varying this cooling capacity to evaluate its impact on the performance indicator at variable ambient conditions.

5.1. Effect of Relative Humidity

The first study was performed by varying the relative humidity between 10% and 90% while keeping all the input variables and other parameters constant at the wet cooling tower design point conditions (see Table 3). In addition, for all the hybrid cooler configurations a split ratio of 50% was considered. The specific water consumption was determined in all cases and the results are shown in Figure 3. A linear decrease in the specific water consumption has been observed when the relative humidity is varied from 10% to 90%. This is because the ability of the wet cooling tower is limited by the relative humidity to evaporate more water. At higher relative humidity, the air saturation conditions are achieved quickly and no further evaporation can take place and hence water consumption is lower. This reduces the overall water consumption but at the expense of a slightly higher cooling water return temperature, which consequently causes a higher pressure in the condenser of the power block and thus a lower power generation. It can also be seen that the specific water consumption is higher in the case of the only-wet cooling tower when compared with the hybrid cooling configurations since wet cooling towers are based on the wet bulb temperature due to its evaporative principle whereas dry cooling towers are based on the ambient dry-bulb temperature. Moreover, the percentage decrease in the specific water consumption is higher in the case of parallel and series-parallel hybrid cooling configurations because of the lower wet cooling fraction in hybrid mode. In other words, although the wet cooling tower is designed for 100% capacity, a 50% split ratio in the case of parallel and series-parallel hybrid cooling systems means that only 50% of the cooling water flows through the wet cooling tower. Moreover, it can be noticed that the specific water consumption by only-wet cooling tower and hybrid cooling systems vary linearly when the relative humidity increases from 10% to 90%, at a certain operating condition.

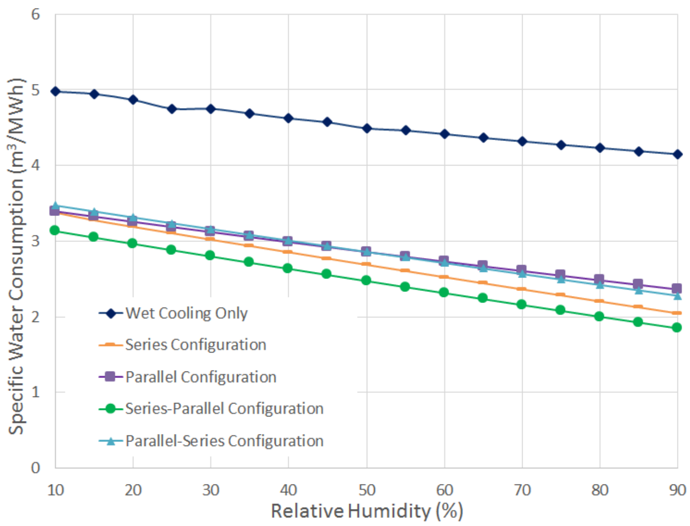

Figure 3. Effect of relative humidity on the specific water consumption.

5.2. *Effect of Ambient Temperature and Split Ratio*

In this section, the performance of hybrid cooling systems is investigated for a range of ambient temperatures and split ratios of 25%, 50% and 75%. It is worth noting that based on the Andasol 1 site location, an average relative humidity of 60% has been considered as an input in this sensitivity study.

Figure 4 shows the effect of ambient temperature on the cooling water temperature at the exit of the hybrid cooler (cooling water return temperature). A 50% split ratio is considered in all hybrid cooling configurations where applicable. These results show that a lower temperature is achieved in the case of series and parallel-series configurations compared to only-wet cooling and the other hybrid cooling configurations. The lower cooling water return temperature in the case of series and parallel-series configurations is because of a higher wet fraction (100%) and due to the fact that the dry cooling tower dissipates part of the cooling water heat before entering the wet cooling tower. The lower cooling water return temperature lowers the saturation pressure in the condenser and consequently a high pressure ratio is achieved in the steam turbine leading to greater power generation. However, at higher ambient temperatures, the performance of the dry coolers is poor, which leads to an insignificant change in the temperature at the inlet of the wet cooling tower and hence the performance of the only-wet cooling tower is almost similar to that of the series and parallel-series hybrid cooling configurations. The impact of the cooling water return temperature on the actual power produced is analysed and shown in Figure 5. It was found that the net power exhibits an almost steady decrease with the increase in the cooling water return temperature. It can be seen that the power output decreases roughly by 3% for every 5 °C temperature rise.

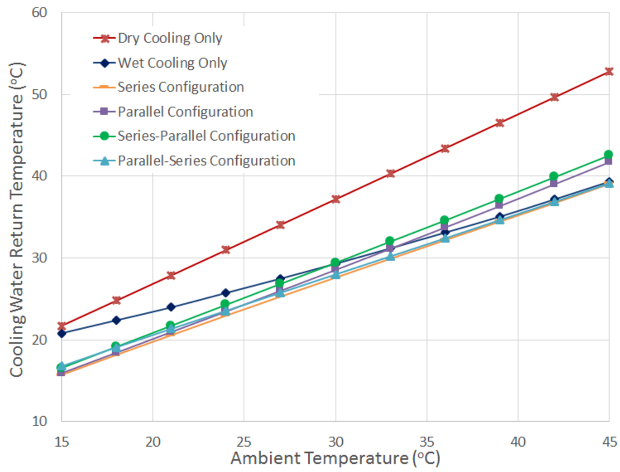

Figure 4. Effect of ambient temperature on the cooling water return temperature.

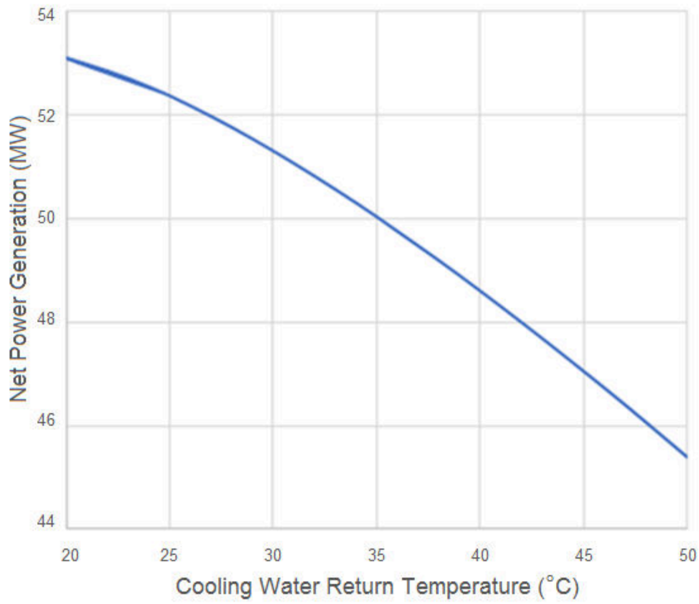

Figure 5. Effect of the cooling water return temperature on the power output.

Table 7 summarises the effect of the ambient temperature and split ratio on the cooling water return temperature, net power generation and water consumption. It can be observed that the cooling water return temperature is lower when the wet fraction is high. This is because, as commented before, the wet bulb temperature is lower than the dry-bulb temperature, which allows higher heat dissipation through the wet cooling tower and hence a lower cooling water return temperature is obtained. In the case of a parallel-series configuration, a slightly higher cooling water return temperature was found when the split ratio was varied from 25% to 75%. This is due to the fact that a higher split fraction leads to a higher dry fraction and therefore the cooling water leaving the dry cooling tower and entering the wet cooling tower will be at a lower temperature, minimising the evaporation in the wet cooling tower.

In the case of the parallel configuration, it was observed that at lower ambient temperatures (below the wet cooling tower design point temperature, see Table 3) the cooling water return temperature decreases when the split ratio is increased up to 50% whereas it increases at split ratios over 50%. This is because the wet and dry cooling towers are designed to take the full load of heat rejected at the condenser. When the split ratio is increased from 25% to 50%, the cooling water return temperature decreases because of a higher wet fraction and due to the fact that the cooling tower is oversized for the 50% coolant flow. However, at higher split ratios less heat transfer area is available compared to the case of 50% flow, which leads to a higher cooling water temperature although the wet fraction is higher.

As expected, it was found that a maximum net power is generated in the case of only-wet cooling system whereas a minimum net power generation is observed in the case of only-dry cooling system. In the hybrid cooling system, higher net power generation was obtained when the wet cooling fraction was increased which allows a lower cooling water return temperature. It is important to highlight that the lowest cooling water return temperature was found in the case of a series configuration. However, in this case, the net power generation was lower compared to only-wet cooling due to the high parasitic load caused by the fans of the dry and wet cooling towers. Notice that the fan power consumption resulting from the simulations in the case of dry cooling system was approximately 5% of the total power generation. Moreover, it has been observed that the performance of the only-dry cooling tower is better at lower ambient temperatures and higher net power generations are obtained compared to the hybrid cooling systems. This is because in the case of a hybrid cooling system, the operation of the wet cooling tower and additional pump (P2 in Figure 1) increases the parasitic load and hence a lower net power is generated at lower ambient temperatures compared to only-dry cooling system. Regarding the water consumption, as expected, this was the highest in the case of only-wet cooling. Additionally, in the case of hybrid cooling systems, water consumption increased when the wet fraction was higher. Moreover, it can be observed that at a given relative humidity, the water consumption increased when the ambient dry-bulb temperature increased in all cases studied. In the case of series-parallel configuration, the water consumption was the lowest of all hybrid configurations. However, this was at the expense of a decrease in net power generation. This reduction in water consumption is due to a lower cooling water temperature at the inlet of the wet cooling tower caused by a pre-cooling effect through the dry cooling tower, which reduces the evaporation losses in the wet cooling tower. It is worth noting that this effect is more visible in the case of a 100% series configuration compared to only-wet cooling system. This gap decreases when the ambient temperature increases due to the fact that the efficiency of the dry cooler drops at higher temperature. Consequently the temperature of the cooling water is higher at the inlet of wet cooler.

Figure 6 shows the trends of the specific water consumption at variable ambient temperatures and split ratios of 25%, 50% and 75%. It can be seen that amongst all the hybrid configurations, the minimum specific water consumption was observed in the case of series-parallel configuration. Specific water consumption as low as 1.21 m^3/MWh, corresponding to a split ratio of 25% and ambient temperature of 12 °C was found in the case of series-parallel configuration. Moreover, it can be noticed that the specific water consumption increases with the increase in ambient temperature and wet fraction. The highest specific water consumption was obtained in the case of only-wet cooling system with 5.71 m^3/MWh water consumption corresponding to the ambient temperature of 45 °C. However, the percentage increase in the specific water consumption was less in the case of only-wet cooling system compared to the hybrid cooling system. This is because both cooling towers are designed for 100% load, being oversized in the hybrid mode, which allows a higher evaporation. In the case of the hybrid cooling configuration, the specific water consumption increased at higher ambient temperatures due to the poor performance of the dry cooler that supply cooling water to the wet cooling tower at a higher temperature which allows higher evaporation rate and consequently higher water consumption. Specific water consumption increased by a factor of 1.5 in the case of wet cooling tower when the ambient temperature was increased from 15 to 45 °C, whereas in the case of hybrid cooling systems with a 50% split ratio, the specific water consumption increased by a factor of 2.2, 2.5 and 2.6 in the case of parallel, parallel-series and series-parallel configurations, respectively.

Table 7. Effect of ambient temperature and split ratio on the cooling water return temperature, net power generation and cooling tower water consumption.

	$T_{ambient}$ ($\circ$C)	Dry Only	Series-parallel Configuration (Split Ratio)			Parallel-series Configuration (Split Ratio)			Parallel Configuration (Split Ratio)			Series Configuration	Wet Only
			25%	50%	75%	25%	50%	75%	25%	50%	75%		
Cooling Water Return Temperature (°C)	15	21.72	17.86	16.56	16.02	16.12	16.77	18.23	16.75	15.92	17.01	15.72	20.81
	21	27.88	23.47	21.72	20.99	20.83	21.34	22.33	22.34	20.95	21.44	20.57	23.97
	27	34.08	29.14	26.85	25.86	25.48	25.78	26.41	28.0	26.0	25.96	25.30	27.49
	33	40.30	34.87	32.01	30.66	30.02	30.21	30.55	33.72	31.13	30.55	29.91	31.19
	39	46.55	40.66	37.24	35.49	34.53	34.65	34.83	39.51	36.36	35.23	34.46	35.07
	45	52.81	46.51	42.57	40.35	39.10	39.14	39.23	45.35	41.73	40.08	39.08	39.35
Net Power Generation (MW_e)	15	50.10	49.62	49.67	49.65	49.64	49.64	49.56	49.95	50.01	49.91	49.62	52.22
	21	49.24	49.14	49.29	49.30	49.31	49.31	49.25	49.52	49.66	49.60	49.29	51.87
	27	47.91	48.24	48.63	48.74	48.79	48.80	48.73	48.72	49.07	49.06	48.77	51.31
	33	46.29	46.97	47.61	47.85	47.99	47.99	47.97	47.51	48.10	48.23	47.96	50.54
	39	44.46	45.46	46.34	46.75	46.99	47.01	47.01	46.03	46.87	47.17	46.95	49.61
	45	42.47	43.76	44.90	45.48	45.83	45.87	45.90	44.37	45.44	45.91	45.79	48.46
Water Consumption (kg/s)	15	0	18.78	22.74	24.45	26.88	30.18	37.40	24.88	31.87	39.03	25.41	54.18
	21	0	22.84	28.58	31.11	34.28	37.32	44.38	29.37	38.04	45.59	32.59	59.21
	27	0	26.92	34.84	38.43	42.15	45.23	51.63	33.74	44.25	52.04	40.54	63.82
	33	0	30.83	41.23	46.3	50.64	53.31	58.81	37.91	50.39	58.49	49.2	68.38
	39	0	34.55	47.55	54.28	59.55	61.49	65.66	41.92	56.38	64.8	58.43	72.84
	45	0	38.08	53.50	62.36	68.21	69.67	72.45	45.66	61.77	70.76	67.41	76.90

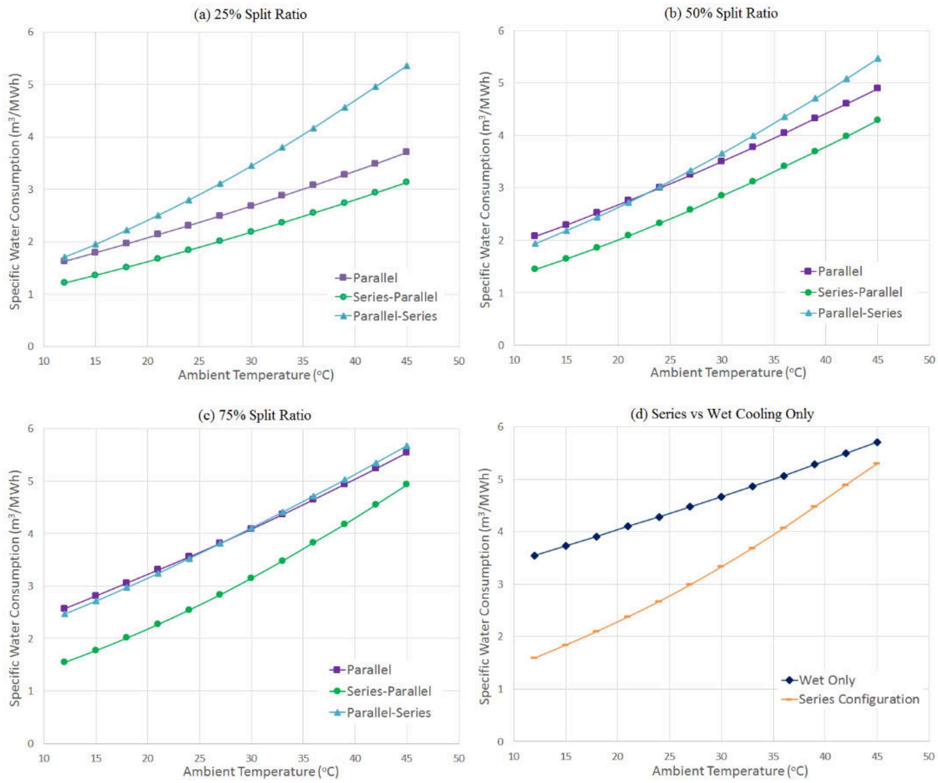

Figure 6. Effect of ambient temperature on the specific water consumption.

5.3. Effect of the Cooling Tower Capacity

In this section, the effect of the cooling tower capacity on the specific water consumption is shown. A hybrid cooling system with variable design capacity of both cooling towers was considered. Based on the results obtained in Section 5.2, the parallel and series-parallel configurations have been selected for this analysis as they have already shown to have the lowest specific water consumption of all the configurations examined.

In the case of the series-parallel configuration, a dry cooling tower with a design capacity of 100% of the total heat rejection load was considered whereas the design cooling capacity of the wet cooling tower was varied in line with the split ratio. For instance, in the case of 25% split ratio, the wet cooling tower is designed with a cooling capacity of 25% of the total power plant cooling load whereas the dry cooling tower would have a designed cooling capacity of 100% of the total power plant cooling load. The results were compared to the base case in which the hybrid cooling system was designed with a 100% cooling capacity dry and 100% cooling capacity wet cooling towers. As expected, a slightly higher power was generated in the case of a hybrid cooling system with each cooling tower designed for 100% cooling capacity. This is because more heat can be dissipated in the cooling towers because of the higher heat transfer area. However, the higher evaporation taking place in the wet cooling tower leads to a higher water consumption which increases the total water consumed per unit of electricity generated. For instance, at an ambient temperature of 30 °C and a split ratio of 50%, the net power generated for the base case was 48.16 MW_e compared to 48.00 MW_e in the case of hybrid system with reduced capacity cooling tower whereas the water consumption was 38.16 m^3 and 26.35 m^3, respectively. Figure 7 shows the specific water consumption of this hybrid cooling configuration at different ambient temperatures. It can be seen that the specific water consumption was higher in the case of the hybrid cooling system with 100% cooling capacity in both cooling towers. For instance, at an ambient temperature of 30 °C, the specific water consumption decreased approximately by 50%, 30% and 15% in the case of 25%, 50% and 75% cooling capacity for the wet cooling tower, respectively, compared to 100% cooling capacities towers.

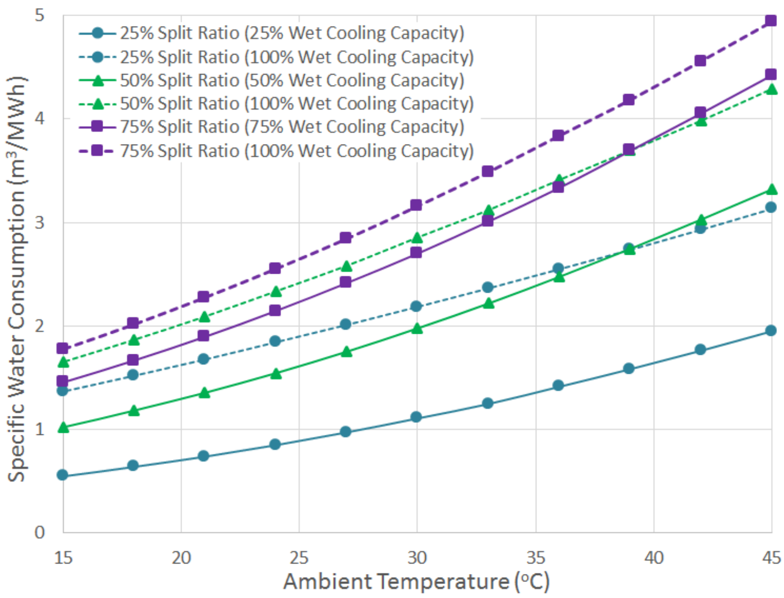

Figure 7. Effect of cooling tower capacities on the specific water consumption at different ambient temperatures (series-parallel configuration).

In the case of the parallel configuration, the cooling capacities of the wet and dry cooling towers were varied in line with the split ratio and the results were compared to a hybrid cooler with 100% cooling capacity in both cooling towers (base case). For instance, in the case of 25% split ratio, the wet cooling tower is designed with a cooling capacity of 25% of the total power plant cooling load whereas the dry cooling tower would have a designed cooling capacity of 75% of the total power plant cooling load. In the case of a hybrid cooling system with the cooling tower designed at reduced capacity, a slightly higher power can be generated by the CSP plant because of the lower parasitic losses due to a lower number of fans operating in both cooling towers. Interestingly, the impact of the cooling tower capacity is higher on the water consumption than on power generation. For instance, at an ambient temperature of 30 °C and a split ratio of 50%, the net power generated for the base case was 48.63 MW_e compared to 49.22 MW_e in the case of a hybrid system with reduced capacity cooling tower whereas the water consumption changed from 47.38 m^3 to 41.96 m^3. Figure 8 shows the effect of the ambient temperature on the specific water consumption for the parallel hybrid cooling system with reduced cooling capacity cooling towers. It can be observed that the specific water consumption was lower in the case of a hybrid cooling system where the wet cooling capacity is reduced in line with the split ratio rather than for a wet cooling capacity of 100%. This is because less water is evaporated in the wet cooling tower due to the lower cooling capacity. For instance, at a temperature of 30 °C, the specific water consumption decreased approximately by 35%, 13% and 2.5% for the hybrid cooling system with 25%, 50% and 75% cooling capacity for the wet cooling tower, respectively, compared to a hybrid cooling system with 100% cooling capacity in both cooling towers.

It is worth noting that in any hybrid cooling system, a reduction in the wet cooling capacity can make a significant reduction in water consumption with only a small impact on the power generation. For instance, in the case of the series-parallel hybrid system with a wet cooling tower with 50% cooling capacity, the decrease in the power generation is only 0.7% whereas a reduction of 40% in the water consumption is possible when compared to a series-parallel hybrid system with each cooling tower designed for 100% cooling capacity.

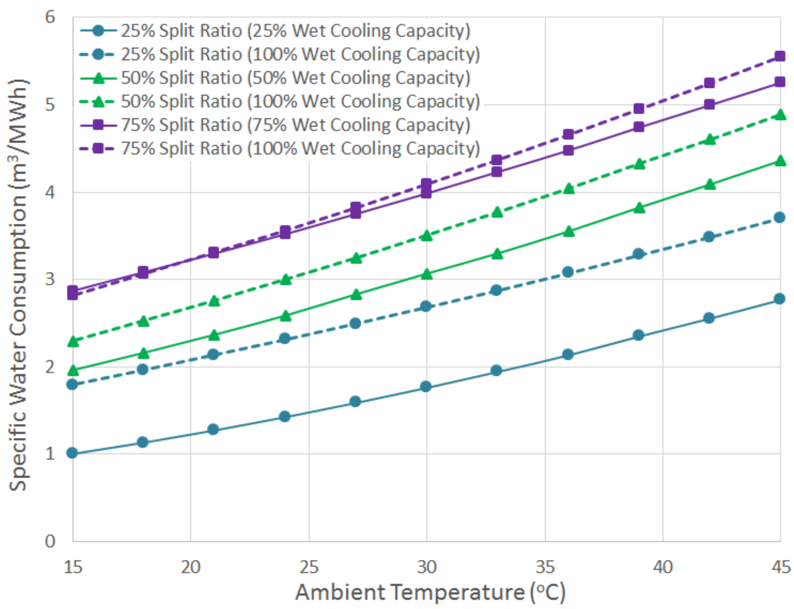

Figure 8. Effect of cooling tower capacities on the specific water consumption at different ambient temperatures (parallel configuration).

6. Conclusions

In this study, a hybrid cooling system has been integrated into a 50 MW_e power block (with the same configuration as the CSP plant Andasol-1) and has been modelled using the Thermoflex simulation tool to assess its performance in different configurations under different operating conditions. The evaluation has taken the water consumption per unit power generated as the performance indicator. The main conclusions obtained from the evaluation are detailed below:

- The most favourable configuration in terms of water consumption is the series-parallel configuration in which a water reduction up to 62% is possible compared to the only-wet cooling option at an ambient temperature of 40 °C, whereas an increase of 2.5% in the power generation is obtained compared to only-dry cooling system.
- The parallel configuration has shown better performance in terms of power generation. An increase of 3.2% in power generation is obtained when compared with only-dry cooling option with a reduction of 30% water consumption compared to only-wet cooling option.
- A 40% of reduction in water consumption can be achievable with a power generation penalty of only 0.7% in the case of a hybrid system with wet cooling tower with a 50% cooling capacity when compared to a hybrid system with a wet cooling tower with a 100% cooling capacity.

Further Developments and Economic Consideration

It is important to highlight that all the theoretical analyses must be validated by tests in either pilot or demonstration plants to push the industry towards the use of this technology. Currently, there are no CSP plants that integrate this cooling technology, but Plataforma Solar de Almería has recently installed a test bench facility to evaluate the efficiency and water consumption of a hybrid cooler composed of a wet cooling tower and an Air-Cooled Heat Exchanger that can be operated at different configurations. This test facility can be used to complete the annual simulations that would allow us to complement the theoretical results to obtain more accurate conclusions.

Despite the fact that the CAPEX of a hybrid cooling system is higher compared to a conventional wet or dry cooling system, the higher power generation compared to only-dry cooling system and the lower water consumption compared to only-wet cooling system would provide an economic benefit depending on the electricity and water prices and the location. This work can be very useful for further studies in terms of the best configuration based on the operating strategies. Annual performance analysis of a hybrid cooling system integrated into a CSP plant could not only provide a better understanding of water consumption but will also allow an economic evaluation of the system.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/11/4739/s1.

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Abbreviation

ACC	Air-Cooled Condenser
ACHE	Air-Cooled Heat Exchanger
CAPEX	Capital Expenditure
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
HTF	Heat Transfer Fluid
HP	High Pressure
IP	Intermediate Pressure
LP	Low Pressure
LCOE	Levelized Cost Of Electricity
MAPE	Mean Absolute Percentage Error
MCR	Maximum Continuous Rating
PT	Parabolic Trough
ST	Solar Tower
SV	Split Valve
WASCOP	Water Saving for Concentrated Solar Power

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