A simple equation for estimating hourly water consumption in CSP plants

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***Abstract*— Unlike conventional thermal power plants which are generally erected in the coastal regions near water bodies, seas and oceans, where water resource availability is not a critical factor, concentrating solar power (CSP) plants are usually installed in high sunny zones which generally characterized by semi-arid and arid climates, where water resources are hard to find and/or to employ. On the other side, the hourly simulations of water consumption in CSP plants are very complex and require many calculations, data analysis and time consuming. Therefore, the aim of this paper is to develop a simple equation to estimate the hourly water consumption of a solar tower plant based on its generated power, and the existing power plant Gemasolar has been chosen to establish the methodology. The obtained results of the statistical analysis show that the cubic model based on the generated power, can be used as a simple and general model to predict hourly water consumption in a large scale solar tower power plant.**

Keywords— Correlation, Gemasolar, statistical analysis, water consumption.

I. Introduction

Unlike conventional power plants which are generally erected in the coastal regions near water bodies, seas and oceans, where water resource availability is not a critical factor, concentrating solar power (CSP) plants are usually installed in high sunny zones which are generally characterized by semi-arid and arid climates, where water resources are hard to find and/or to employ. Therefore, more intensive works should be performed to explore the techno-economic competitiveness of cooling systems in this type of thermal power plants. In order to fill the gap of such kind of works, several studies have been performed to study the techno-economic behavior of cooling systems integrated to CSP plants from a side, and decrease the water use from the other side. For example, Colmenar-Santos et al [1] taking in consideration that water is a key parameter in sustainable development of concentrating solar power plants, they assessed water consumption in different cooling options (wet, dry and hybrid) of a parabolic trough solar thermal power plant (PTSTPP). This will help researchers in Spain, to identify the most appropriate locations for installation of this kind of plants. While Ben Fares and his colleague [2] presented a numerical study based on System Advisor Model (SAM) software package, to estimate both water consumption of an existing PTSTPP (Noor 1), the considered plant is operating in Morroco. Furthermore, they compared the simulated data with real industrial data, and reported some recommendations to reduce water use in the investigated plant. Additionally, Liqreina and Qoaider [3] evaluated the techno-economic performances of a typical Andasol (PTSTPP) with a dry cooling technology in the power block instead of wet one. At first, they simulated the considered plant in its original site (Granada, South of Spain). Then, the simulations were performed in another location (Ma'an, Jordan). Their main results show the possibility of saving about 92 % of water consumption used in these kind of plants by using dry cooling mode. In addition to the type of the primary heat transfer fluid in the solar field, Yilmazoglu [4] studied the effects of cooling mode in a parabolic trough solar thermal power plant on its performances including generated power, plant efficiency, in addition to investment cost and levelized cost of electricity (LCOE). Another study reported by Poullikkas et al [5], where they performed a parametric optimization of 17 different configurations of modular air cooled condenser with 8 different condenser sizes for each configuration, to find the optimum size to be integrated in a dry cooling system of a PTSTPP. While Deng and Boehm [6] presented a study to estimate and improve the yearly performances of a generic trough power plant installed in Las Vegas (USA), working with the two cooling options (wet and dry). Furthermore, the typical condenser temperature was also reported. Moreover, a hybrid life cycle assessment (LCA) of a PTSTPP (with both cooling technologies) installed in Daggett has been presented by Burkhardt [7], this LCA includes four sustainability metrics: cumulative energy demand, energy payback time, gas emissions, and water usage. However, according to our knowledge concluded from the literature, despite the amount of works reported the modelling of CSP cooling system, no study has been found that present any correlations to estimate water consumption in this kind of plants. As the hourly simulations of water consumption in CSP plants are very complex and require many calculations, data analysis and time consuming. Thus, this study gives for researchers and engineers an excellent and a simple approach to estimate water usage in CSP plants, and takes the existing plant (Gemasolar) as a case study

II. Data And Methodology

A. Chosen site for the simulation

In the present study, Bechar (latitude 31.38' N, longitude 2.15'W, altitude 806 m) has been chosen, it is located in the southwest of Algeria (Figure 1), and it is characterized by its high average direct normal irradiance (about 7.04 kWh/m2/day), which is a favorable factor for installation of CSP systems.

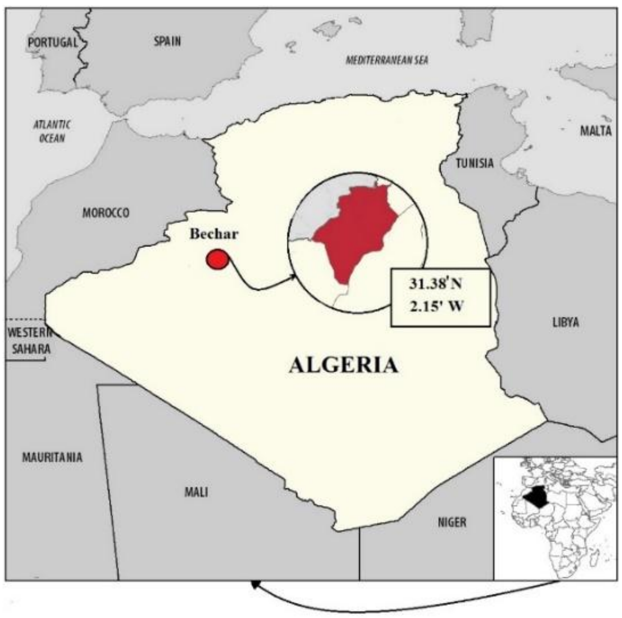

Fig. 1. Considered site for the simulations.

B. Investigated plant

A reference solar tower power plant working with molten salt as the primary heat transfer fluid in the solar field was selected. It represents a STPP with an incorporated fuel backup system (FBS) and thermal storage system (TSS) to enhance the dispatch capacity of the plant as presented in Figure 2. This layout is similar to the configuration in Gemasolar plant with a total capacity of 19.9 MW, located in Andalucia (Spain), which is the first commercial-scale power plant of its type.

The solar field consists of hundreds to thousands arrays of tracking mirrors called heliostats, they focus solar radiation onto a receiver installed on the top of a tower. As the heliostats field is the main and the most important subsection in CSP plants, and represents about 38–45% of the total power plant cost [8], heliostats must be positioned in such a way that there is minimum optical losses between them and the solar receiver. Again, in this study, a solar field design such that of Gemasolar power plant has been chosen to perform the study. The use of molten nitrate salt (60% $NaNO_3$+ 40% KNO_3) as a working heat transfer fluid both in the solar field and thermal storage system was successfully demonstrated in Gemasolar plant. At design point, the considered plant is working with a temperature range of 290-565 °C.

The power block is using a superheated steam Rankine cycle technology as most conventional thermal power plants. However, unlike these last plants, the operating conditions of CSP (such as generated power, energy fluxes and mass flow rates, working pressures and temperatures) are highly dependent on solar resource availability, and ambient conditions. Therefore, the power cycle model should include off-design simulation to avoid miscalculations of power plant performances, and maintain a high level of accuracy in prediction [9]. The mathematical modelling of this plant was developed within System Advisor Model (SAM), version 2017.9.5. While the main inputs of the investigated configuration (Gemasolar plant) are summarized in Table 1.

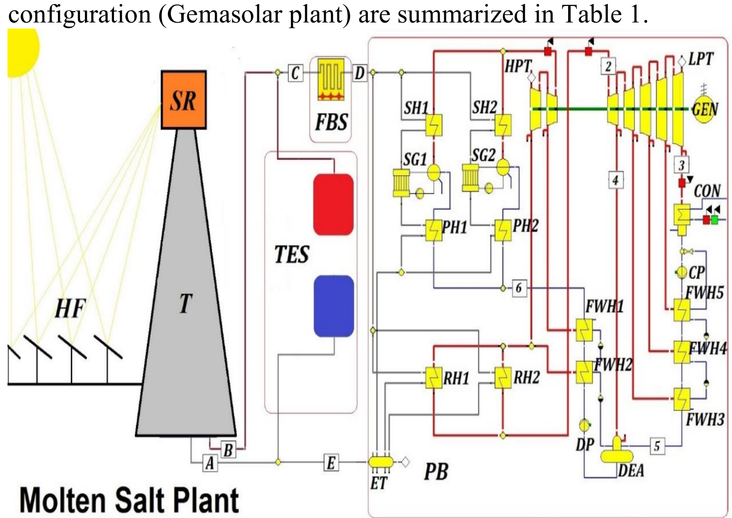

Fig. 2. The schema of the studied plant (Gemasolar).

TABLE I. THE MAIN INPUTS OF THE PLANT [10-13].

Subsystem	Parameter	Value
Solar field	Working fluid [-]	(60% $NaNO_3$+ 40% KNO_3)
	Inlet temperature [°C]*	290
	Outlet temperature [°C]*	565
Heliostat field	Heliostat surface area [m^2]	305,401
	Number of heliostats [-]	2650
	Heliostat stow deploy angle [°]	8
Tower and receiver	Tower height [m]	140
	Type of the receiver [-]	External receiver
	Receiver height [m]	14.22
	Receiver diameter [m]	8.89
	Number of panels [-]	16
	Tube outer diameter [mm]	40
	Tube wall thickness [mm]	1.25
	Coating emittance/ absorptance [-]	0.88/0.94
Power block	Design turbine gross output [MW]	19.9
	Thermodynamic cycle efficiency [%]	41.20
FBS	Fossil fuel fill fraction [-]	0.5
	FBS boiler efficiency [%]	90
TSS	Storage type [-]	Two tank salt
	Full load hours [hours]	15
	Tank diameter [m]	14.87
	Tank height [m]	20

C. Regression analysis

In order to predict the hourly water consumption of the considered solar tower power plant in a simple way and without passing through detailed modelling and yearly round simulations, three curve fit models (linear, quadratic, and cubic) were used to correlate the hourly water consumption curves with the hourly values of the generated power (Figure 3). The performances of the three established correlations were explored using four different statistical parameters, namely, root mean square error (RMSE), mean percent error (MPE), coefficient of variation (COV) and the coefficient of determination (R^2). These parameters were formulated in terms of output value (y_{output}), target value (y_{actual}), average of target ($\bar{y}_{actual}$) and pattern (n):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_{output} - y_{actual}\right)^2}$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_{output} - y_{actual}}{y_{output}}\right)$$

$$COV = \frac{\sum_{i=1}^{n}\left(y_{output} - \bar{y}_{output}\right)\left(y_{actual} - \bar{y}_{actual}\right)}{n} \times 100$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(y_{output} - \bar{y}_{output}\right)\left(y_{actual} - \bar{y}_{actual}\right)}{\sqrt{\sum_{i=1}^{n}\left(y_{output} - \bar{y}_{output}\right)^2 \sum_{i=1}^{n}\left(y_{actual} - \bar{y}_{actual}\right)^2}}\right]^2$$

III. Results And Discussion

The three models were established and evaluated, and theirs regression coefficients have been presented in Tables 2, then, for these correlations, the statistical indicators were calculated using the evaluation independent data series.

While the ideal values of statistical tests such as RMSE, MPE, and COV are 0 or closer to 0, the best values of R^2 should be 1 or close to 1. As shown in Tables 2, the three correlations are very satisfactory, and can be handled to estimate the hourly water consumption with an acceptable accuracy. Furthermore, the highest values of coefficients of determination (R^2) for these three regression models can be obtained by the cubic correlation, with 0.9824. Moreover, as shown in the same table, the lowest values of other statistical indicators including mean percent error (MPE), mean bias error (MBE), and root mean square error (RMSE) are derived from the same model as COV=4.9122, MPE=3.7311, and RMSE= 2278.33.

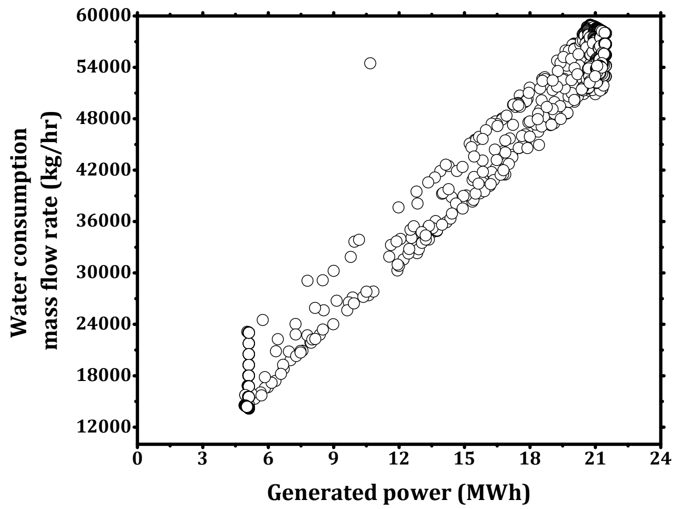

Fig. 3. Hourly water consumption vs. generated power of the considered plant.

TABLE II. STATISTICAL RESULTS OF EACH DEVELOPED CORRELATION..

Mod	*Correlation coefficients*				*Statistical analysis*			
	a	**b**	**c**	**d**	**COV**	**MPE**	**RMSE**	**R^2**
Linear	2494.1	3342.2	-	-	4.9678	3.397	2304.09	0.9820
Quad.	-32.835	3356.5	-227.94	-	4.9265	3.358	2284.94	0.9823
Cubic	-2.9822	83.407	2041.5	3805.6	4.9122	3.731	2278.33	0.9824

As a consequence, it could be reasonable to recommend this cubic model based on the generated power, to be used as a general model to predict annual water consumption in a large scale solar tower power plant on the basis of their performances, the established model for estimating hourly water usage are presented as follows:

$$V_{water} = -2.9822PG_{plant}^{3} + 83.407PG_{plant}^{2} + 2041.5PG_{plant} + 3805.6$$

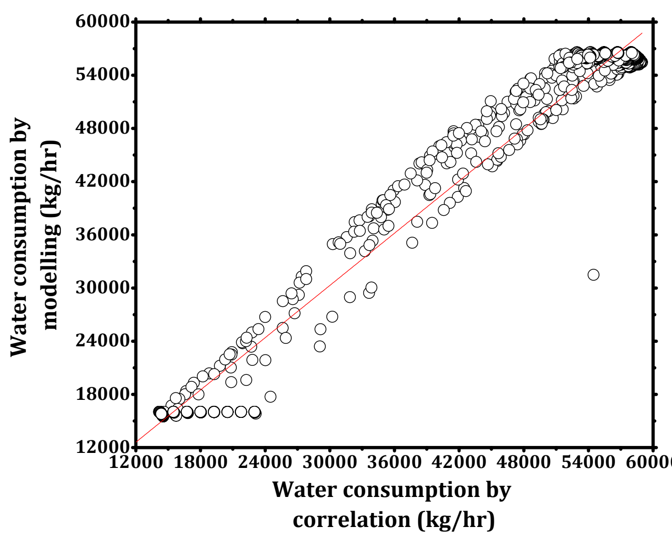

Fig. 4. Predicted water consumption by modelling vs. by cubic correlation.

Figure 4 represents the comparison between data obtained by the correlation analysis (Cubic model) and those obtained by modelling using SAM. It is quite clear that this model can predict hourly water consumption with a good accuracy.

IV. Conclusion

In the present paper, new regression models have been established to correlate between hourly water consumption and power plant output, to predict water usage in large scale solar tower plants, and the existing commercial plant (Gemasolar) has been chosen. These correlations can estimate annual water usage in such kind of plants based on its generated power with a good accuracy.

However, it should be pointed out that these correlations can be used to estimate annual water consumption of this kind of plants simulated in locations with similar meteorological conditions and solar resources as the site where simulations have been presented. Furthermore, there is a large need to compare these models with modern approaches like Artificial Neural Network (ANN) to simulate water consumption with more accuracy, and with more inputs including the plant design output, type of plant, as well as other meteorological data such as ambient temperature. Therefore, more work is required and the results will be further communicated.

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