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AN INNOVATIVE METHOD OF FORECASTING THE PERFORMANCE PARAMETERS OF THE SOLAR WATER PUMPING SYSTEM

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ABSTRACT

The design aspects and performance of the Solar Water Pumping Systems (SWPS) have been discussed already in earlier literature. But, unlike other authors, this paper is presented with the novelty of prediction of output parameters of SWPS like output energy of photovoltaic (PV) array, the energy in excess that can be supplied to the grid, load energy, and the discharge of water for irrigation. Non-linear curve fitting through the Polynomial Regression Analysis (PRA) method is used to achieve the above-said parameters. Primarily, the objective of this paper is to predict these parameters directly by using the solar insolation values. The predicted values of these parameters are compared with estimated values. This method of approach is used to reduce the complexity in the estimation of all the above parameters using the conventional procedure presented in this paper.

Keywords: SWPS, PRA, output energy of PV array, excess energy, load energy, water discharge.

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INTRODUCTION

For the socio-economic development in developing countries, the application of solar water pumping systems (SWPS) plays an emerging role as it has the greatest potential for sustainability. In recent times, SWPS has become a promising source of power in the areas of photovoltaic applications. These are mainly useful in rural or remote areas where water is to be supplied. In general, SWPS is employed with no storage batteries. Most of the time water is stored in the water tanks in the majority of pumping purposes. However, batteries are also used in particular days full of clouds. SWPS is useful in many sectors like domestic, agriculture, and rural villages [1-2]. Many of the studies have been carried out both theoretically and practically regarding the installation of SWPS in remote areas for drinking and agriculture purposes [3-7].

Various theoretical and experimental analyses with results have been published regarding SWPS. Then any other motors, the efficiency of the motor being selected is significantly elevated. Without a maximum power point tracker (MPPT), the performance of the DC motor driven with solar PV power has been observed [8]. In [9], the SWPS has been analyzed with the variation of motor constant. A solar-electric water pumping system is combined with a wind-electric water pumping system to form a hybrid system that has been proposed [10]. Also, a direct-coupled SWPS with MPPT for which the generalized method has been developed to evaluate the long-term performance [11]. The subsystem of the pumping being matched with an array of the PV system is comprehensively studied [12,13]. The different models have been developed by different researchers for the simulation of PV array performance [14-17]. The studies have been carried out for developing the models for the pump, motor, inverter and MPPT. Nevertheless, to understand the complicated nonlinear relationships among the above models, numerical skills are required. From the above-proposed models, it is observed that the relation between the electrical power of the pumping system and the water discharge is not direct.

Nevertheless, average efficiencies of the components are utilized in many models that are available in the manufacture datasheets. The variations in the system due to the variations in the source of solar have been ignored in all these models. Besides, based on the specific pump and motor, the models have been developed for any specific site. Therefore, it is difficult to use these models in various locations. Another factor is that the pump set data is provided by manufacturers only. As a result, a common method is required to develop a system wherein long-term performance of SWPS is to be simulated for a given site.

Recently, SWPS with a helical rotor pump and its performance is investigated [18]. With the PV array optimized configuration, the effect of the solar insolation and the operating head at the site on the water discharge of the pump has been evaluated. The study is about different pumping heads such as 4bar, 6bar, 8bar, and 10bar have been studied. The performance of the pump has been investigated based on the variation of insolation effect. The helical rotor pump at the total head of 10bar has given the best efficiency. With other different features, the performance of SWPS has been studied by researchers [19, 20]. The present condition of research on SWPS is explored [21]. In comparison with conventional pumping systems, SWPS is found to be feasible. The nonlinear relation between water flow rate and solar power has been obtained experimentally in the first step and then used for performance prediction [2].

The main objective of this present work is to implement a simplified procedure for the prediction of the SWPS output values at the working location through solar insolation. The methodology for designing the SWPS considered in this study is based on the land extent of one

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acre and the crop type is paddy. We have used the solar insolation data at a geographical location situated at (17.08° N, 82°E) of the state of Andhra Pradesh, India. The use of photovoltaic (PV) energy as an electrical source to supply pumping systems is a well-adapted solution for a great partof these areas. Initially, the process of prediction is done for January whereas the measured values are compared with predicted values. Then the same procedure is extended to implement for the remaining months of the year also. This method is useful in agriculture applications where the system designer can make use of the regression equations to get rid of the complex design procedure of the SWPS.

PROPOSED METHODOLOGY

The following are the steps of the proposed methodology.

Step-1: Estimation of monthly average hourly solar insolation (I_t).

Step-2: The Penman-Monteith method for the estimation of discharge of water (Q), and hydraulic energy required.

Step-3: Estimation of PV array area.

Step-4: Estimation of output energy of PV array (E_o), load energy (E_L), and excess energy (E_{ex}) using the utilizability concept.

Step-5: Estimation of Q through the simulation using PV Syst software.

Step-6: Non-linear curve fitting using PRA method to predict the E_o, E_L, E_{ex}, and Q through I_t.

Step-7: Comparison of predicted values with estimated values obtained in step-4 & step-5.

Step-1: Estimation of monthly average hourly solar insolation (I_t)

Using monthly average daily insolation incidents on the horizontal surface, PV system output is estimated. The PV system output is maximized by varying the tilt angle of the solar panels. For design and performance calculations of PV systems, solar insolation data is the basic requirement. Two types of solar insolation data are widely available. The first one is monthly average daily solar insolation and the second is hourly total insolation on a horizontal surface. As most of the data is for horizontal surfaces, there is a need to estimate the insolation on tilted surfaces of a collector from the solar insolation on a horizontal surface. Insolation on the tilted surface [21], can be obtained from equation (1).

$$H_t = H_b R_b + H_d R_d + H_g R_r \quad (1)$$

where H_b, H_d and H_g are beam, diffuse and ground reflected insolation, respectively. R_b, R_d, and R_r are tilt factors of beam, diffuse and ground reflected solar insolation, respectively. The slope and azimuth angle of solar collector affect the total energy received on a monthly, seasonal, or annual basis. For maximizing the annual energy availability, the slope or tilt angle of the collector is changed monthly. The hourly insolation data from the monthly average daily insolation can be obtained by using the equation (2).

$$I_t = I_b R_b + I_d R_d + I_g R_r \quad (2)$$

where, I_b, I_d, and I_g are beam, diffuse and ground-reflected insolation on an hourly basis, respectively. The hourly insolation data on the tilted surface is quite useful in understanding the temperature, and efficiency of the PV array.

Step-2: The Penman-Monteith method for the estimation of discharge of water (Q), and hydraulic energy required

The analysis of the performance of the various calculation methods reveals the need for formulating a standard method for the computation of reference evapotranspiration (ET_o). The FAO Penman-Monteith method is recommended as the sole standard method. It is a method with a strong likelihood of correctly predicting ET_o in a wide range of locations and climates and has provision for application in data-short situations [23]. Authors of [24] discussed the estimation ofdaily water and hydraulic energy requirements for the paddy. This data has been taken into consideration in this particular study.

Step-3: Estimation of PV array area

For a required amount of daily hydraulic energy, PV array size can be determined based on the worst radiation month. Equation (3) can be used to obtain the array size of the PV system.

$$A_{pv} = \left| \frac{E_{h,ax}}{y_{p,ref}\, y_d\, y_e\, y_p\, H_{t,min}} \right| \quad (3)$$

Step-4: Estimation of output energy of PV array (E_o), load energy (E_L), and excess energy (E_{ex}) usingthe utilizability concept

Equation (4) represents the output energy of PV array. In this equation, 'i' represents the particularhour of the day.

$$E_o = A_{pv}\, I_t\, \eta i \quad (4)$$

Equation (5) represents the load energy on an hourly basis is expressed in equation (5).

$$E_l = (1 - \emptyset_i)_o \quad (5)$$

In the above equation, $\emptyset_i$ represents the utilizability factor on a monthly average hourly basis. Therefore, the energy can be supplied to the grid in the form of excess energy is given by using equation (6).

Step-5

$$E_e = \emptyset_i\, E_o \quad (6)$$

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Estimation of Q through the simulation using PV Syst software

In this study, simulation software called PV Syst 6.3.4 is used to perform the simulation for carrying out the hourly values Q for given electric power generated by solar PV.

Step-6: Non-linear curve fitting using the PRA method to predict the E_O, E_L, E_{ex}, and Q through I_t

The main objective of this paper is to predict the monthly average hourly values of PV array output energy, load energy, excess energy, and discharge of the water through the monthly average hourly values of insolation. For this reason, non-linear curve fitting using the Polynomial Regression Analysis (PRA) method has been used.

Step-7: Comparison of predicted values with estimated values obtained in step-4 and step-5

The estimated values of solar PV array output energy, excess energy, load energy, and water discharge are to be compared with the predicted values for the validation of the results using the curve fitting method.

RESULTS AND DISCUSSIONS

Step-1: Estimation of monthly average hourly solar insolation (I_t)

Monthly average hourly solar insolation (I_t) data on the tilted surface shown in equation (2) can be obtained through the daily average monthly insolation shown in equation (1). The data has been obtained for the location where the solar insolation potential is high and its geographical location situated at (17.08° N, 82°E) of state of Andhra Pradesh, India. Data of the daily average monthlyinsolation obtained using equation (1) is shown in Table-1.

Table-1. Monthly insolation values on a daily average basis.

Month	Insolation (kWh/m^2/day)
January	4.95
February	5.74
March	6.43
April	6.71
May	6.18
June	4.65
July	4.26
August	4.34
September	4.44
October	4.49
November	4.46
December	4.56

The hourly insolation values data have been obtained and shown in Figure-1 and Figure-2. In Figure-1, the data is shown only for five months from January to June (May month excluded). Similarly, in Figure-2 also, data is shown from July to December (November excluded). Because these two months are being treated as crop holidays. During the crop holiday period, the entire energy supplied by the PV array can be transferred to the grid where the framer can generate the revenue based on the PV array size in terms of kWp installed.

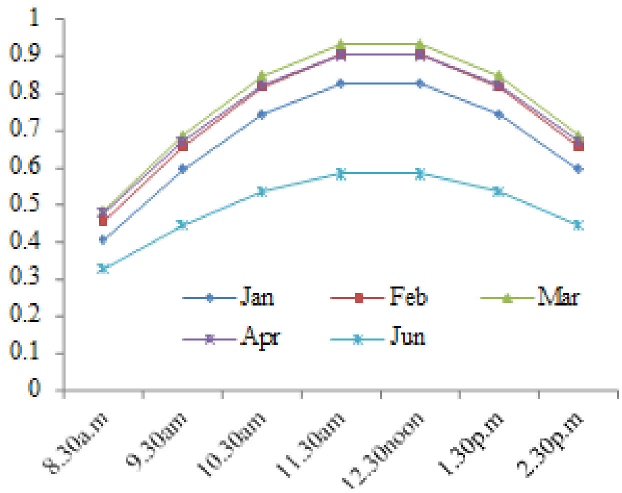

Figure-1. Hourly insolation from Jan to June.

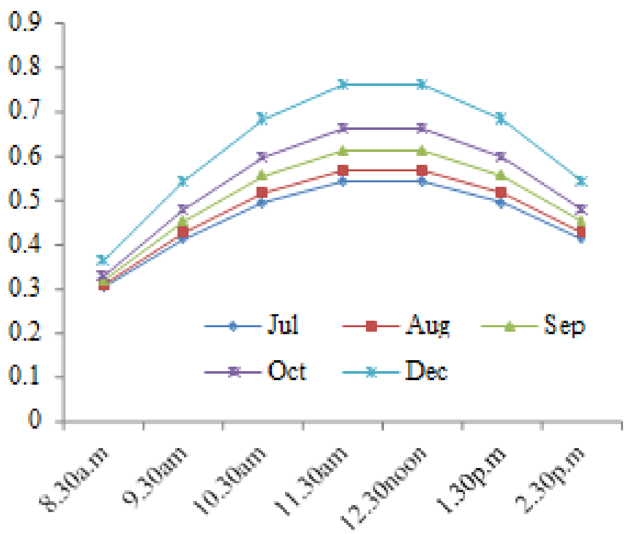

Figure-2. Hourly insolation from July to December.

Step-2: The Penman-Monteith method for the estimation of discharge of water (Q), and hydraulic energy required

In Table-2, the data of the monthly average daily hydraulic energy requirement based on the daily water requirement has been presented. For May and November, the values are shown as '0' because they have been considered as a crop holiday period.

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Table-2. Water & hydraulic energy requirements on a monthly average daily basis.

Month	Wr,m (m^3/day/acre)	Eh,m (kWh/day)
January	14.07	2.11
February	18.35	2.75
March	20.16	3.02
April	16.84	2.52
May	0	0
June	17.35	2.60
July	13.46	2.02
August	14.82	2.22
September	13.64	2.05
October	11.56	1.73
November	0	0
December	14.46	2.16
Annual Average daily requirement	15.47 m^3	2.32 kWh

Step-3: Estimation of PV array area

Using equation (3), PV array area has been sized to meet the daily load energy requirement shown in above Table-2. The size of the PV obtained is 18m^2 and which requires the installed peak powerof 2.2kWP.

Step-4: Estimation of output energy of PV array (E_O), load energy (E_L), and excess energy (E_{ex}) usingthe utilizability concept

In Figure-3, the hourly energy in kWh generated by the PV array from 8.30 A.M to 2.30 P.M (duration of 7 peak sunshine hours) is shown. This figure represents the data from January to June and the same data from July to December is shown in Figure-4. The data shown in both figures have been obtained using equation (4). Energy (kWh) that can be supplied to the load for pumping the water is obtained using equation (5) and the data has been shown in figure 5 and figure 6 respectively. Figure-6 and Figure-7 represents the data of excess energy (kWh) that can be supplied to the grid. This can be accomplished by using equation (6).

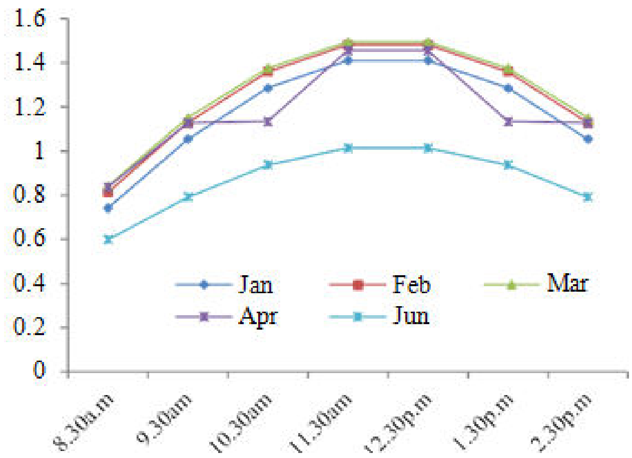

Figure-3. Hourly PV array energy from Jan to June.

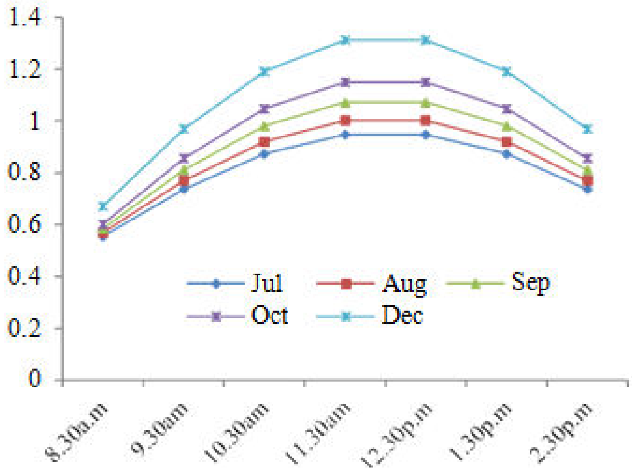

Figure-4. Hourly PV array energy from July to December.

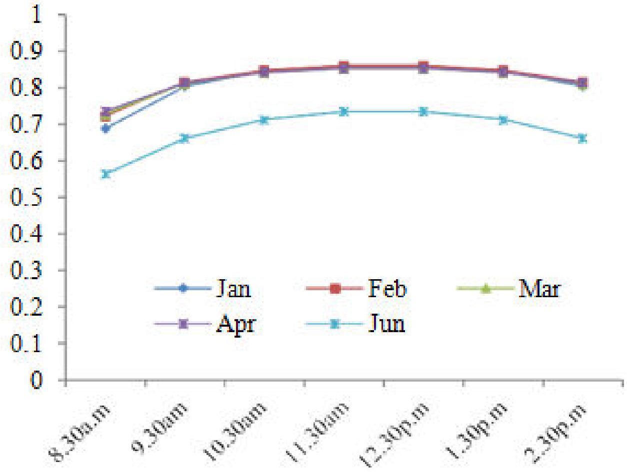

Figure-5. Hourly load energy from Jan to June.

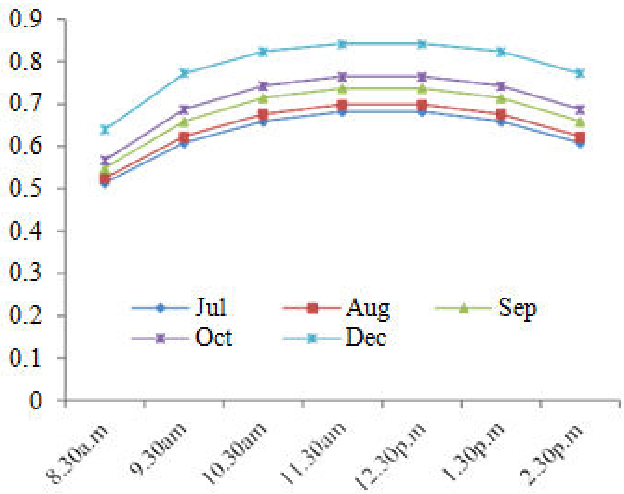

Figure-6. Hourly load energy from July to December.

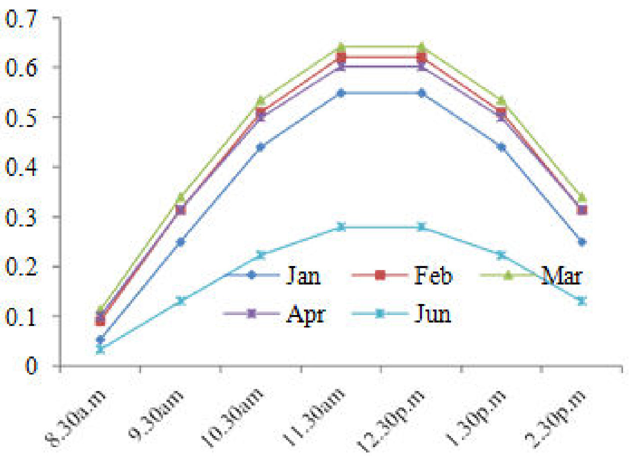

Figure-7. Hourly excess energy from Jan to June.

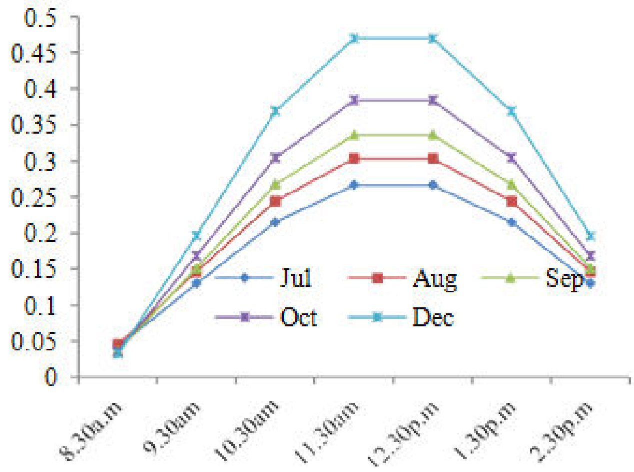

Figure-8. Hourly excess energy from July to December.

Step-5: Estimation of Q through the simulation using PV Syst software

In this particular study, hourly discharge of the water (m^3) from the pump has been obtained using the simulation software called PV Syst 6.3.4. This software provides an environment wherein the pump can be chosen according to the amount of energy reaching the load. As shown in Figure-9, the 867W pump has chosen to discharge the water at an assumed operating head of 55m in the area of the study. Once the hourly load energy values are available, the water discharge of the pump for a particular hour or flow rate can be obtained as shown in Figure-10. For all the hours from 8.30 A.M to 2.30 P.M, daily average hourly values of water discharge in all the months excluding May and November have been shown in Figure-11 and Figure-12 respectively.

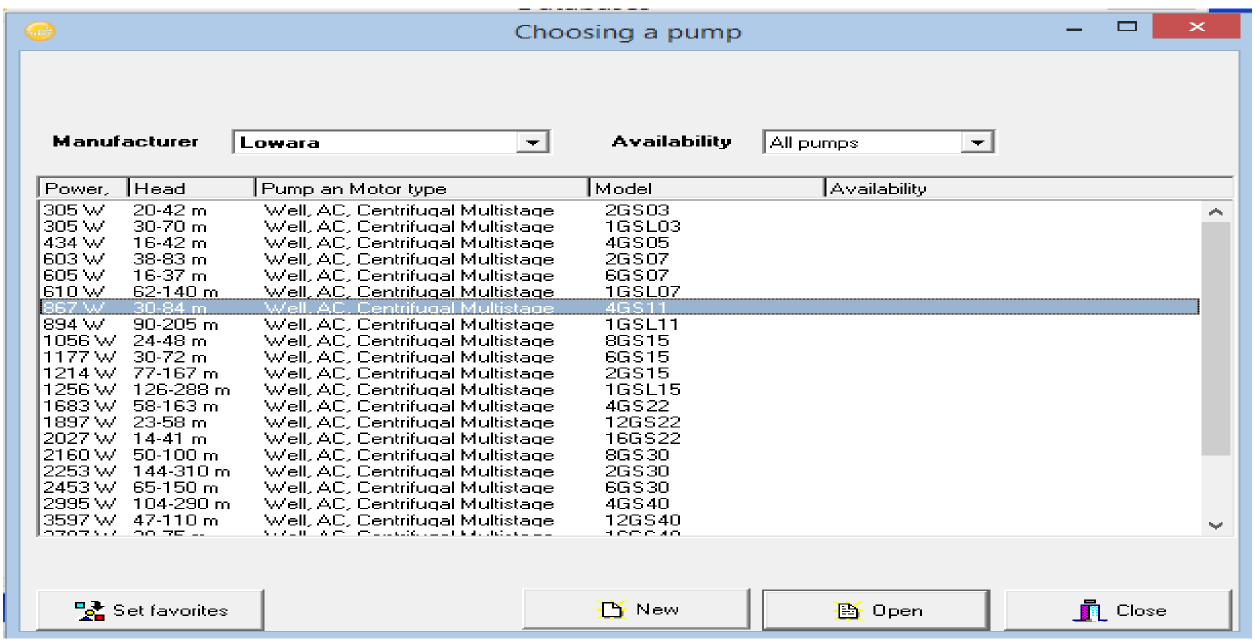

Figure-9. Selection of the pump using PV Syst.

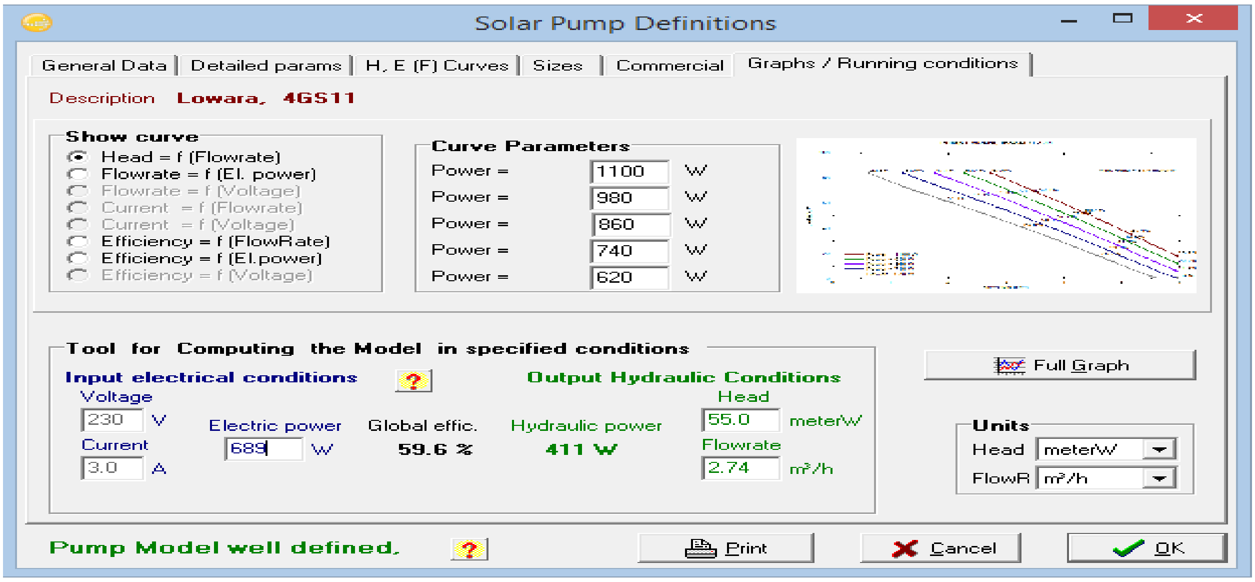

Figure-10. Estimation of the water discharge using PV Syst.

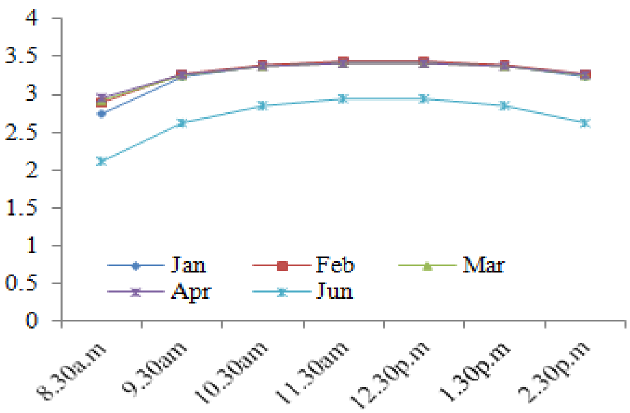

Figure-11.

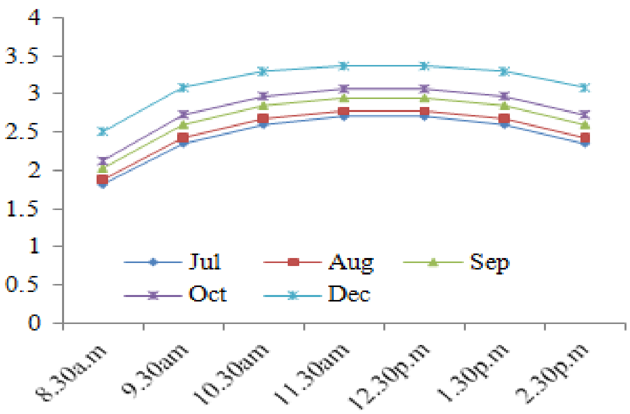

Figure-12.

Step-6: Non-linear curve fitting using PRA method to predict the E_O, E_L, E_{ex}, and Q through I_t

Initially, the hourly data of E_O, E_L, E_{ex}, and Q for January taken into consideration and used to fit the curves through the PRA method. The curve has been fitted with already available data of estimated E_O and I_t is using regression analysis in the MS-Excel platform. The second-order polynomial equation for E_O in terms of I_t has shown in the Figure-13. Similarly, from figure 14 to Figure-16 polynomial equations are shown for E_{ex}, E_L, and Q respectively through non-linear curvefitting analysis.

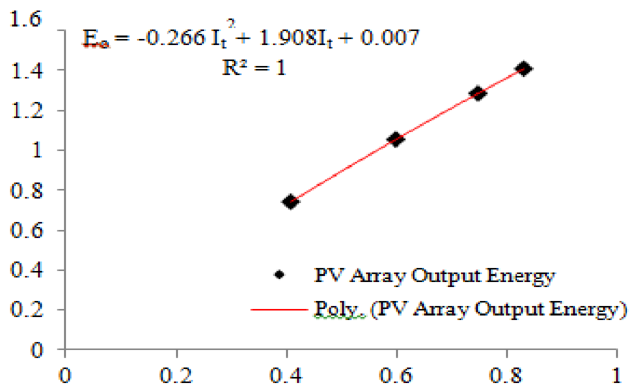

Figure-13.

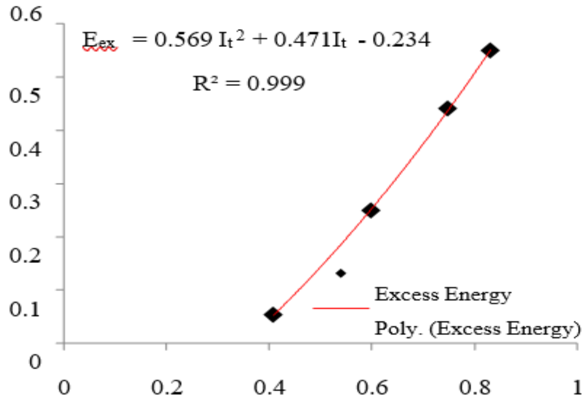

Figure-14.

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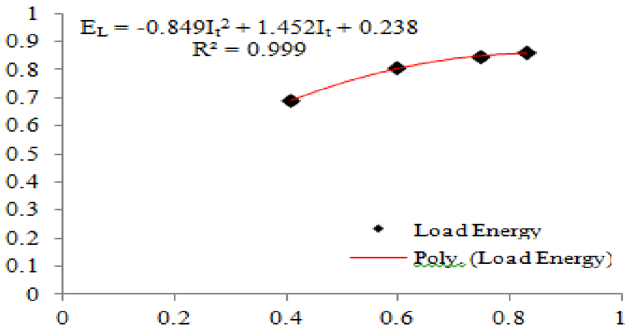

Figure-15.

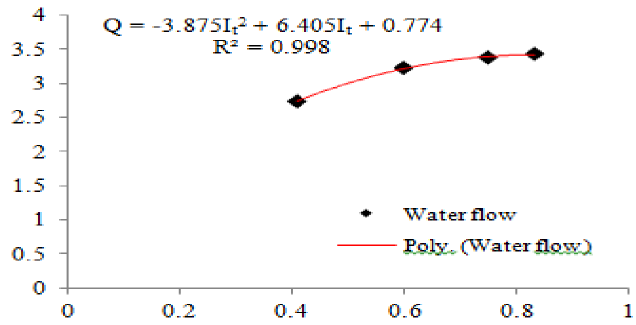

Figure-16.

For instance, the summary output of polynomial regression analysis carried out for the Q has beenpresented in Table-3. Predicted values of the Q are being compared with estimated values. The corresponding residuals are also shown in the above table. It is observed from these results that the predicted values have closely matched with estimated values.

Table-3. The summary output of polynomial regression analysis

Regression Statistics								
Multiple R	**0.999**							
R Square	0.998							
Adjusted R Square	0.995							
StandardError	0.023							
Observations	4.000							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	2	0.297	0.149	291.99	0.041			
Residual	1	0.001	0.001					
Total	3	0.298						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.774	0.215	3.603	0.172	-1.957	3.505	-1.957	3.505
X	6.405	0.736	8.699	0.073	-2.951	15.762	-2.951	15.76
X^2	-3.875	0.595	-6.514	0.097	-11.436	3.685	-11.43	3.685
RESIDUAL OUTPUT								
Observation	Predicted Q	Residuals						
1	2.743	-0.003						
2	3.219	0.011						
3	3.397	-0.017						
4	3.421	0.009						

Step-7: Comparison of predicted values with estimated values obtained in step-4 and step-5

With the above validation process, all polynomial equations are extended to use for predicting the values of E_O, E_L, E_{ex}, and Q through the I_t for all remaining months. Table-4 represents the comparison of predicted values with estimated values. The above four polynomial equations are well suited for obtaining the E_O, E_L, E_{ex}, and Q by directly substituting the corresponding hourly insolation, I_t.

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Table-4. Comparison of estimated and predicted values.

Month	It	Eo		Eex		El		Q	
		Estimated	Predicted	Estimated	Predicted	Estimated	Predicted	Estimated	Predicted
Jan	0.408	0.742	0.747	0.053	0.052	0.689	0.689	2.741	2.743
	0.598	1.054	1.052	0.249	0.251	0.805	0.802	3.213	3.219
	0.748	1.286	1.285	0.440	0.436	0.846	0.849	3.389	3.397
	0.831	1.410	1.408	0.549	0.550	0.860	0.858	3.426	3.421
Feb	0.459	0.813	0.826	0.090	0.102	0.090	0.102	2.891	2.902
	0.661	1.128	1.152	0.313	0.325	0.313	0.325	3.273	3.312
	0.820	1.360	1.393	0.510	0.534	0.510	0.534	3.396	3.423
	0.908	1.482	1.553	0.621	0.660	0.621	0.660	3.441	3.396
Mar	0.485	0.841	0.869	0.112	0.120	0.729	0.742	2.928	2.964
	0.690	1.150	1.210	0.339	0.361	0.811	0.835	3.256	3.346
	0.850	1.376	1.430	0.534	0.577	0.842	0.858	3.375	3.418
	0.938	1.495	1.600	0.642	0.708	0.853	0.852	3.415	3.372
Apr	0.482	0.836	0.864	0.100	0.120	0.736	0.740	2.956	2.964
	0.674	1.128	1.190	0.314	0.341	0.814	0.830	3.265	3.336
	0.824	1.343	1.390	0.499	0.540	0.843	0.857	3.377	0.423
	0.906	1.456	1.550	0.602	0.650	0.854	0.856	3.411	3.396
Jun	0.331	0.598	0.610	0.033	0.015	0.564	0.620	2.110	2.461
	0.447	0.792	0.806	0.130	0.100	0.662	0.710	2.626	2.523
	0.536	0.936	0.953	0.223	0.190	0.713	0.770	2.854	3.095
	0.585	1.014	1.032	0.279	0.236	0.735	0.796	2.947	3.195
Jul	0.307	0.556	0.567	0.042	0.030	0.514	0.600	1.822	2.377
	0.414	0.737	0.751	0.130	0.060	0.608	0.690	2.356	2.766
	0.497	0.874	0.889	0.215	0.141	0.659	0.740	2.604	3.002
	0.543	0.948	0.964	0.266	0.192	0.682	0.776	2.713	3.105
Aug	0.313	0.570	0.575	0.045	0.030	0.525	0.600	1.887	2.302
	0.43	0.770	0.780	0.146	0.070	0.623	0.700	2.434	2.811
	0.521	0.920	0.928	0.244	0.166	0.676	0.760	2.688	3.055
	0.571	1.002	0.944	0.303	0.220	0.699	0.780	2.783	3.168
Sep	0.322	0.585	0.593	0.036	0.020	0.549	0.617	2.033	2.433
	0.455	0.811	0.820	0.151	0.100	0.659	0.722	2.602	2.885
	0.559	0.981	0.990	0.267	0.210	0.714	0.784	2.856	3.147
	0.616	1.073	1.08	0.336	0.270	0.737	0.810	2.953	3.242
Oct	0.332	0.602	0.611	0.035	0.015	0.567	0.621	2.137	2.475
	0.482	0.855	0.864	0.168	0.130	0.687	0.743	2.734	2.968
	0.601	1.047	1.057	0.304	0.254	0.743	0.802	2.977	3.225
	0.666	1.150	1.160	0.384	0.332	0.765	0.826	3.072	3.323
Dec	0.367	0.671	0.670	0.032	0.015	0.639	0.656	2.514	2.608
	0.545	0.969	0.967	0.196	0.191	0.772	0.777	3.091	3.112
	0.686	1.192	1.190	0.369	0.356	0.824	0.834	3.305	3.344
	0.764	1.312	1.300	0.470	0.457	0.842	0.851	3.373	3.405

CONCLUSIONS

The methodology proposed in this work helps the researchers to predict the output values of the SWPS through insolation data available at the site. This study reaches its objectives using the results obtained. The results of this study contribute the way to the system designer for the prediction of the values of solar PV array energy output, load energy, excess energy, and the water discharge for a particular crop such as paddy at a specified location on one care base. The main advantage of this proposed methodology is that one could predict the above-said values by using the PRA method without performing complex calculations and hence suggested.

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