Modeling of a Solar Pumping System in Agrivoltaic Environments Using Artificial Neural Networks

Yahia SERBOUH[(1)*], Djamel BENAZZOUZ[(1)], Mohamed Abdessamed AIT CHIKH[(2)] Sami TOUIL[(3)]
[(1)] LMSS, Faculty of Technology, M'hamed Bougara University, Boumerdes, Algeria
[(2)] Faculty of Technology, M'hamed Bougara University, Boumerdes, Algeria
[(3)] Faculty of Science and Technology, Djilali Bounaama University Khemis Miliana, Algeria
[*]y.serbouh@univ-boumerdes.dz

Abstract: The aim of the study was to employ mathematical modeling in the analysis of a photovoltaic (PV) water pumping system designed for agriculture irrigation in an Agrivoltaic environment that combines crops in the ground with PV panels, using as a case study the region of Khemis Meliana in Algeria in northwest Africa. System performance was optimized by considering the variation in solar irradiance level, ambient temperature, generated PV power, pump flow rate and head, and water demand for irrigation. The maximum power point tracking (MPPT) of the PV module was estimated from the I-V curve model. The performance equation that expresses the flow rate of the pump as a function of input power and the total head was modeled based on the manufacturer's performance curves using a feed-forward backpropagation network. Results showed that an increase in irradiance intensity increased the pump flow rate. A higher head gave a lower flow rate, regardless of the change in solar irradiance intensity. The power excess was predicted monthly. This power can be further utilized for secondary applications. The PV water pumping arrangement model enables advance estimation of system outputs and allows for optimization and improvement in the performance and reliability, accounting for variation in solar irradiance level, different pump operating parameters, and the water demand for irrigation. Future studies are suggested on excess power analysis including economics and considering the targeted plants to better optimize the system in terms of water need and frequency for irrigation.

Keywords: Agrivoltaic (APV), Intelligent irrigation, Integrity, Performance optimization, Photovoltaic (PV), Reliability, Smart agriculture, Solar pumping system.

1. Introduction

A system that combines crops in the ground with photovoltaic (PV) panels installed a few meters above the ground is called an agrivoltaic system [1]. Agrivoltaic systems are a key technology for achieving sustainable development goals by reducing the use of land for food versus land for energy. Agrivoltaic systems are at the core of the balance between electricity generation, agricultural production, and irrigation water savings [2]. Agrivoltaic systems provide a solution to the growing demand for food and energy while reducing water consumption [3]. Furthermore, an agrivoltaic farm can be used as a stand-alone energy source to water pumping systems for irrigation in areas where the electrical grid is insufficient or non-existent [4]. Smart agriculture can enhance agricultural performance in a more effective and sustainable manner [5]. Therefore, a reliable and economical irrigation system is needed. Irrigation level management plays a very important role in saving water for different purposes and using it economically. More than 25% of water is wasted while using traditional irrigation methods [6]. An improved irrigation system can save a large amount of water that is being wasted due to improper water management. Hence, the need for a reliable and economical irrigation system. Photovoltaic (PV) pumping systems are considered as an alternative approach to water supply for irrigation [7]. [8] presented an extensive overview of the solar photovoltaic powered water pumping system, its major elements, and applications. Economic and environmental considerations were also addressed. [9] analyzed a method of distributing the generated power in a photovoltaic pumping system having two identical pumps, working in parallel to determine a strategy for distributing the generated power that maximizes the flow rate of the two pumps together. [10] proposed a method for the modelling, simulation and analysis of solar PV water pumping system. [11] presented a mathematically based evaluation procedure for a reliable, stand-alone PV-battery water pumping system to evaluate the function of the proposed system for a rural housing unit in Malaysia. [12]

suggested a methodology for optimizing the performance of solar photovoltaic pumps by considering the effect of irradiance and temperature variations and different grid configurations on the performance of the water pump. [13] evaluated experimentally a solar PV pumping system used for irrigation purpose in India. [14] performed a selection procedure to identify the most significant factors for predicting the performance of the photovoltaic pumping system, by analyzing which factors have the most effect on the performance ratio to perform a satisfactory calibration to decrease the system losses. Adaptive neuro fuzzy inference system has been used for this purpose.

[15] conducted a comparative study to investigate the head effect on the optimum photovoltaic array configuration, pump and pumping system total efficiency by performing experiment on the centrifugal deep well pump, with different photovoltaic modules configuration. [16] performed an experimental investigation to select the optimum photovoltaic array configuration (PVAC) to supply electric power to solar photovoltaic water pumping system (SPVWPS) and effect of seasonal variations on its output by investigating the performance of SPVWPS with different PVACs. [17] developed experimentally a model that highlights the relation between water flow rate and solar power for system performance prediction. The PV pumping system efficiency is highly impacted by the climatic conditions which vary throughout the day and the year [18]. Hence, the need for a reliable and validated model taking into consideration all the variables and constraints.

The aim of the current study was to employ mathematical modeling in the analysis of a photovoltaic (PV) water pumping system designed for smart agriculture irrigation, using as a case study the region of Khemis Meliana in Algeria in northwest Africa. System performance was optimized by considering the variation in solar irradiance level, ambient temperature, generated PV power, pump flow rate and head, and water demand for irrigation. The maximum power point tracking (MPPT) of the PV module was estimated from the I-V curve model using the single diode model of the PV cell, then, the pump performance characteristic was modeled based on the manufacturer performance curve using ANN. The hourly irradiance data (G) and the ambient temperature were collected 365 days, and the average value was calculated along with the PV cell temperature. The model was then simulated to obtain the hourly produced power, the average monthly flow rates, and the guaranteed volume. Finally, the quantity of PV modules which satisfies the daily required volume was defined and the average monthly power excess was calculated.

2. System Modeling

2.1. PV module modeling

The modeling of PV module involves a range of parameters provided by the manufacturer's data sheet (Appendix.1).
To be able to evaluate the performance of a PV system, we first need to understand the detailed electrical characteristics of the PV module.

The equation that describes the I-V characteristic mathematically is defined based on the single diode model of the PV cell (Fig. 1) [19].

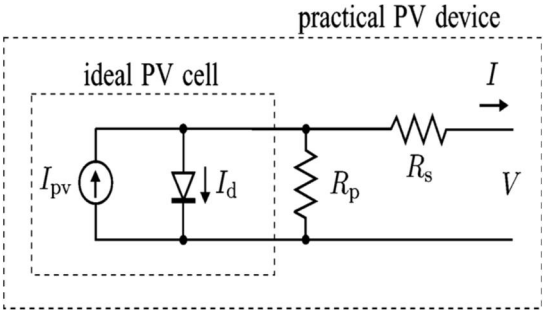


Fig. 1. Single-diode model of the theoretical PV cell and equivalent circuit of a practical PV device

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+IR_s}{aN_sV_t}\right) - 1\right] - \frac{V+IR_S}{R_p} \quad (1)$$

The light-generated current I_{Pv} is expressed in function of the nominal light current $I_{pv,n}$, both are calculated using the equation 2 and 3 respectively. [20]

$$I_{\mathrm{pv}} = \left(I_{Pv,n} + \mathrm{K}_{Isc}(T - T_n)\right)\frac{G}{G_{amb}} \quad (2)$$

$$I_{Pv,n} = \frac{R_P+R_S}{R_P} I_{Sc,n} \quad (3)$$

The PV cell temperature varies with the ambient temperature and solar irradiance as presented in equation 4 [21]

$$\mathrm{T} = T_a + \frac{\mathrm{G_{amb}}\left(\mathrm{T_{NOCT}} - \mathrm{T_{a,NOCT}}\right)}{\mathrm{G_{NOCT}}} \quad (4)$$

The diode saturation current and the nominal saturation current can be expressed by the following: [22]

$$I_0 = I_{0,\mathrm{n}}\left(\frac{T_\mathrm{n}}{T}\right)^3 \exp\left[\frac{qE_\mathrm{g}}{ak}\left(\frac{1}{T_\mathrm{n}} - \frac{1}{T}\right)\right] \quad (5)$$

$$I_{0,n} = \frac{I_{sc,n}}{\exp(V_{oc}/aV_{t,n})-1} \quad (6)$$

The thermal voltage and nominal thermal of the module are calculated as below [23]

$$V_{t,n} = K\frac{T_n}{q} \quad (7)$$

$$V_t = K\frac{T}{q} \quad (8)$$

2.2. Weather data modeling

This study was conducted under the meteorological conditions of the city of Khemis Miliana in Algeria, which is located on coordinates of 36^0 of latitude and 2^0 of longitude. The climatic data such as irradiance and ambient temperature were collected hourly for 365 days during the year of 2019, accordingly, the monthly average of irradiance and ambient temperature was calculated. The cell temperature was also calculated based on Equation 4.

2.3. Pump performance modeling

This study utilizes the manufacturer's performance curve (Appendix.2), to predict the hourly performance characteristics of the PV pumping system. Understanding this curve is critical to accurately predict pump performance, select the right pump size, and design PV-powered water pumping systems that work efficiently under varying operating conditions.

Even though the pump performance curve is a valuable engineering data produced by the manufacturer, it is not convenient to use the curve directly in this analysis. Hence the requirement of extracting the performance equation that allows the pump performance modeling, the same was achieved using a feed-forward backpropagation network which offers several advantages for modeling complex relationships compared to the fifth-degree polynomial method used in the literature.

The pump characteristic model was extracted from the performance curves provided by the pump manufacturer. The features are the electrical power and head, whereas the flow rate is considered as target, all the training and testing data points were extracted from the performance curves of the pumps.

The model was created by a feed-forward backpropagation network [24][25] using MATLAB toolbox. With three hidden layers and seven neurons of each one, the absolute error between the model output and target is about 0.63%.

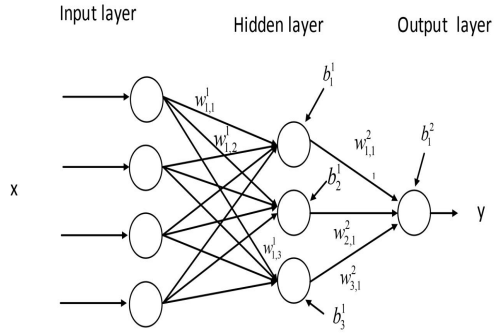


Fig. 2 Back-propagation neural network architecture

The first step was computing the output of each layer from input x into the output y according to the flowing equation:

$$a^{m+1} = F^{m+1}(W^{m+1}a^m + b^{m+1}) \quad (9)$$

Where m=0, 1, ……. M-1

$$n_i^m = \sum_{j=1}^{NR^{m-1}} w_{i,j}^m a_j^{m-1} + b_i^m$$

NR: Number of neurons
m: Number of layers
b: Bias vector of different layers
W : Weight matrix of different layers

At m=0 a=x
At m+1=M a=y
F is the activation function at m+1 layer

The second step was the back propagation for adjusting the weight w, that is based on the sensitivities backward "S" through the network:

$$s^M = -2\dot{F}^M n^M (y_t - y)$$
$$s^m = -2\dot{F}^m (n^m)(w^{m+1})^T s^{m+1} \quad (10)$$

y_t is the target data
m =M-1, ...,2,1

$$\dot{F}^m(n^m) = \begin{bmatrix} \dot{f}^m(n_1^m) & 0 & \dots & 0 \\ 0 & \dot{f}^m(n_2^m) & \dots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & \dot{f}^m(n_{NR^m}^m) \end{bmatrix}$$

$$\dot{f}^m(n_j^m) = \frac{\partial f^m(n_j^m)}{\partial n_j^m}$$

Finally, the weights matrices and biases vectors were updated using the approximate steepest descent rule:

$$W^m(k+1) = W^m(k) - \alpha s^m (a^{m-1})^T$$
$$b^m(k+1) = b^m(k) - \alpha s^m \quad (11)$$

where α is the learning rate

3. Simulation, results, and discussion

3.1. Variation in average irradiance, ambient, and cell temperature

The monthly average of irradiance and ambient temperature which were calculated based on the meteorological data collected at site are presented in (Fig. 3 and Fig. 4). e.g., in January at 2 pm the average irradiation was 400 W/m^2 and the ambient temperature was 11C◦, respectively. The cell temperature, calculated based on Equation 4, is represented in Fig. 5, e.g., in July at 10 am the cell temperature is 40C◦, while in January the cell temperature will be 5C◦ during the same time i.e., 10 am.

Knowing the photovoltaic (PV) cell temperature is important because temperature directly affects the performance and efficiency of solar panels. Higher temperatures decrease the panel's output voltage and efficiency, while lower temperatures can increase efficiency. Understanding this relationship is crucial for accurately predicting energy production and for optimizing system design and performance.

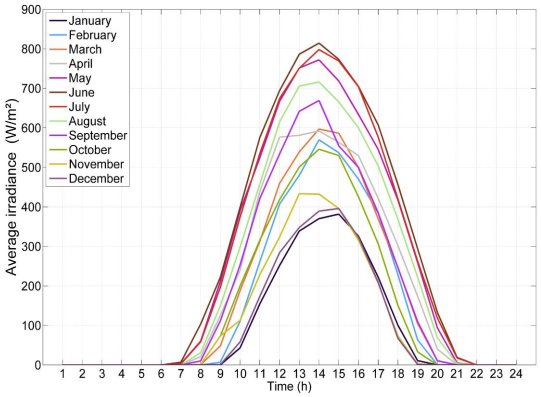


Fig. 3 Average hourly irradiance variation

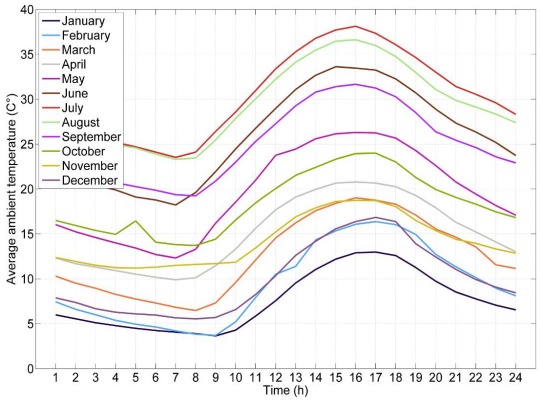


Fig. 4 Average hourly ambient T^0 variation

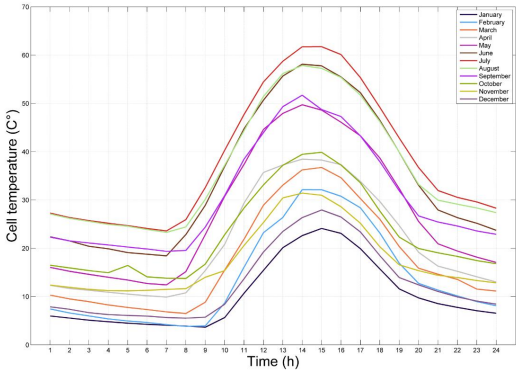


Fig. 5 Calculated hourly PV Cell T^0 variation

3.2. PV module simulation results

Fig. 6 and Fig. 7 present the modelling results for I-V and P-V characteristics of the PV module at 25◦C cell temperature for varying irradiance level. The data shows that PV module exhibits a nonlinear I-V and P-V characteristics which vary with the irradiance intensity and cell temperature.

Fig. 6 presents modelling results for electrical characteristics of the PV module on current versus voltage for different irradiance value. From the figure the short circuit current (Isc) increases significantly with the increase of irradiance level, while it has less effect on the open circuit voltage (Voc) of the PV module.

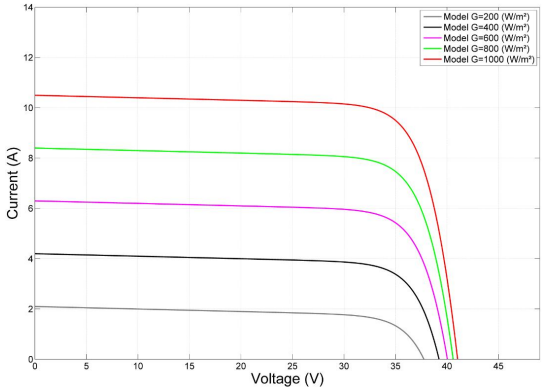


Fig. 6. I-V Characteritic for different irradiance values

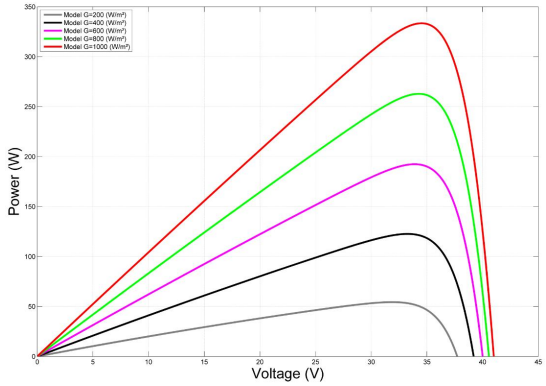


Fig. 7. P-V Characteritic for different irraidiance values

The proposed model of the PV module I-V and P-V characteristic curves is compared to manufacturer's experimental data (Appendix.3). The I-V and P-V characteristics (i.e., solid lines) predicted by our model closely matched those from the experimental results (i.e. dashed lines) achieved by the manufacturer, as shown in Fig. 7 and Fig. 8.

The I-V curve allows for the identification of the maximum power point (P_{max}) which is the point where the panel produces the most power. Knowing this value is essential for designing a system that can efficiently capture the panel's output.

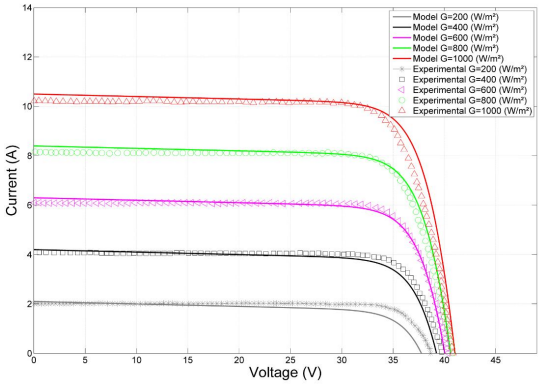


Fig. 8 I-V Characteristic of proposed model vs experimental (manufacturer) data

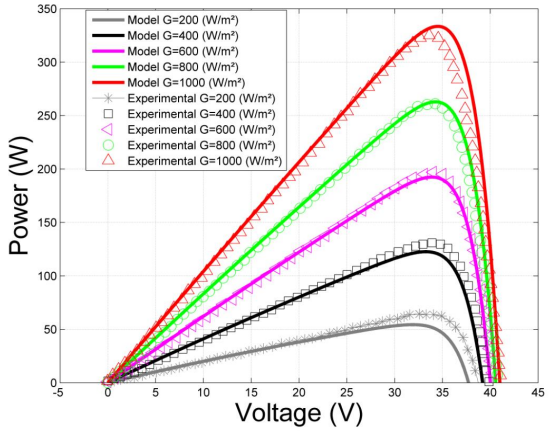


Fig. 9 P-V Characteristic of proposed model vs experimental (manufacturer) data

3.3. PV pumping system simulation results

The obtained modeled performance curves of the pump (i.e., solid lines) predicted by our model closely matched those from the experimental results (i.e. dashed lines) achieved by the manufacturer, as shown in Fig. 10.

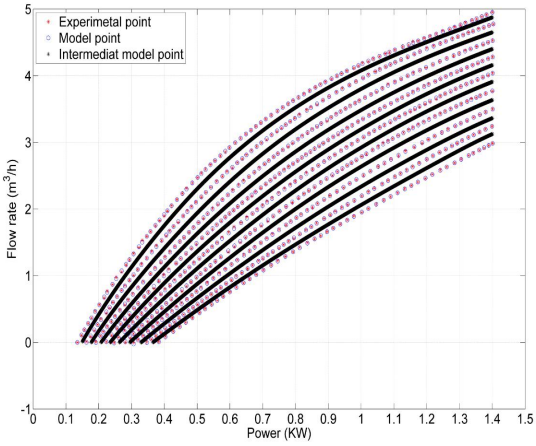


Fig. 10 Pump performance curve vs extracted model

The hourly estimated flow rate for each month and for various head values is depicted in Fig. 11 -13. An increase in irradiance intensity results in an increase in pump flow rate, but a higher head result in a lower flow rate regardless of the change in solar irradiance intensity.

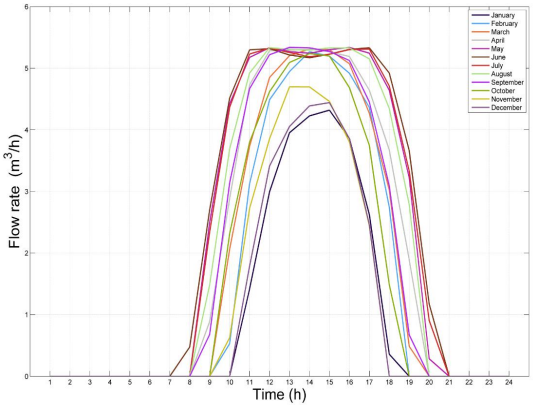


Fig. 11 Hourly predicted flow rate for H=35m

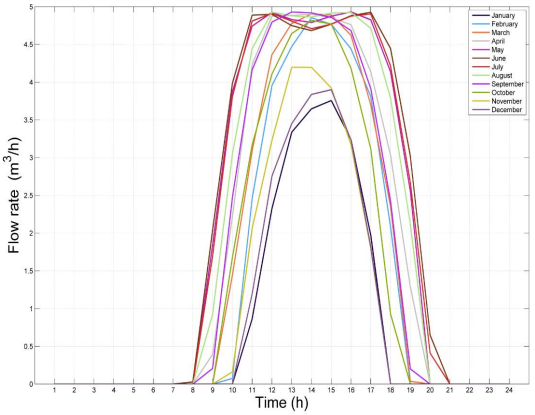


Fig. 12 Hourly predicted flow rate for H=45m

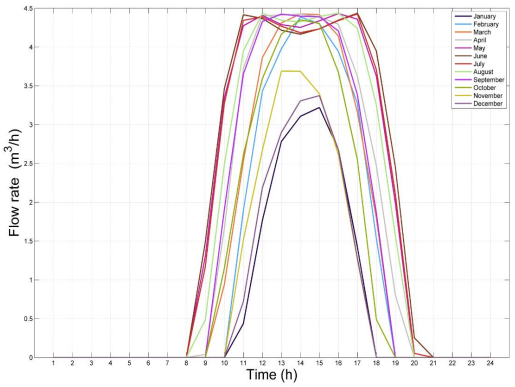


Fig. 13 Hourly predicted flow rate for H=55m

The number of modules required to achieve the requested volume of 23 m^3 of the storage tank number of PV module was defined based on the worst-case scenario i.e, the month with the minimum irradiance level, the same has been optimized to 10 modules.

The pump operating time is represented by Fig. 14, the minimum avergae working time is 7 hours during the month of December, while the maximum operating time is 13 hours during the month of June.

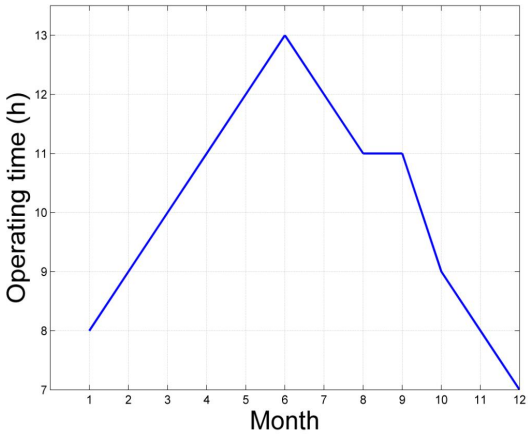


Fig. 14. Average monthly pump operating time

Fig. 15 and Fig. 16 represent the average monthly flow rate and the average monthly guaranteed volume respectively. The average monthly flow rate varies from its minimum value in the month of january (less than 3 m^3/h) to its maximum value in the month of august (~ 4.44 m^3/h). The average monthly guaranteed volume increases from less than 25 m^3 in the month of January to its maximum value (~ 54 m^3) in the month of June and then decreases to less than 25 m^3 in the month of December.

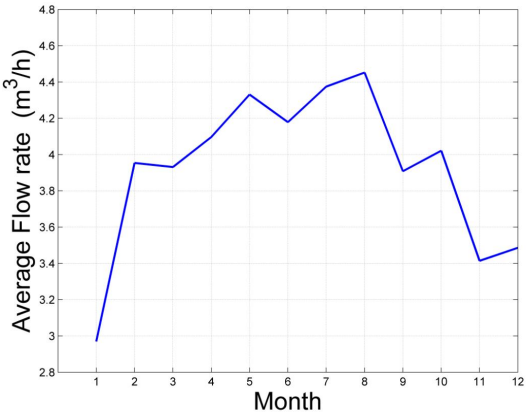


Fig. 15. Average monthly flow rate

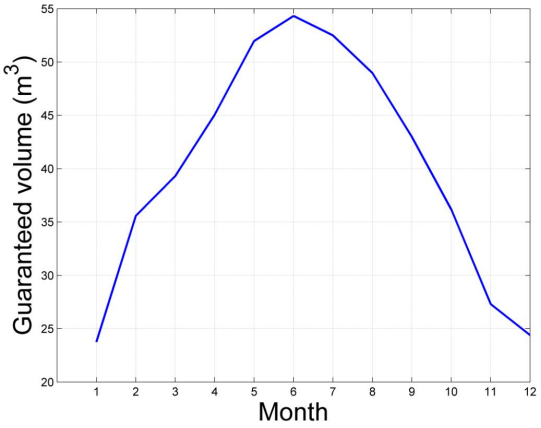


Fig. 16. Average monthly guaranteed volume

The hourly predicted power of PV modules is represented by Fig. 17. The results indicate that the maximum power was in the month of June while the minimum power was in the month of January.

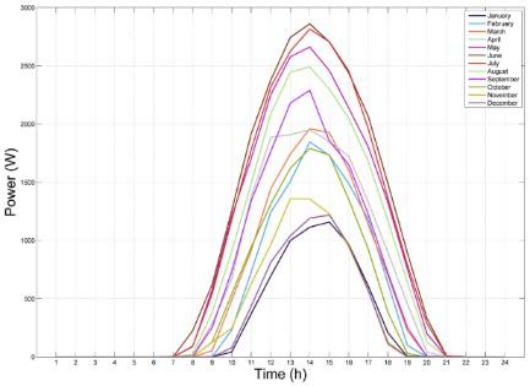


Fig. 17 Hourly predicted PV power variation

The system was designed for the month of January which has the minimum power (i.e., less than 800 W) as shown in Fig. 18. The model allows for predicting the excess of power produced every month. The maximum excess power was around 970 W during the month of July as highlighted in Fig. 19.

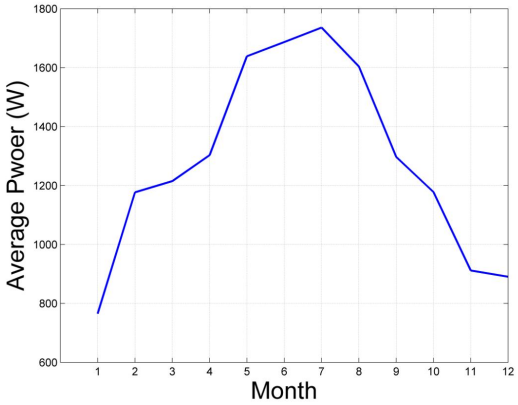


Fig. 18 Average monthly available power

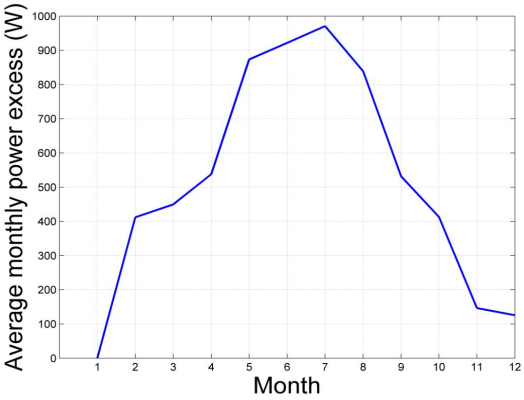


Fig. 19 Average monthly power excess

Conclusion

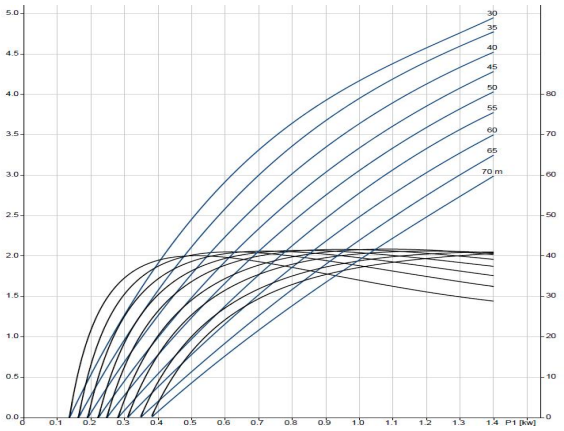
This study has contributed to the understanding of agrivoltaic systems and the modeling of photovoltaic water pumping for irrigation, providing insights into system performance under varying conditions. The approach developed in this study allows predicting the solar pumping system performance of any set of pumps, at any specific flow rate and pumping head accounting for the climatic condition of any location. This will provide a powerful tool for system performance optimization and system integrity improvement The mathematical modeling analysis of a photovoltaic water pumping system designed for agriculture irrigation in the region of Khemis Meliana, Algeria in northwest Africa, showed that an increase in irradiance intensity increased the pump flow rate. A higher head gave a lower flow rate, regardless of the change in solar irradiance intensity. The number of PV modules was defined and optimized to satisfy the required water demand. The power excess was predicted monthly, this power can be further utilized for secondary applications. The Artificial Neural Network (ANN) method was chosen due to its ability to make accurate predictions based on complex data patterns. The PV water pumping system model enables advance estimation of system outputs and allows for optimization and improvement in the performance and the integrity of the system, accounting for variation in solar irradiance level, different pump operating parameters, and the water demand for irrigation. Future studies are suggested on excess power economic analysis and on considering the targeted plants to better optimize the system in terms of water need and frequency for irrigation.

Appendix

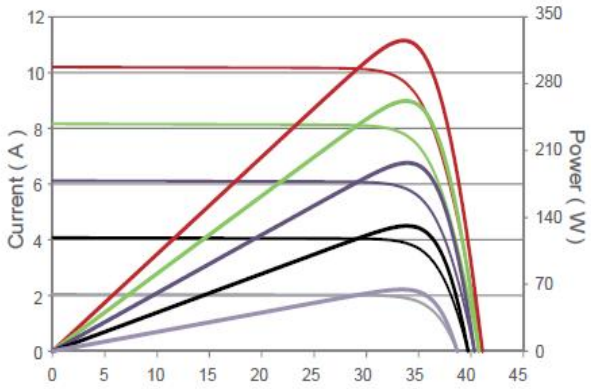
Appendix. 1 PV module specifications

Module Type	JKM325M-60-V
Cell type	Mono PERC 158.75×158.75mm
No. of cells	60 (6×10)
Dimensions	1665×1002×30mm
Maximum Power (P_{max})	325Wp
Maximum Power Voltage (V_{mp})	33.6V
Maximum Power Current (I_{mp})	9.68A
Open-circuit Voltage (V_{oc})	41.1V
Short-circuit Current (I_{sc})	10.50A
Operating Temperature (°C)	-40°C~+85°C
Temperature Coefficients of P_{max}	-0.37%/°C
Temperature Coefficients of V_{oc}	-0.29%/°C
Temperature Coefficients of I_{sc}	0.048%/°C
Nominal Operating Cell Temperature (N_{OCT})	45±2°C

Appendix. 2 Pump manufacturer performance curves



Appendix. 3 PV Module experimental (manufacturer) electrical Performance



References

[1] S.Amaducci, X.Yin, M.Colauzzi, Agrivoltaic systems to optimise land use for electric energy production, Applied Energy, 220 (2018) 545-561

[2] A.Agotini, M.Colauzzi, S.Amaducci, Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment, Applied Energy, 281 (2021) 116102.

[3] S.Touil, A.Richa, M.Fizir, B.Bingwa, Shading effect of photovoltaic panels on horticulture crops production: a mini review, Reviews in Environmental Science and Bio/Technology, 20 (2021) 281–296.

[4] H.Dinesh, J.M.Pearce, The potential of agrivoltaic systems, Renewable and Sustainable Energy Reviews, 54 (2016) 299-308.

[5] A.R.D.A.Zanella, E.D.Silva, L.C.P.Albini, "Security challenges to smart agriculture:Current state, key issues, and future Directions", Array, 8 (2020) 100048.

[6] S.Sumathi, S.Krishnan, "Artificial intelligence for smart solar power irrigation: Comprehensive Review", Advanced Science and Engineering, 7 (3) (2021) 1894-1903.

[7] M.Aliyu, G.Hassan, S.A.Said, M.U.Siddiqui, A.T.Alawami, I.M.Elamin, "A review of solar-powered water pumping systems", Renewable and Sustainable Energy Reviews, 87 (2018) 61–76.

[8] S.Verma, S.Mishra, S.Chowdhury, A.Gaur, S.Mohapatra, A.Soni, P.Verma, "Solar PV powered water pumping system – A review", Materials Today: Proceedings, 33 (2020) 303-307.

[9] M.Gasque, P.G.Altozano, R.P.G.Colomer, "Optimisation of the distribution of power from a photovoltaic generator between two pumps working in parallel", Solar Energy, 198 (2020) 324–334.

[10] E.M.Salilih, Y.T. Birhame, S.H.Arshi, "Performance analysis of DC type variable speed solar pumping system", Solar Energy, 208 (2020) 1039–1047.

[11] B.A.Bhayo, H.H.Al-Kayiem, S.I.Gilani, "Assessment of standalone solar PV-Battery system for electricity generation and utilization of excess power for water pumping", Solar Energy, 194 (2019) 766–776.

[12] Renu, B.Bora, B.Prasad, O.S.Sastry, A.Kumar, M.Bangar, "Optimum sizing and performance modeling of solar Photovoltaic (SPV) water pumps for different climatic conditions", Solar Energy, 155 (2017) 1326–1338.

[13] P.Santra, "Performance evaluation of solar PV pumping system for providing irrigation through micro-irrigation techniques using surface water resources in hot arid region of India", Agricultural Water Management 245 (2021) 106554

[14] S.Statkic, B.Jovanovic, A.Micic, N.Arsic, S. Jovic, "Adaptive neuro fuzzy selection of the most important factors for photovoltaic pumping system performance prediction", Journal of Building Engineering, 30 (2020) 101242.

[15] V.Sontake, A.K.Tiwari, V.R.Kalamkar, "Performance investigations of solar photovoltaic water pumping system using centrifugal deep well pump", Thermal Science, 24(5) (2019) 2915-2927.

[16] V.C.Sontake, A.K.Tiwari, V.R.Kalamkar, "Experimental investigations on the seasonal performance variations of directly coupled solar photovoltaic water pumping system using centrifugal pump", Environment, Development and Sustainability, 23 (2021) 8288–8306.

[17] M.Benghanem, K.O.Daffallah, A.Almohammedi, "Estimation of daily flow rate of photovoltaic water pumping systems using solar radiation data", Results in Physics, 8 (2018) 949-954.

[18] P.M.Kumar, C.Sharmeela, S.Amosedinakaran, S.Lokesh, C.Vimalarani, "Performance analysis of modified mppt techniques for pv pumping systems", Electrical Engineering, 72 (2021)

[19] S.Bana, R.P.Saini, "Identification of unknown parameters of a single diode photovoltaic model using particle swarm optimization with binary contraint", Renewable Energy, 101 (2017) 1299-1310.

[20] E.M.Salilih, Y.T.Birhane, "Modelling and performance analysis of directly coupled vapor compression solar refrigeration system", Solar energy, 190 (2019) 228-238.

[21] M.Premkumar, C.Kumar, R.Sowmya, "Mathematical modelling of solar photovoltaic cell/panel/array based on the physical parameters from the manufacturer's datasheet", Renewable Energy Development, 9 (1) (2020) 7-22.

[22] M.G.Villalva, J.R.Gazoli, E.R.Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays", IEEE Transactions on Power Electronics, 24 (5) (2009).

[23] M.Rasheed, O.Y.Mohammed, S.Shihab, A.A.Adili, "A comparative analysis of PV cell mathematical model", Journal of Physics: Conference series, 1795 (2021) 012042.

[24] M.T.Hagan, H.B.Demuth, M.H.Beale, O.Jesús, "Neural network design", PWS Publishing Co. (1997).

[25] T. L. Fine, "Feedforward neural network methodology". Springer Science & Business Media. (2006).