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Research article

An improved model and performance analysis for grid-connected photovoltaic system in Oman

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ABSTRACT

The PV systems' sources are environmentally friendly, but at the same time, they are constantly changing with time. When evaluating solar energy resources, it is necessary to consider the variability and effects of different environmental operation parameters like solar irradiances, ambient temperature, and module temperature. The study introduces a method to simulate an existing photovoltaic system using a mathematical model that permits intelligent strategies to optimise the efficiency and adjust the most effective operational parameters for the solar energy systems. A mathematical analysis for the data framework, including correlation and regression coefficients, was calculated to identify and chart the relationships between the system's most influential parameters and the generated power from the PV system. An improved mathematical model was built with the most influential parameters. The improved model was simple, accurate, and based on the loss ratio by eliminating the unknown parameters. The system's efficiency was analysed using an existing data framework-recorded hourly from 1st January 2017 to December 2018 for a grid-connected photovoltaic system installed in the south of Oman. The results showed that the most influential parameters on the efficiency were the module's solar irradiance and surface temperature. The operating parameters such as ambient temperature, wind speed, and air humidity had a negligible effect on the generated power compared to the cell temperatures and solar radiation. The dissipation factor was used in the new output current and voltage equations to stimulate the output power of the PV model. The improved model was validated in a MATLAB Simulink and showed a more promising output with a lower RMSE of 5 %.

1. Introduction

The energy demand has increased dramatically, putting more pressure on governments and private sectors to build new power plants to meet the demand. Most power plants worldwide run on gas or coal, which, along with other causes, will contribute to an expected increase in the Earth's temperature by 2.0 °C in 2050 [1,2]. Energy production technologies are rapidly developing to be more reliable and environmentally friendly. Wind power and solar power are the most widely used alternative and renewable energy sources [1]. These resources are sustainable and non-depletable, but they change depending on the nature of the source itself and weather conditions. Therefore, improving the renewable energy power station's efficiency and reliability can have the potential to utilise the RESs further. The processes for improving system efficiency deal with the system's productive output and the best methods to represent them in a computational model. The computational model helps study their current state and evaluate potential improvement methods. Various works have been carried out to investigate the relationship between the dependent operation parameters, the output parameter and the efficiency of the renewable energy system. Most of the obtained results are either theoretical or fitted to the laboratory measurements [2, 3, 4]. The different outdoor parameters, such as irradiance, temperature, humidity, wind speed, and dust, affect the output power produced by a PV power system by affecting the voltage and current. For example, the open-circuit voltage decreases when the ambient temperature increases, and the short-circuit current slowly rises, reducing Photovoltaic performance [5]. It was reported that the efficiency of the PV-PCM module could be enhanced by increasing the heat transfer

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between the PCM and the aluminum plate [6]. Because electrical energy is more costly than heat energy, the heat control should be carefully designed. Poor fluid heat transfer properties, such as water, are a significant obstacle to enhancing heat exchange and making heat exchangers more effective [7, 8]. In the grid-connected system, the output voltage is affected by the environment parameters fluctuation during the power generating process, which can be controlled by a DC converter when needed [9]. The obtained data for the photovoltaic systems under actual operating conditions are essential for studying the system's efficiency, estimating the electricity generated, and studying the system's behavior during different seasons. Data reliability investigations attempt to understand the system's current state and help make strategic planning and control [10]. The actual data framework for the system operating parameters is an essential reference for the operators to operate the system efficiently. These parameters affect system energy output, so it is necessary to evaluate their impact in the actual operating environment. In addition, a model has been developed to estimate the appropriate values for the most influential operating factor in order to improve its efficiency. The simulation model's accuracy is directly related to the chosen parameters and data consistency [11]. The precision of the data prepared for use as an input to the models will significantly impact output performance and the optimum value. As solar power plants, especially in the desert and high-temperature areas, suffer from a decline in their production efficiency despite the high level of solar radiation on the solar cells, it is necessary to evaluate their current efficiency and related factors.

The main contribution of this study can be summarised as follows:

- To analyse the performance of a current PV solar power station in the south of Oman using actual data from the targeted site.
- To determine the most impacted parameters that are affecting the PV power output.
- To generate an improved mathematical model for the case of this study by using the most affected parameters with loss ratio to model the PV power output rather than techniques used to determine unknown parameters.

The paper is organized as follows: Section 2 reviews the literature on PV module parameters, the mathematical models for the PV modules, and their applications in renewable energy planning, management and control. The methodology used for performance analysis of the solar system, statistical analysis and improved mathematical model process development is discussed in Section 3. In Section 4, the validations of the improved model based on a real case study evaluate the differences between the actual data and the output from the proposed mathematical model. Section 5 presents case study descriptions and details, followed by a discussion of the results, whereas the main conclusions are in the last section. The framework objectives are to demonstrate new methods to the PV energy operators and researchers in energy optimisation to operate solar power plants effectively by controlling the operation parameters and enhancing the generated power of the targeted system using intelligent heuristic methods.

2. Review on PV cell and related modelling approaches

Photovoltaic cells depend on semiconductor materials used to manufacture the PV modules, and their efficiency changes according to the type of semiconductor used. Nevertheless, all these cells have one way of working and take similar steps in producing energy. The standard parameters that are used to evaluate the performance of PV cells are the peak power (P_{max}), the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}) and the fill factor (*FF*). The highest produced voltage from a solar cell is the open-circuit voltage, which occurs when no current is applied [12]. The (*FF*) is the ratio at which the peak value of power can be obtained and can be calculated at a given value of (V_{OC}) and (I_{SC}) [13]. These common factors interact with the external parameters of the photovoltaic cell, concluding in changing the values of these parameters. The properties of the PV cell, the level of the incident solar irradiation and the area of the cell affect the values of the short circuit current and other stander parameters [14]. Therefore, it was necessary to study these factors and how they affect the power output from the PV cell. The literary works reviewed showed that the system-impacting parameters like the outdoor conditions, temperature, direct sunlight and dust affecting the PV cell parameters had the potential to increase or decrease system performance [15]. Temperature is one of the essential factors that influence the performance of the photovoltaic cells [16].

Moreover, similar conclusions were also reported in various research works which demonstrated that the most significant parameters to influence the performance of PV cells were temperature and solar irradiance. The simulation results for the PV cell using MATLAB in [17] showed the effect of the PV surface temperatures on the PV cell operations. The reverse saturation current for the PV cell increased when the cell temperature increased, and the open-circuit voltage (V_{oc}) was reduced, which decreased the fill factor; hence the output power of the solar cell dropped. It proved that the power produced by the PV module decreased by 0.47 % for each 1 °C increase above the surface temperature under standard test conditions [17, 18]. Therefore, the fluctuation of (V_{oc}) and (I_{sc}) resulted in decreased or increased PV system performance. These findings emphasise the importance of studying the impacts of these factors on the efficiency of solar power plants and determining the factors that influence energy production, permitting proper control. The starting point is to analyse the system's efficiency under actual operating conditions and calculate the efficiency rates. The PV solar system located in the hot regions suffers from a decline in its production despite the high level of solar radiation. Therefore, identifying the parameters that have more impact on the stations' productions will help facilitate and enhance monitoring their operations, which will lead to increased efficiency. The PV station's mathematical analysis is the key to understanding the relationship between the outdoor operating variable and the generated power. Correlations and regression are mathematical tools used to examine the relationships amongst variables and analyse how strong the relationships are. The values of the output coefficients decide the relationship between the variable and more data, leading to more accurate models and outputs [19]. The standard mathematical model for the PV cell is not reliable, but it is enough to understand the phenomenon within the PV cell parameters during working hours [20]. The mathematical model with series resistance works well for the crystalline module but shows an error when modelling the slim film innovation module [21]. It is concluded from the previous literature that most mathematical models have used unknown parameters like series and shunt resistance inputs. Different authors have considered standard parameter values like fill factor, series resistance, PV panel datasheet, and shunt resistance in modelling the PV power output [22, 23, 24, 25].

The aforementioned studies did not answer which model could provide the best reliable PV power output under actual operation issues. Hence, the use of known parameters like shunt resistance and series resistance in modelling the PV system leads to producing optimal values based on an assumption value and will not be accurate or cannot improve the efficiency in the actual operating environment. Therefore, there is an urgent need to develop a more reliable mathematical model to stimulate the PV power stations leading to finding the optimal solution to enhance the energy conversion efficiency. This model should be simple, accurate and validated based on real cases. In this work, identified real-data from Al-Mazyona PV power station, Sultanate of Oman have been adopted. An integrated data preparation framework for the established mathematical models has been designed. Besides, specialized mathematical models using MATLAB Simulink have been created for the identified measurements' optimization and validation processes. The root mean square error was the main performance indicator has been also considered in this study.

3. Performance analysis methods

The reliability and energy conversion efficiency of a conventional photovoltaic power station could be optimised when the most influential operational parameters could be controlled to fulfil the designated operational conditions. In this study, the methodology is divided into three main stages. Firstly, the efficiency of the targeted PV power plant will be analysed using the actual data captured from the site. In this stage, the analysis will evaluate the performance of the system. Secondly, the data's statistical analysis will help define the most influential parameters amongst the different studied operation parameters. Thirdly, developing a mathematical model to create a clear operational map of the relationship between the most influential parameters and the generated power output aims to address the reduction in the efficiency and enhance the output of the PV power station. These stages are discussed in sections 3.1 to 3. to 3.3.

3.1. Analysis using performance ratio

In general, the stability of solar power generation systems is evaluated in terms of the performance ratio. The performance ratio of solar power generation reflects the annual conditions of solar farms, which should be 0.7 to 0.9 [24]. Two methods are used when assessing the maximum power production of solar modules. The first approach calculates the peak power based on the (I–V) curve under certain conditions, such as the standard test condition (STC). In this first approach, PV module manufacturers evaluate their products according to the STC, which uses a standard spectrum of 1000 W/m^2 irradiation, a cell temperature of 25 °C and an air mass of AM 1.5 (corresponds to ASTM G173-03). The second approach uses a regression analysis of long-term data on module power generation. According the to IEC 61724 standard [25], the performance of the grid-connected PV system is evaluated by the final yield (Y_f)capacity factor (*CUF*), reference yield Y_r, and temperature loss coefficients (C_{tmp}) and the total energy generated by the PV system (E_{AC}). The performance evaluation of this grid-connected system can help develop, operate, and maintain existing and new grid-connected systems [26].

Final yield(Y_f): Is the total generated power divided by the rated power installation [27] as shown in Eq. (1). It is an essential factor to evaluate system efficiency.

$$Y_f = \frac{E_{AC}}{E_{RPV}} \times 100 \tag{1}$$

Where (E_{AC}) is the total generated power during a specific time, and (E_{RPV}) is the rated generated power by the system for the same period.

Capacity factor (CUF): Is the compression between the actual output from the PV solar station and the theoretical amount during a year [27] which can be calculated with the following equation:

$$CUF = \frac{E_{AC\ (kwh)}}{E_{RPV\ (kwh)}} \tag{2}$$

References yield (Y_r): Is the solar irradiance resources for the PV solar station defined as [28] and equation by:

$$Y_r = \frac{H_t}{G_o} \tag{3}$$

where (H_t) is the measured solar irradiance in W/m^2 on the PV panel, and (G_o) is the global irradiance at STC in W/m^2.

The performance ratio (PR): Describes the relationship between the PV solar station's actual and theoretical energy output [29] and calculated with the following equation:

$$PR\,\% = \frac{Y_f}{Y_r} \tag{4}$$

Temperature loss coefficient (C_{tmp}): The loss in the generated power from the PV module because of the surface temperatures [29] and calculated with the following equation:

$$C_{tmp} = 1 + \beta(T_{PV} - 25) \tag{5}$$

Where (β)is the temperature factor for the PV module, and (T_{PV}) is the surface temperature of the PV module in °C.

The actual recorded data play a vital role in evaluating any solar PV system efficiency after the installation. The data analysis process begins by examining the behaviour of the system's behaviour concerning the power generated. The operating variables are the primary parameters that determine the system's performance and are called independent variables. The strategy process for the data analysis in this paper has been divided into two parts. Firstly, the data analysis was conducted for the two years of 2017 and 2018 to understand the system's behaviour and determine the efficiency parameters like performance ratio (PR) and Temperature loss coefficient (C_{tmp}). Secondly, a correlation and regression analysis was performed to identify the most effective weather parameters for system efficiency: solar irradiation, ambient temperatures, surface temperatures, wind speed and humidity.

3.2. Correlation and regression analysis for the PV system

Statistical research is used on data to examine trends, patterns and relationships. The long-term data is used to create models to simulate operations at different meteorological values. Ambient temperatures, PV surface temperatures and solar radiation are the main factors that influence the PV power output with other operating parameters. An increase in the temperature of a solar module leads to a decrease in its performance. The PV power drops by 0.4% for every 1.0 °C of temperature increase [30]. The forecasting for the production of the PV solar for the short term or long term can help the operator or owner efficiently and economically use the renewable resources [31].

Correlation analysis is a mathematical tool used to determine the relationships amongst variables in a data set and the strength of those relationships. The output coefficients determine the relationships between the variables and the output. The correlation are defined as [19]:

$$p\,(a, b\,) = \frac{E\,(ab)}{\sigma a\;\sigma b} \tag{6}$$

$$R = \frac{n\left(\sum_{i=1}^{n} xy\right) - \left(\sum_{i=1}^{n} x\right)\left(\sum_{i=1}^{n} y\right)}{\sqrt{\left[n\sum_{i=1}^{n} x^2 - \left(\sum_{i=1}^{n} x\right)^2\right]}\sqrt{\left[\sum_{i=1}^{n} y^2 - \left(\sum_{i=1}^{n} y\right)^2\right]}} \tag{7}$$

Where E (ab) is the covariance for (a) and (b), and the (σa) and (σb) are the standard deviation of the variables (a) and (b), respectively. The squared Pearson correlation coefficient (SPCC) would be easier to use in most cases. The value of $p^2(a, b)$ must be between 0 and 1. It indicates the frequency of the linear relationship between two random variables. When the value of $p^2\,(a, b)$ is close to one, it means there is a clear relationship between variables and vice versa is correct. The two variables are independent when $p^2\,(a, b) = 0$. The other explanation for correlation officiation is defined in (7). The (R) is the correlation coefficient, *(x)* and *(y)* represent the first and second data set values, respectively, and *(n)* is the total number of values.

Regression analysis is a procedure used to chart the relations between the dependent and independent variables. There are various types of regression analyses, including linear, multiple linear and nonlinear. Nonlinear regression analysis is generally used for more complex data sets with a nonlinear relationship between the dependent and independent variables [32]. In this study, the dependent variable was the hourly generated power data, and the ambient temperatures, surface temperatures, wind speed, humidity and solar irradiances were the independent variables. Moreover, the received solar irradiation difference is caused by environmental factors, such as air temperature, wind velocity and the angle of incidence. From the actual data analysis, the amount of power generated is closely associated with irradiance. However, the air temperature, cell temperatures, humidity and wind velocity degree of influence is not very clear. Therefore, a regression method was selected to analyse the relations between all operation parameters: irradiance, air temperature, cell temperatures, humidity and wind velocity with the power generation amount. Based on a season, the correlation and regression analysis between the operation variable and solar farm output were studied. Furthermore, according to the regulator, the price of electricity is higher in summer than in winter, which makes generating electricity more profitable in summer than in winter.

3.3. PV system models

Several equations for the equivalent circuit were derived based on the standard theory. The mathematical model of the solar cell works via operating parameters such as solar radiation, temperature values and constant variables of the module, which is explained in [33]. The mathematical model for the PV was established and improved from the ideal photovoltaic model to a model with series and shunt resistance. The ideal or standard photovoltaic cell consists of a single diode connected in parallel with a light-generated current source. This model is not entirely accurate, but it is clear enough to describe the phenomenon occurring within a PV cell. By applying Kirchhoff's circuit law to the ideal PV cell, the output current of the ideal PV cell (I_{out}) can be calculated using Eqs. (8) and (9) [34]:

$$I_{out} = I_{Ph} - I_d \tag{8}$$

$$I_d = I_o\left[exp\left(\frac{V}{aV_T} - 1\right)\right] \tag{9}$$

The (I_{out}) is the output cell current in mA; (I_{ph}) is the solar cell photocurrent produced by incident light, which is directly proportional to sun irradiation; and (I_d) is the current across the diode. The current through the diode results from the reverse saturation current or leakage current (I_o) in mA which equation in (9). The diode voltage (V) in volts is generated by the movements of electrons used with the ideality factor-a and the thermal voltage (V_T) as shown in equation in (10) to calculate the diode current [31].

$$V_T = \frac{KT_{PV}}{q} \tag{10}$$

$$I_s = I_{rs}\left(\frac{T_{pvk}}{T_{refk}}\right)^3 \times e^{\frac{q\times E_g}{a\times K}\left[\frac{1}{T_{pvk}} - \frac{1}{T_{refk}}\right]} \tag{11}$$

$$I_{rs} = \frac{I_{sc-ref}}{\left(e^{\left(\frac{(q\times V_{OC})}{(T_{pvk}\times a\times K\times N_S)}\right)} - 1\right)} \tag{12}$$

$$I_{Ph} = G_r\left[\left(T_{pvk} - T_{refk}\right)k_i + I_{Ph.ref}\right] \tag{13}$$

The thermal voltage in the PV cell [35] is a relationship between the electrostatic potential and the electric current across a P–N junction expressed as shown in (10). Where (k) is the Boltzmann's constant, $= 1.38 \times 10^{-23}$ *J/K;* (T_{PV}) is a solar cell operating temperature in Kelvin (k) and the Electron charge is (q) $= 1.6021 \times 10^{-19}$ C. The diode current in the PV cell is small and divided into different currents: the saturation or leakage current of the diode (I_s) and the reverse saturation current (I_o) or (I_{rs}) as expressed in (11(11) and (12)(12) [36]. Various parameters must be measured, some of which are fundamental values given by manufacturers and dependent on the PV cell's materials and technologies. The test temperature for the module in Kelvin is (T_{refk}), the operation or surface temperature for the module in Kelvin *is* (T_{pvk}) and (E_g) is the bandgap energy of the semiconductor.

The ($I_{sc\text{-}ref}$) is the short circuit currents of the diodes of PV cells under standard test conditions (STCs). The STC is an industry-standard test that specifies cell output at 25 °C cell temperature and 1000 W/m^2 irradiance for an air mass of (AM1.5). Ns denotes the number of connected series cells in the PV module. After calculating reverse saturation current (12), it is vital to identify (I_{ph}) and calculate the total output current as explained in (8). The light-generated currents (I_{ph}) depend on the irradiance and temperature of the PV cell as shown in (13). The (k_i) is the short circuit current (A/K) coefficient temperature provided by the manufacturer. The (G_r) is the measured irradiances in W/m^2 on the PV surface and ($I_{ph.ref}$) is the light generated current at (STC).

3.4. PV module model with series resistance

An upgraded version model adds a series resistance (R_s) to the circuit and is named the (R_s-model). The series resistance (Rs) reflects the internal resistance to current flow and is affected by the semiconductors' p-n junction depth and contact resistance [37]. Despite being more accurate than the standard model, it shows considerable inaccuracy when subjected to high-temperature fluctuations since it does not reflect the open-circuit voltage coefficient. Moreover, it is suited well for the crystalline module, for example, mono and multi-crystalline. However, it shows an error when applied to slim film innovation.

This upgraded model can neglect the series resistance (R_s) and shunt resistance (R_{sh}), ignoring leakage current and losses. The main impact of series resistance is to reduce the fill factor. This model is more reliable than the ideal one, but it is not perfect, and the output current (I_{out}) can be expressed as in (14) where (I_s) represents the internal losses of the PV cell:

$$I_{out} = I_{Ph} - I_d - I_s \tag{14}$$

3.4.1. The improved model for the PV cell

The model with (R_s) and (R_{sh}) is the most widely used for simulating the operation of a photovoltaic panel. This model considers all resistances incorporated in a PV cell: internal resistance (R_s) and manufacturer defects (R_{sh}), producing more realistic results. This model consists of five parameters: series resistance (R_s), shunt resistance (R_{sh}), diode ideality factor A, diode current (I_d) and solar photocurrent (I_{ph}) [38, 39, 40, 41]. The current output (I_{out}) equals the light-generated current (I_{pv})minus the diode-current (I_d) and shunt-leakage current ($I_{sh,}$) as seen in (15). The shunt resistance (R_{sh}) is inversely related to the leakage current, and its effect is particularly severe at low light levels since there will be less light-generated current. Therefore, the loss of this current to the shunt has a more significant impact by providing a new path for the current flow. The current flow in the shunt resistance is determined by the following equations:

$$I_{out} = I_{Ph} - I_d - I_{sh} \tag{15}$$

$$I_{sh} = \left(\frac{(V + R_s\, I)}{R_{sh}}\right) \tag{16}$$

The increase in the shunt resistance will significantly decrease currents with a marginal decrease in open-circuit voltage. In addition, the PV conversion efficiency is sensitive to slight variations in *(Rs)*. The mathematical model for each case study cannot be represented using these established equations without further development or modification [42, 43]. There is a set of standard values for different parameters. In this paper, we have used a modification to develop the mathematical model corresponding to the captured data and the data sheet of the PV cell. For simplicity, the shunt resistance (R_{sh}) is assumed to be infinity since the production in the study case starts when the solar irradiance is high. Hence, the shunt current is equal to zero and can be ignored. The new equation of the (I_{out}) then becomes:

$$I_{out} = I_{Ph} - I_D \tag{18}$$

The diode current in the PV cell is divided into different currents, which are the saturation or leakage current of the diode (I_s) and the reverse saturation current (I_{rs}) and is equal to $I_D = I_s + I_{rs}$. By solving the equation in (18) for the diode currents, the output current (I_{out}) is obtained as following:

$$I_{out} = I_{Ph} - I_s - I_{rs} \tag{19}$$

The PV module is tested at a cell temperature of 25 °C, an irradiance of 1000 W/m^2, standard reference spectrums with an air mass of *AM 1.5*, and in this condition, the (I_{sc}), (I_{mp}), (V_{mp}) and (V_{oc}) are obtained in the data sheet. In this case, $T_{pvk} = T_{refk}$ and then Eq. (12) will be as follow:

$$I_s \cong I_{rs}\left(\frac{T_{pvk}}{T_{refk}}\right)^3 \times e^{\frac{q\times E_g}{a\times K}\left[\frac{1}{T_{pvk}}-\frac{1}{T_{refk}}\right]}$$

$$I_s \cong I_{rs}\left(\frac{T_{refk}}{T_{refk}}\right)^3 \times e^{\frac{q\times E_g}{a\times K}\left[\frac{1}{T_{refk}}-\frac{1}{T_{refk}}\right]}$$

$$I_s \cong I_{rs}(1\ )^3 \times e^0$$

$$I_s = I_{rs} \tag{20}$$

By substituting the values of (I_s) under the standard test conditions from Eq. (20) into Eq. (19), it yields to new equation for (I_{out}) as following:

$$I_{out} = I_{Ph} - 2\, I_{rs} \tag{21}$$

$$I_{out} = G_r\left[\left(T_{pvk} - T_{refk}\right)k_i + I_{Ph.ref}\right] - 2 \times \left[\frac{I_{sc-ref}}{\left(e^{\left(\frac{(q\times V_{OC})}{(T_{pvk}\times a\times K\times N_S)}\right)} - 1\right)}\right] \quad mA \tag{22}$$

The temperature coefficients for the open-circuit voltage (k_{tv}) describe the change in the output voltage. The output voltage from the PV module varies with the change of the surface temperature (T_{pvc}) and open circuit voltage (V_{oc}) *as* per the below equations.

$$V_{pv} = k_{tv}\left(T_{stc} - T_{pvc}\right) + V_{oc,} \tag{23}$$

$$V_{pv\ (model)} = k_{tv} \times T_{stc} - k_{tv} \times T_{pvc} + V_{oc} \tag{24}$$

$$V_{pv\ (\text{model})} = k_{tv} \times T_{stc} + V_{oc} - k_{tv} \times T_{pvc} \tag{25}$$

$$V_{pv\ (model)} = D - k_{tv} \times T_{pvc} \tag{26}$$

The *(D)* vector is obtained from the parameters provided by the manufacturer and equals $D = k_{tv} \times T_{stc} + V_{oc}$. The model Eqs. (22) and (26) must be interconnected and tested to simulate the actual PV power station. The best power from one panel will readily be seen when the voltage is 29.8 V, and the output current equals 8.39 A, which are the values for the best efficiency. The mathematical model must provide the same results that characterise the electrical properties of the PV plate.

The PV panel performance has been reduced during the life span, and the reduction in the PV panel is 0.63% per year, according to the Yingli-250 Wp manufacturer, as seen in Figure 1. When establishing the mathematical model, these constraints must be considered. The captured data belonged to 2017 and 2018, three years after the commencement of the solar farm operation. The commissioning of the PV panel was two years before 2015, the date of the completion of the project. After five years, the performance of the PV panel was 94.35 %, and this percentage has been used in the analysis and the improved mathematical model. The mathematical model would be a 250 Wp PV cell, so the output power must be 250 W as illustrated in the panel's data sheet under STCs. The voltage at this power must be 29.8 V. The new output voltage equations from the PV module should have the loss factor. The loss factor is the ratio between the voltage at 250 W and open-circuit voltage for $(V_{pv\ (model)})$, (I_{sc}) and (I_{mp}), representing the PV cell loss in current and voltage. The mathematical model will be validated according to a data sheet of the modelled PV panel as shown in Table 2 [41].

For AL Mazyonah PV station simulation, several PV panels were connected in parallel and series. The (N_p) represented the number of PV modules connected in parallel, and (N_s) was the number of PV modules connected in series. The improved mathematical model should have

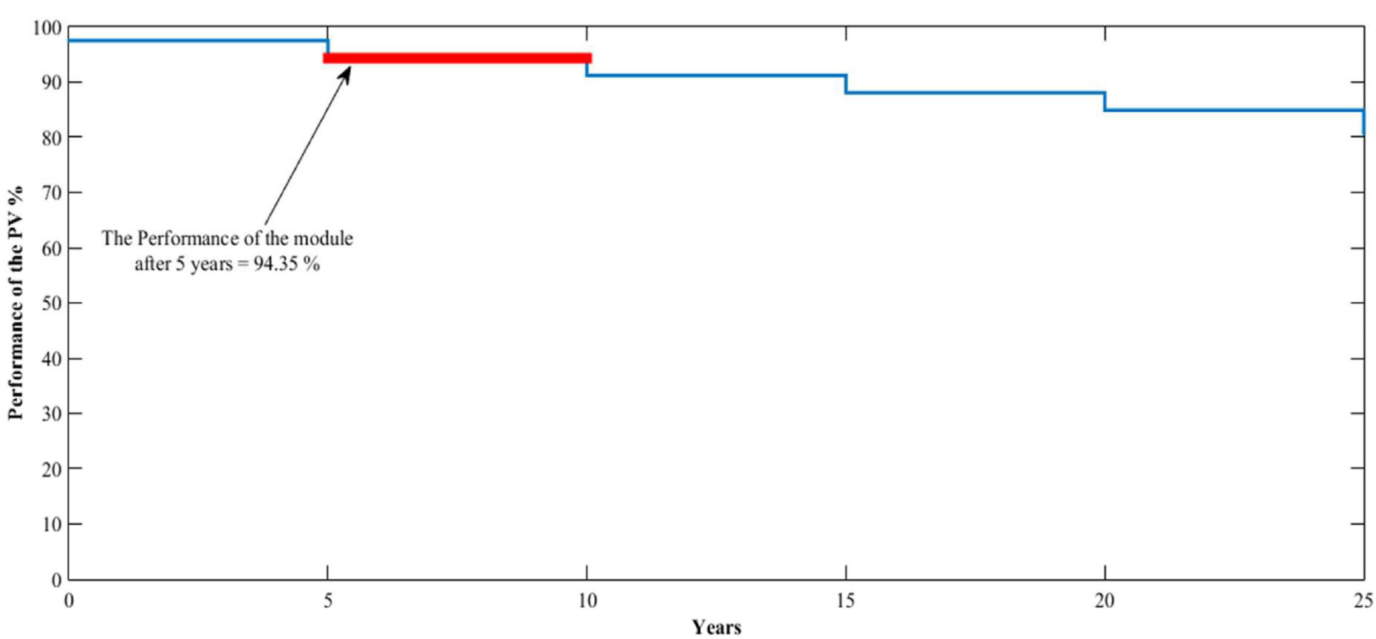

Figure 1. Performance of the PV panel during its life span.

generated the same output power as the existing PV power station by connecting 65 panels in one string and 19 arrays with 1235 panels. The new output current equations from the PV module should have had the loss factor. The loss factor is the ratio between the current at 250 W and the short-circuit current for *(It-out)* can be calculated using Eq. (27).

$$I_{t-out} = \frac{Imp}{Isc} \times I_{out} = 0.94 \times I_{out} \tag{27}$$

and the total output voltage was shown in Eq. (28)

$$V_{pv(model)} = \frac{Vmp}{Voc} \times V_{pv(model)} = 0.793 \times V_{pv(model)} \tag{28}$$

and the total generated voltage is shown in Eq. (29)

$$V_{tpv(model)} = N_P \times V_{pv\ (model\ )} \tag{29}$$

By using values in the data sheet, Eq. (26) =

$$V_{pv\ (model\ )} = (0.254 \times T_{pvc}) + 23.47 \tag{30}$$

It can be concluded that the mathematical model for the Al Mazyonah PV power station is as given in Eqs. (31) and (32). The unknown parameters like shunt resistance, series resistance and the saturation current can be ignored, and the loss in PV cells is represented by the loss factor, which simplifies the modelling process.

$$P_{(model)} = N_s \times I_{out} \times N_p \times V_{pv\ (model)} \tag{31}$$

$$P_{(model)} = I_{t-out} \times V_{tpv\ (model)} \tag{32}$$

Finally, the accuracy of the proposed model results will be validated in the next section by comparing the simulation results in MATLAB Simulink with other published papers using the non-ideal PV mathematical models, and rated output power and rated currents of the PV cell provided by the manufacturer. The photocurrent is the tested parameter assumed to equal the short-circuit current [40]. The efficiency for this model was calculated compared to the MAPE mean absolute percentage errors in [42, 43], which equals 6.4% as the best efficiency. Figure 2 demonstrates the working of the developed mathematical model.

3.5. Model validation

Irradiance and PV surface temperature were used as the input to the established mathematical model. The output current, output power and output voltage from the PV cell were calculated using (27), 28) and (29), which are shown in Figure 3.

The mathematical model results are promising and fit into the data sheet of the PV module. The differences between the values in the data sheet and the results obtained from the developed model were minor. The mathematical model developed in MATLAB has been validated with the data sheet of the modelled PV module. The MAPE for the tested parameters is equal to 5.8 %, better than the 6.4 % observed in other studies. The established mathematical model in the MATLAB software has been tested using the actual data captured from the site. According to (32), the input parameters are the system's data sheet, irradiances and surface temperatures. The established mathematical model has generated promising results with the actual data from the solar system. The root-mean-square error, which measures the differences between the

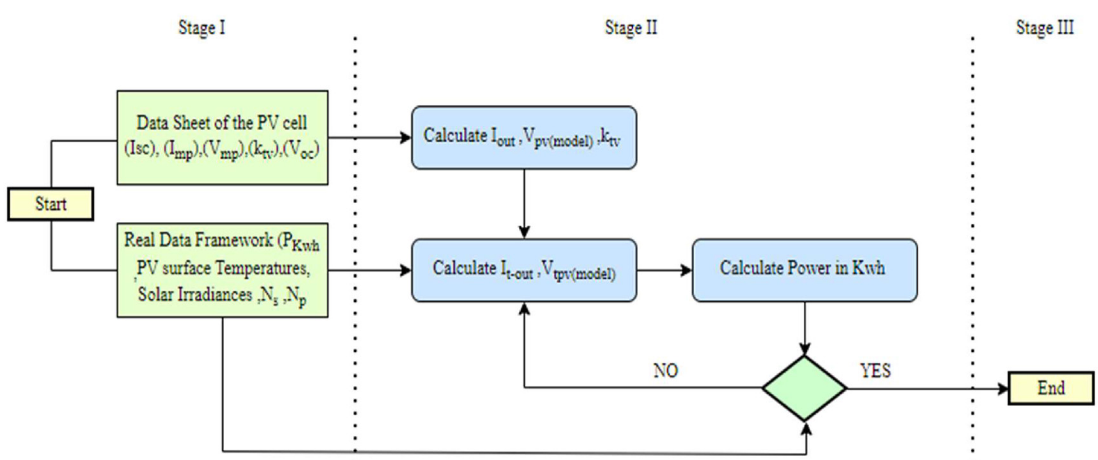

Figure 2. Flow chart for the developed Mathematical model.

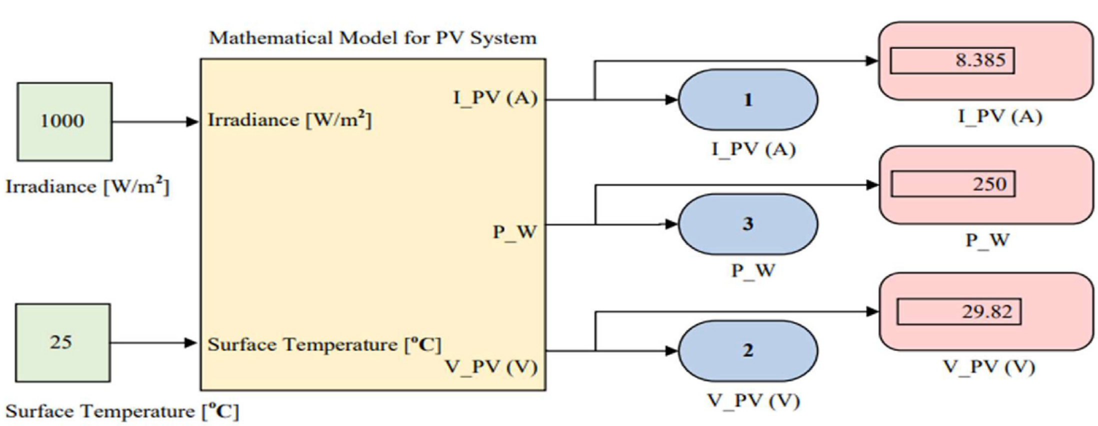

Figure 3. Mathematical model output using equations [26, 27, 28] for one PV cell.

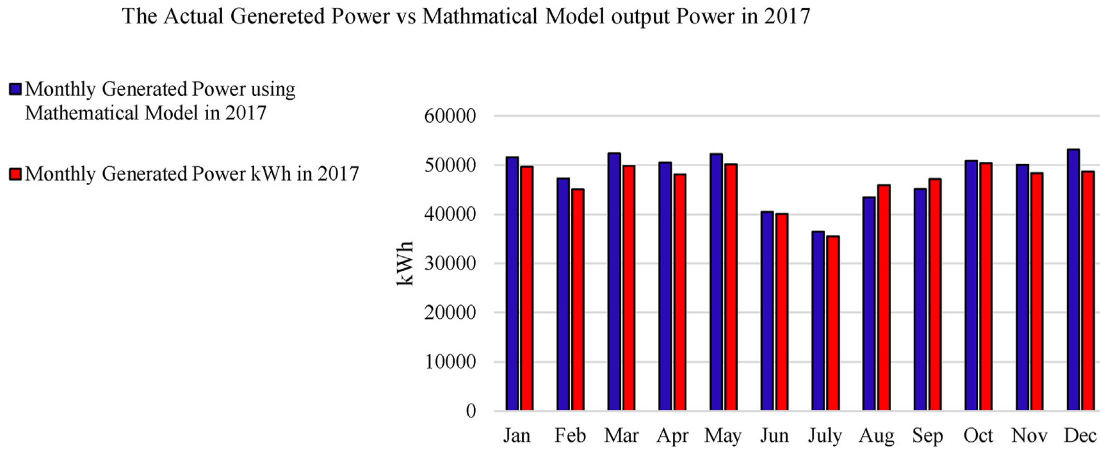

Figure 4. Performance of the PV mathematical model with actual data in 2017.

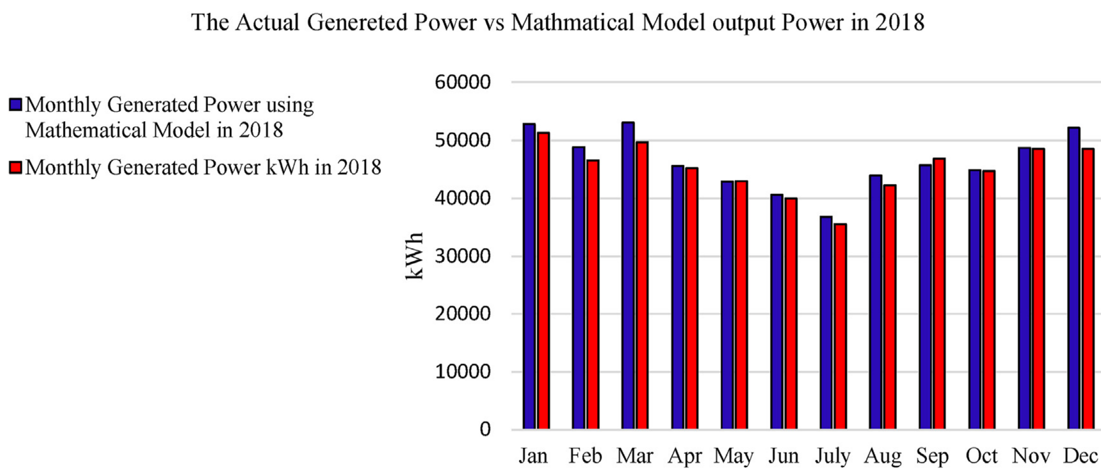

Figure 5. Performance of the PV mathematical model with actual data in 2018.

actual values and the values from the model, is equal to 15.9 kW, almost 5% of the rated power. Figures 4 and 5 below show the monthly generated power using the actual empirical data for 2017 and 2018 with the output from the improved mathematical model. The figures indicate the good fit between the outcome from the mathematical model and actual data. The approved mathematical model can investigate the relationship between operational parameters and generated outputs. In addition, this model can be used to optimise the selected parameters to improve the performance of the power plants.

4. PV power station case studies

Solar power plants in hot regions like the Al Mazyona PV station suffer from a decline in production in different seasons due to fluctuating climatic conditions and high temperatures. During the study of the efficiency of these PV stations and the various factors affecting them over their actual operation time, these factors can be identified, as well as the means through which it can be improved by simulating and overcoming them and increasing production.

In September 2015, Oman launched the first solar plant in the Wilayat of Al Mazyona in the Governorate of Dhofar. The project was intended for a daily output capacity of 307.7 kWh. The project's annual output was estimated to be 558 MWh. It consists of 1617 solar panels, whereas its land area is about 8,000 square metres. Figure 6 shows the location of the PV solar station.

Like other solar power stations, the PV power station includes PV cells and inverters. The solar farm is located in a desert environment and uses two types of PV cells. A YINGLI 250 Wp makes up the first type, and NEXPOWER makes up the other PV cells. The solar farm is equipped with a dry transformer that steps up the output voltage before linking to the 33 kV network substation. Table 1 shows the main components of the PV power station. The fundamental values for various parameters have been extracted from the manufacturers' PV panel data sheets [44] and are shown in Table 2.

Many technologies for PV cells are available today, including polycrystalline, mono-crystalline, multi-crystalline, multi-junction and concentrating cells. The main advantage of mono-crystalline cells is the high efficiency; however, producing mono-crystalline silicon requires a more complex operating system, making it more costly and less commercially demanded. On the other hand, multi-crystalline cells are less expensive and marginally less efficient than mono-crystalline cells because of the simple manufacturing process. The latest research uses multi-junction cells of various bands aiming to increase the energy conversion efficiency of conventional PC cells. However, this technology is more complex and costly, and has lower economic viability than other forms. The primary specification for the studied solar station consisted of different module sizes, different makes and technologies as shown in Table 1. The Yingli module was chosen to simplify the analysis and build the mathematical model in MATLAB software because it is more in the production's contribution than others. In addition, the Yingli PV 250 W PV model data sheet is clear with essential information as shown in Table 2. In this case, it needed to be connected with 65 PV cells in a series and 19 PV cells in parallel to produce 307.7 kWp.

Figure 6. The location of the PV power station.

5. Result analysis and discussion

In this section, the study results will be discussed and analysed. The efficiency evaluation of the targeted solar system under actual operation parameters is shown. The correlation coefficient between the operating parameters and the generated power is analysed to map the relationships. The reliability of the mathematical model used and the conclusion obtained from this research are presented.

5.1. System efficiency analysis

The system efficiency analysis is vital to understanding the system behaviours with the operation parameters and their impacts. The field data for the case study were collected on daily bases from 9.00 a.m. to 6.00 p.m. with various sensors to measure the operating parameters of the adopted PV power plant. The monthly electricity generation for 2017 and 2018 was analysed based on irradiation, ambient temperature, surface temperature, wind speed and humidity. The monthly average power generation and the performance ratio in 2017 are shown in Figures 7 and 8. The total amount of electricity generated in 2017 was 559.237 GWh and reached 218.96 GWh in summer (May, Jun., July, Aug., Sep.), which was about 39% of the annual electricity generation. In the winter 2017 (Jan., Feb., March, Apr.) and (Oct., Nov., Dec.), the generated output was 340.27 GWh, corresponding to approx. 60.8% of the annual electricity generation in that year. The monthly performance rate of the power plant fluctuated between 71% and 77% in 2017, as can be seen from Figure 7. These results have shown that the system had more efficiency in winter when the temperature was low. In the summer, the temperature loss coefficients were high because the PV surface temperatures were high, which led to a reduction in the power generated.

The system in January 2018, as shown in Figure 9, recorded a peak in electricity generation with a maximum of 51.34 GWh, followed by March 2018 with 49.67 GWh, which accounted for around 18.6 per cent of the total electricity generated by the PV system in 2018. The lowest electricity generation was in July with around 35 GWh, which made up about 6.5 per cent of the total annual electricity generation. The best performance ratio of the PV system was in January with 81%, and the lowest efficiency was in August with 69% as seen in Figure 10. As mentioned earlier, the lower temperature in January had played a significant role in increasing the productivity of the solar panel.

The total electricity production in 2018 was 542.138 GWh, 3% less than in 2017, whereas the average irradiation in 2018 was 650 W/and 660 W/min in 2017, which was almost the same. The loss in temperature coefficients were more in 2018 as seen in Figure 11. The system in 2018, as seen from the results, produced more energy in winter than in summer. The values of other parameters like solar irradiance were almost the same, but the cell temperature was high in summer, which proved that the cell temperature played a significant role. The average cell temperatures in 2018 were 2.6° higher than in 2017, and the average ambient temperatures were higher in 2018 than in 2017. It can be concluded that 2018 was warmer than 2017 and had less output from the system. Figure 10 shows the temperature loss coefficient for the PV cell, which needs further investigation to map the relationship. The other operating parameters, such as wind speed and humidity, remained the same. When

Table 1. Main component for solar system.

Component	Number	Total size	Contributions to the system	Reference
YINGLI 250 Wp - (Poly-Si)	609 cells	152.2 kWp	49.4 % in overall production	[44]
NEX-POWER 150 Wp- Thin film (a-Si)	576 cells	86.4 kWp	28.1 % in overall production	[45]
NEX-POWER 160 Wp- Thin film (a-Si)	432 cells	69.1 kWp	22.5 % in overall production	[45]
SMA inverter	10 inverters	Up to 10 kv	32 % in overall transformations from DC to AC	[46]
SMA inverter	21 inverters	Up to 14.7 kv	68 % in overall transformations from DC to AC	[47]

Table 2. PV module specification.

YINGLI 250 PV module	Specification
Power rating	250 Wp
Number of cells	1235
Peak efficiency	15.4 %
The voltage at max power	29.8 V
The current at max power	8.39 A
The short circuit current	8.92 A
The voltage at the open circuit	37.6 V
Maximum system voltage	714.4 V

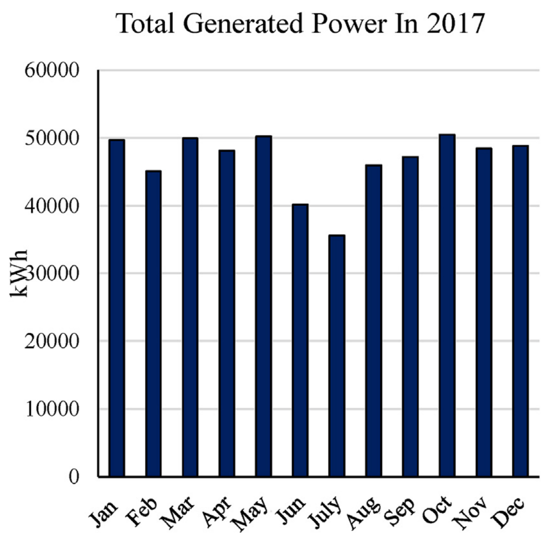

Figure 7. Monthly generated power in 2017.

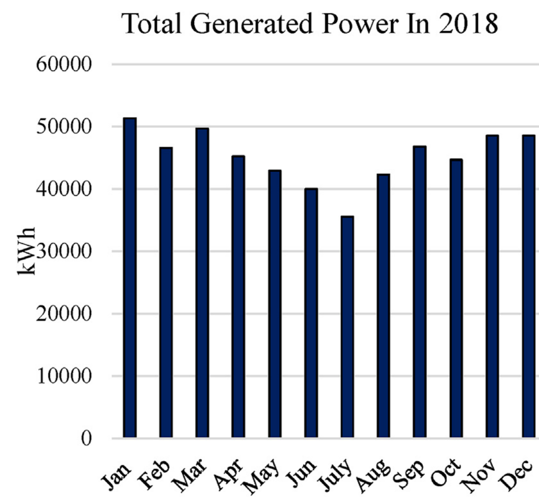

Figure 9. Monthly generated power in 2018.

discussing the properties of the relationship between the electricity production of a solar cell and external factors, the cell temperature and solar irradiance were generally seen as the dominant factors in the solar system.

5.2. Correlations and regression analysis

The correlation analysis shows that the humidity and wind speed had relatively small effects on the efficiency of the investigated solar farm. The correlation parameters (*R*) for each variable between the output and the operating parameters were analysed. The range of change in the daily output generated by the system was significant. The generated power was influenced by various operating parameters such as irradiation intensity, air temperature, surface temperature, wind speed, humidity etc. The correlation coefficients between the operation's parameters and generated output in the winter of 2017 are shown in Figure 12.

The solar irradiance and the cell temperatures had more impact on the generated power as seen in Figure 12. The other studied parameters had low correlation coefficients, meaning there was no clear relationship between these parameters and the generated power. Figure 13 shows the correlation coefficients between the generated power and the operation's parameters in the summer of 2017.

Like the winter months, the solar irradiance and the cell temperatures had more impact on the generated power than other parameters. Compared to the winter months, the impact of cell temperature was less in summer as seen in Figure 12. Figure 14 shows the correlation coefficients between the generated power and operation parameters from winter 2017 to the first quarter of 2018.

There was no clear relationship found between the generated power and wind speed, humidity and ambient temperatures. The correlation coefficients were more between the solar irradiance, cell temperatures and generated power than other parameters in winter 2017–2018 as seen in Figure 14. Figure 15 shows the correlation coefficients in the summer of 2018.

Figure 16 shows the correlation coefficients in winter 2018 between the generated power and the operation parameters. As seen in Figure 15, the solar irradiance and the cell temperatures had more impact on the generated power than other parameters. On the other hand, wind speed and humidity had a less negative correlation coefficient on power.

The solar irradiance and the cell temperatures had more impact on the generated power than other parameters as seen in Figure 16. The correlation between the generated power and the solar irradiance was almost the same during the analysis periods. The second parameter with a high correlation was the PV cell temperature, and it was more in winter than in summer. The solar farm generated more electricity in winter than

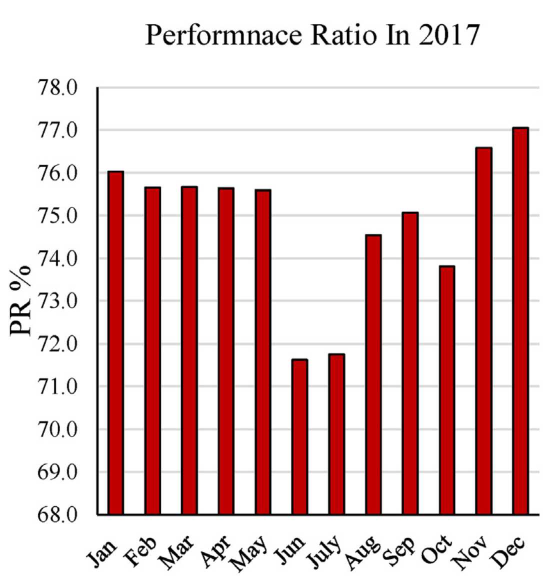

Figure 8. Monthly performance ratio in 2017.

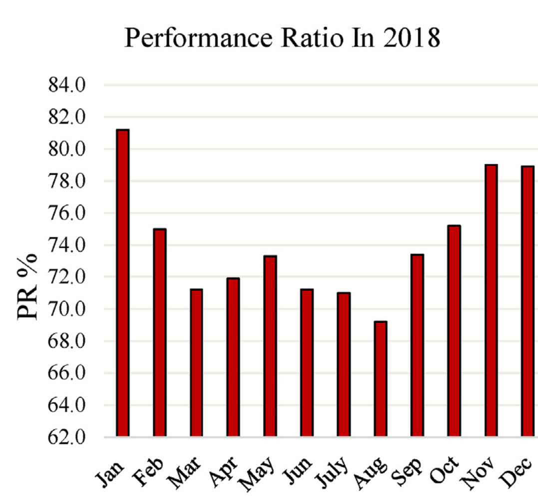

Figure 10. Monthly performance ratio in 2018.

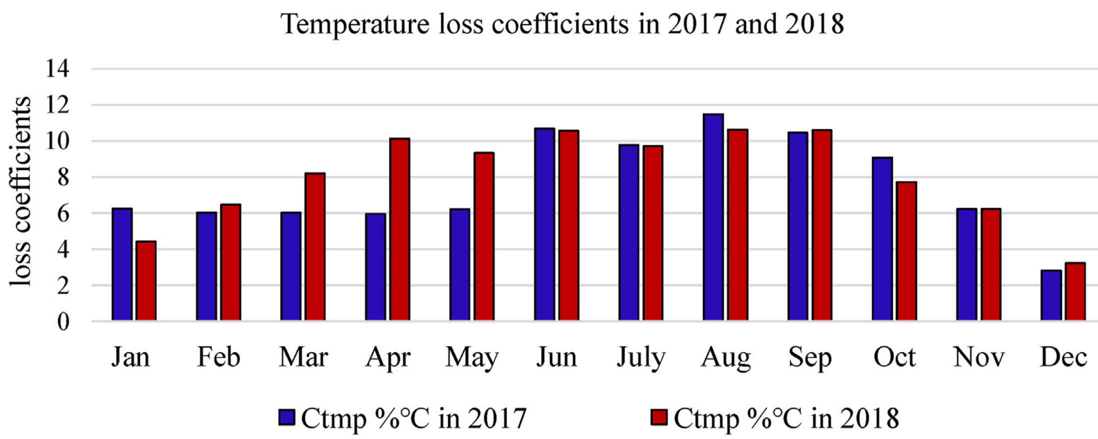

Figure 11. Temperature loss coefficients in 2017 and 2018.

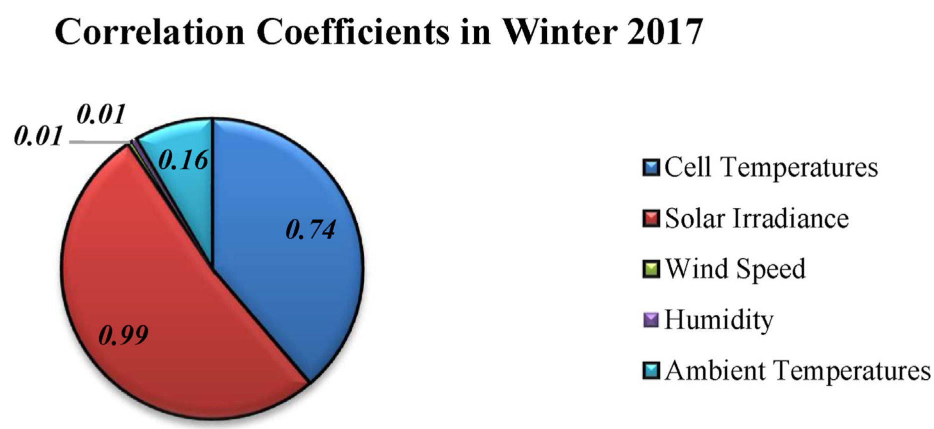

Figure 12. Correlation between the generated power and the outdoor parameters in winter 2017.

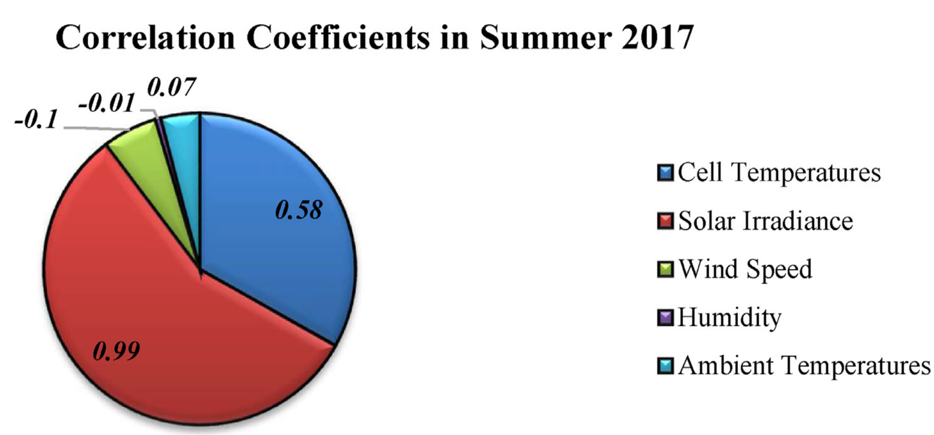

Figure 13. Correlation between the generated power and the outdoor parameters in summer 2017.

in summer. There was a clear linear relationship between the average solar radiation and the average generated power.

On the other hand, the increase in cell temperature in the summer affected the electricity production although the average solar radiation in summer was generally high. Based on the results from the correlation analysis, the influential variables on the systems were evaluated and have been listed in Table 3. The monthly regression line between the PV cell temperature and generated power is shown in Figure 16.

The regression line for the cell temperature in winter had a steeper slope than in summer, as shown in Figure 17, which means that the cell temperature had more impact in winter than in summer. In contrast, solar irradiance had the same impact in both seasons. In 2017, the average cell temperature was 44 °C, and in 2018, it was 45.2 °C, where the highest cell temperatures were observed in June and July. The average cell temperature in winter 2017 was 40.68 °C, whilst it was 41.93 °C in winter 2018. In 2018, the average cell temperature increased by 2% in the summer, reaching 49.82 °C. Figure 18 shows the monthly regression lines between the generated power and the solar irradiance.

In Figure 18, the regression line slope for the solar irradiances during the year was close to one and almost the same value for all seasons, which

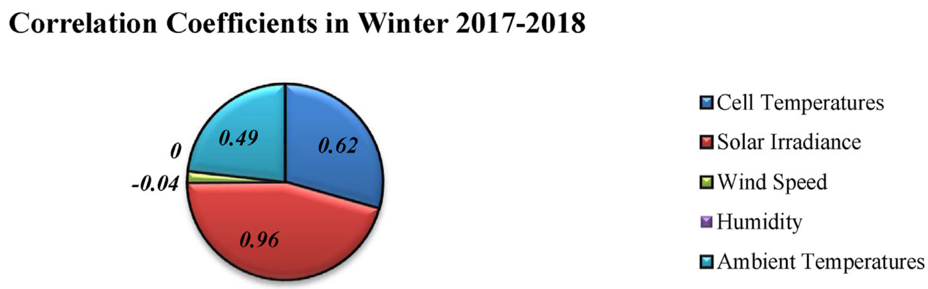

Figure 14. Correlation between the generated power and the outdoor parameters in winter 2017–2018.

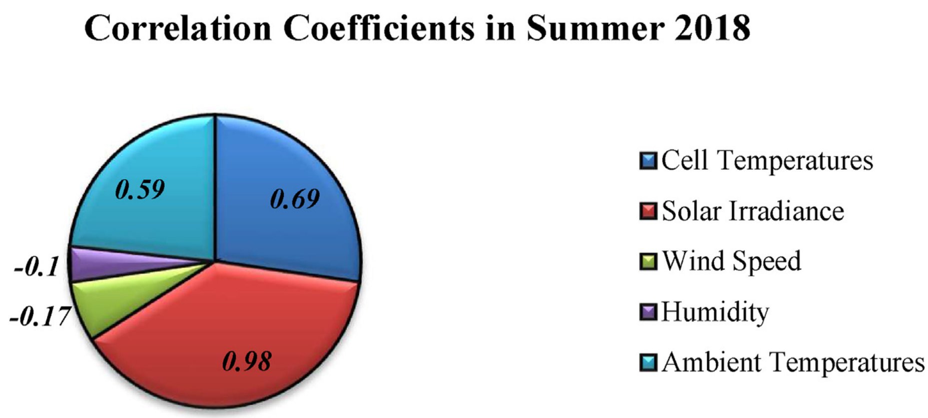

Figure 15. Correlation between the generated power and the outdoor parameters in summer 2018.

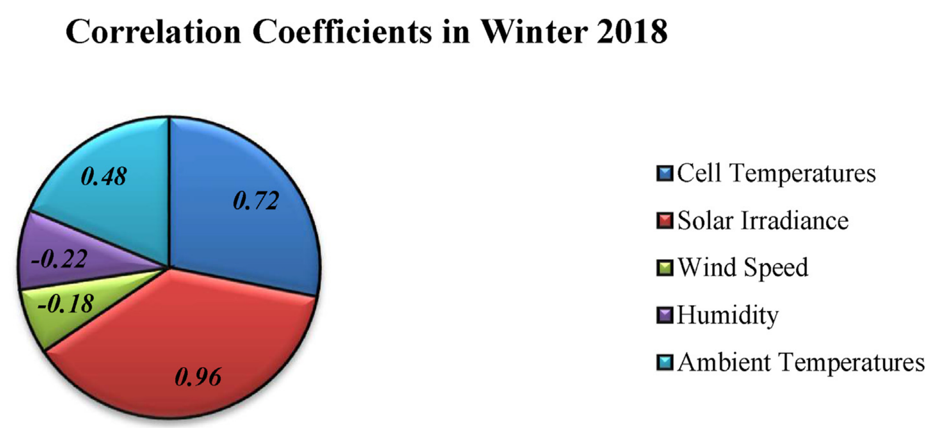

Figure 16. Correlation between the generated power and the outdoor parameters in winter 2018.

means that the solar irradiances had the same impact. In any season, the R-square for the standard and multiple regression coefficients of solar irradiance was more significant and more than 0.93. Therefore, radiance was considered the most critical influence factor for power generation, and the direct relationship was empirically proved. The obtained R square from the regression analysis during the data periods is shown in Figure 19.

In Figure 19, the R-square for the standard and multiple regression coefficients of cell temperatures in all seasons was more than other studied parameters. Therefore, cell temperature could be considered the second most vital influence factor in power generation. That is to say, a rise in the ambient temperature would increase the cell temperature, which would decrease the conversion efficiency of the module. On the other hand, it was found that the best R-square values for the standard and multiple regression of the air temperature, wind speed and humidity were only -0.34, 0.0333 and 0.048, respectively. These values showed that the influence of air temperature, wind speed and humidity on the amount of power generation was comparatively low as proved by the correlation analysis. Generally, the cell temperature is influenced by wind velocity. The influence of wind velocity has been included in expressing relations of the cell temperature and output characteristics of

Table 3. The summary for the correlation analysis.

Parameters	Correlations
Solar Irradiances	Very high correlation
PV Surface Temperature	High correlation
Ambient Temperatures	Moderate correlation
Wind Speed and Humidity	Can be ignored or weak correlation

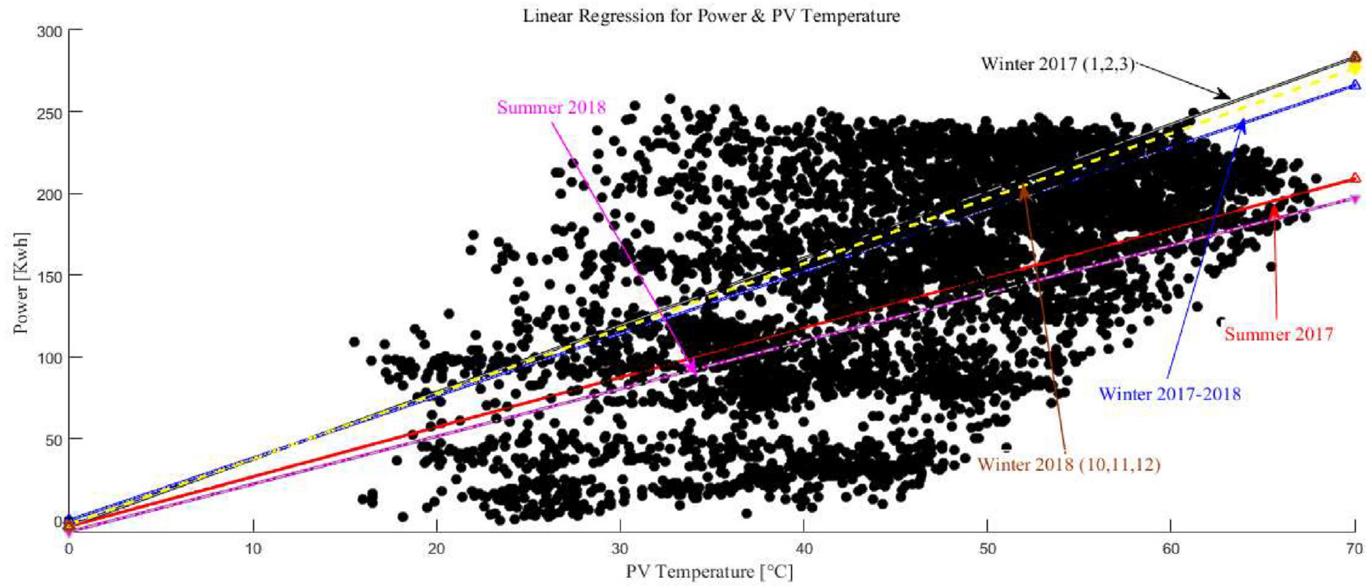

Figure 17. Regression lines for the power and PV temperatures in different seasons from 2017 and 2018.

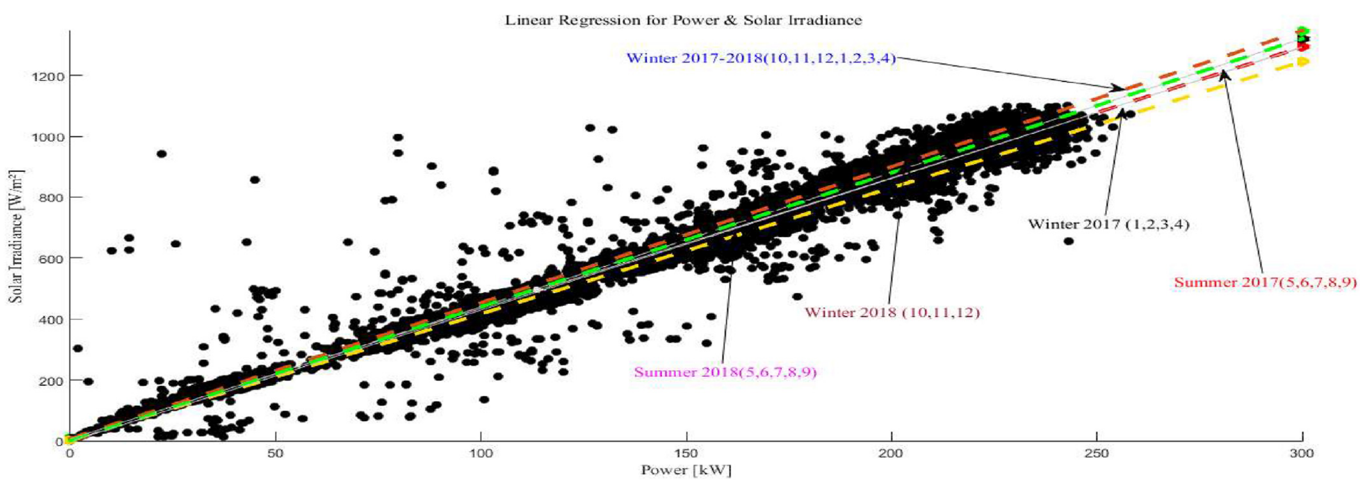

Figure 18. Regression lines for the power and solar irradiances in different seasons from 2017 and 2018.

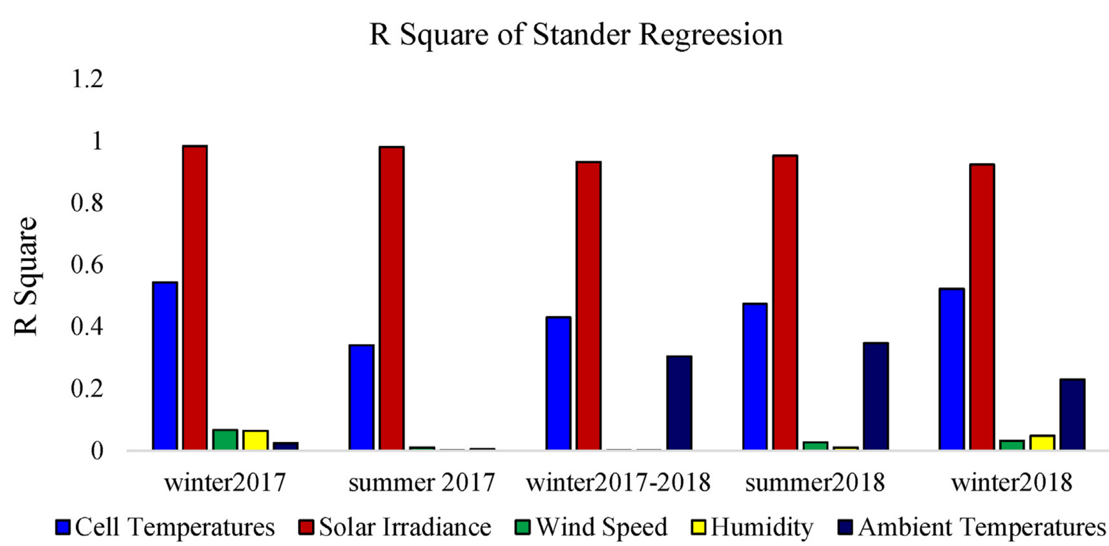

Figure 19. The R square obtained from the regression analysis.

solar cells in other research documents. However, in this case study, it was found that the effect of wind velocity on the amount of power generation was minimal and not clear from the regression and correlation analysis. In our judgment, wind velocity might have had an essential effect in cooling down the cell temperatures. The most critical factor of power generation was found to be irradiance, followed by cell temperatures and other operating parameters that had a negligible effect.

6. Conclusion

This study developed a mathematical model that can be used and applied to the intelligent algorithm to optimise the most effective operating variable and enhance the power generated from the targeted station. The data analysis was carried out for an existing 307.7 kWh grid-connected solar system in the south of Oman. The consistency of the data framework prepared for use as input directly impacted the outcomes of this study since no data planning strategy had been offered, and the operator had not previously considered it. The efficiency ratio in 2018 was 3% lower than in 2017 as obtained from the performance analysis. The performance study of the grid-connected system can help with the development, operation and maintenance of existing and new grid-connected solar systems. The most influential parameters of the generated power were identified as solar irradiance and cell temperature as shown in the correlation and regression analyses. The other operating parameters, such as ambient temperature, wind speed, and air humidity, had less influence on the generated power than the cell temperatures and solar radiation. The proposed approach provides an improved mathematical model for the Al Mazyonah solar farm, allowing the researcher to analyse the performance of the targeted system and achieve the planned goals. The improved mathematical model for the case was developed, based on previous models and PV cell temperatures with loss ratio, to model the PV power output rather than techniques used to determine unknown parameters. The main contribution of the established mathematical model is that the new output current and output voltage equations having the dissipation factors (27) and (28) with the reverse saturation current can be used to calculate the output power of the PV module. The mathematical model was validated in a MATLAB Simulink compared to previous studies and actual data, which showed a good fit with a lower RMSE equal to 5 %. In future work, the efficiency of the PV power station can be optimised using heuristic methods to control and optimise the PV cell temperature and increase the generated power.

Declarations

Author contribution statement

Firas B Ismail Alnaimi, Omar A Al-Shahri, Nizar F.O. Al-Muhsen, Ammar Al-Bazi, M A Hannan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

The data that has been used is confidential.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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