Experimental study on the influence of temperature and radiation on photovoltaic power generation in summer

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Abstract. The power generation of photovoltaic systems is random and uncertain, which is the result of a variety of factors. However, there are few studies considering the interaction of two or more factors at the same time. Therefore, the influence of air temperature and radiation on photovoltaic power generation is considered in this paper, and based on the physical system, the experimental data is processed and analyzed through SPSS and DPS data analysis software and the multiple nonlinear regression analysis model. The processing results show that whether it is the quadratic and cubic nonlinear regression equations or the quadratic and cubic trend surface fitting degrees all reach a significant level, it can be used to reveal the law of the influence of two factors on the power generation under the test environment. The analysis results found that the combined effect of temperature and radiation on photovoltaic power generation is more complicated, but the overall impact of solar radiation is significant and greater than the air temperature; low temperature and high radiation, high temperature and high radiation and low radiation conditions have side effects on photovoltaic power generation; when the two are enhanced at the same time, it will help increase the photovoltaic power generation; when the two “one increase and one decrease”, the photovoltaic power generation first increases and then decreases, and there is an optimal air temperature, solar radiation, and maximum photovoltaic power generation.

1. Introduction

The operation of the photovoltaic system is an unbalanced random process. The amount of solar radiation and the working temperature of photovoltaic modules are considered to be the two main factors affecting photovoltaic output[1,4,6], but the working temperature of photovoltaic modules is a combination of air temperature and solar radiation. Therefore, in the final analysis, the main impact on the output of the photovoltaic system is the meteorological conditions where the system is located.

Rahman et al.[2,3] used different methods to test and study photovoltaic systems in 2015 and 2016. Through discussion of factors affecting system performance, they found that the operating temperature, solar radiation, humidity and dust of photovoltaic modules have significant impact on the working performance of photovoltaic modules. Hahsim et al.[4] conducted experimental research under Baghdad climate conditions, and discussed the influence of air temperature on the power generation performance of crystalline silicon, amorphous silicon and CIGS photovoltaic modules at 10 ~ 35°C. Aish[5] used a photovoltaic panel analyzer to conduct professional tests on the power generation performance of monocrystalline silicon, polycrystalline silicon, and CIGS photovoltaic modules at different air temperatures (25°C, 35°C, and 45°C). The test results show that when the solar radiation is 100~1000W/m², the power generation of the three will decrease with the increase of
air temperature, the degree of which is monocrystalline silicon(0.54%/°C) > polycrystalline silicon (0.49%/°C) > CIGS(0.38%/°C). Zhu Honglu et al.[6] qualitatively and quantitatively analyzed the impact of various environmental factors on the output of photovoltaic system, and calculated the efficiency of photovoltaic system under the influence of various environmental factors. The results show that the influence degree of environmental factors on the output of photovoltaic system is solar radiation > photovoltaic module temperature > air humidity (the impact is small and can be ignored). Wang Qi et al.[7] used simulation methods to analyze the power generation characteristics of the photovoltaic power generation system at a radiation intensity of 1000W/m² and an air temperature of 25°C and 50°C. Yu Jiahe et al.[8] systematically summarized the influence of temperature on photovoltaic modules, and proposed that environment and the structure of PV modules are the main factors affecting the module temperature. Wang Chunlong et al.[9] discussed the influence of photovoltaic module surface temperature on its output voltage, current and power generation under low temperature conditions.

In summary, it can be found that most of the research on the factors affecting the power generation of photovoltaic systems focuses on the impact of a single factor, and less considers the simultaneous impact of multiple factors. Therefore, this paper analyzes the impact of air temperature and solar radiation on photovoltaic system power generation based on the experiments, which has extremely important practical significance.

2. Experiment device and design

2.1. Experiment device
The independent photovoltaic power generation system in this experiment is mainly composed of photovoltaic array, battery, controller, inverter and AC load. The system connection schematic diagram is shown in Figure 1, and the actual system diagram is shown in Figure 2.

![Figure 1. Schematic diagram of independent photovoltaic power generation system](image1)

![Figure 2. Physical drawing of independent photovoltaic power generation system](image2)

2.2. Experimental design
This experiment is based on a 1kW independent photovoltaic power generation system installed in Tianjin University of Commerce, Beichen District, Tianjin. During a week from July 18th to 23rd, 2020, the data of average solar radiation, average air temperature and photovoltaic system power generation from 6 am to 20 pm were recorded hourly. In order to ensure the accuracy of the data, the hourly solar radiation and air temperature are obtained in two ways, as references to each other: One is to record the hourly temperature through the temperature tester, and the hourly solar radiation by TES-
1333R solar meter; the other is to retrieve hourly average solar radiation and average air temperature from 6 am to 20 pm every day in a week through API data interface of China Meteorological Science Data Center website. The operation data of photovoltaic system such as power generation can be obtained through the data monitoring software matched with the controller. Theoretical analysis and methods

2.3. Theoretical analysis of factors affecting solar cell power generation

Photovoltaic cell panel is a series of photovoltaic elements with “photovoltaic” effect to convert light energy into electric energy. Its power generation effect is usually affected by many factors, such as solar radiation, temperature, wind speed, air humidity and the cleanliness of photovoltaic panels. When characterizing the power generated by photovoltaic panels, equations (1) [10] is usually used as the theoretical basis:

\[ P_{pv} = P_{STC} \frac{G_s}{G_{STC}} \left[ 1 + \gamma(T_e - T_{STC}) \right] \] (1)

Where: \( P_{pv} \) —The output power of photovoltaic panel when it works, kW; \( P_{STC} \) —The rated output power of the photovoltaic panel, kW; \( G_s \) —The amount of solar radiation when the photovoltaic panel is working, kW/m²; \( \gamma \) —Power temperature coefficient; \( G_{STC} \) —The standard rated light intensity, 1kW/m²; \( T_{STC} \) —Standard rated air temperature, 25°C; \( T_e \) —The temperature of the PV panel during operation, °C.

Among them:

\[ T_e = T_{air} + KG_s \] (2)

Where: \( T_{air} \) —air temperature; K—the proportional constant.

Then equation (1) can be changed to equation (3):

\[ P_{pv} = \frac{P_{STC}}{G_{STC}} \left( KG_s^2 + \gamma G_s T_{air} - G_s T_{STC} + G_s \right) \] (3)

The accumulation of power generation over a period of time is the power generation capacity of photovoltaic panels, then:

\[ P_c = \int_{n=1}^{24} P_{pv}(T_{air}, G_s) \] (4)

Where: \( P_c \) —Photovoltaic panel power generation capacity; \( n \) —Time of day(i=1~24).

It can be seen from the above formula that the relationship between solar radiation, air temperature and photovoltaic panel power generation capacity is nonlinear.

2.4. Data analysis method

SPSS data analysis software and DPS data processing software were used for regression equation and trend surface fitting respectively. Among them, SPSS was used for partial correlation analysis of each regression coefficient in the equation, and the significance of each regression coefficient was reflected by p value (the significance level of multiple regression could be enlarged to 0.25).

In this paper, the equation and trend surface fitting in the two kinds of software are both binary nonlinear regression model. When the highest degree of the independent variable is 2, the model of the binary quadratic nonlinear regression equation is as follows:

\[ Z = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 x^2 + \beta_4 xy + \beta_5 y^2 \] (5)
When the highest degree of the independent variable is 3, the model of the binary cubic nonlinear regression equation is as follows:

\[ Z = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 x^2 + \beta_4 xy + \beta_5 y^2 + \beta_6 x^3 + \beta_7 x^2 y + \beta_8 xy^2 + \beta_9 y^3 \]  

(6)

Where: \( \beta_i \) — The regression coefficient, the degree of influence of independent variable on dependent variable; \( x \), \( y \) — Independent variable; \( Z \) — Dependent variable.

3. Results and discussion

3.1. Regression equation results and discussion

Take the hourly photovoltaic power generation capacity \( P_c \) from 6 a.m. to 20 p.m. every day within a week as the dependent variable, average air temperature \( T_{air} \) and radiation \( G_s \) as the independent variables. The multivariate nonlinear regression model is used to fit the binary quadratic nonlinear regression equation and the binary cubic nonlinear regression equation. The partial correlation analysis of each equation and its corresponding regression coefficient is shown in Table 1 and Table 2.

| Table 1. Binary quadratic nonlinear regression equation |
|-------------------------------------------------------|
| \( P_c = -125.7481 + 10.4454 T_{air} + 0.3175 G_s - 0.2107 T_{air}^2 \) | \( -0.0058 T_{air} G_s + 0.0001 G_s^2 \) |
| \( p \) | \( \text{Fitting} \) |
| t | p |
| 2.0218E-37 | 88.17% |

| Regression coefficients | Regression coefficient value | t | p |
|-------------------------|-------------------------------|---|---|
| \( \beta_0 \) | -125.7481 | -0.8781 | 0.3824 |
| \( \beta_1 \) | 10.4454 | 0.9977 | 0.3213 |
| \( \beta_2 \) | 0.3175 | 3.6700 | 0.0004 |
| \( \beta_3 \) | -0.2107 | -1.9993 | 0.0488 |
| \( \beta_4 \) | 0.0058 | -1.1261 | 0.2633 |
| \( \beta_5 \) | 0.0001 | 2.5355 | 0.0131 |

| Table 2. Binary cubic nonlinear regression equation |
|---------------------------------------------------|
| \( P = -1584.7996 + 186.7830 T_{air} - 1.5016 G_s - 7.2267 T_{air}^2 + 0.1476 T_{air} G_s \) | \(-0.0009 G_s^2 + 0.0914 T_{air} G_s^2 - 0.0030 T_{air}^2 G_s + 0.00003158 T_{air} G_s^2 + 0.000000823 G_s^3 \) |
| \( p \) | \( \text{Fitting} \) |
| t | p |
| 1.0851E-36 | 90.25% |

| Regression coefficients | Regression coefficient value | t | p |
|-------------------------|-------------------------------|---|---|
| \( \beta_0 \) | -1584.7996 | -1.5364 | 0.1284 |
| \( \beta_1 \) | 186.7830 | 1.6468 | 0.1035 |
| \( \beta_2 \) | -1.5016 | -2.0849 | 0.0403 |
| \( \beta_3 \) | -7.2267 | -1.7611 | 0.0820 |
| \( \beta_4 \) | 0.1476 | 2.9642 | 0.0040 |
| \( \beta_5 \) | -0.0009 | -2.5377 | 0.0131 |
| \( \beta_6 \) | 0.0914 | 1.8688 | 0.0653 |
| \( \beta_7 \) | -0.0030 | -3.4992 | 0.0008 |
Observing Table 1 and Table 2, we can find that the fitting degrees of the binary quadratic and cubic nonlinear regression equations are 88.17% and 90.25%, respectively, and the fitting degrees are both high. Therefore, a simpler quadratic nonlinear regression equation can be selected for analysis.

Analyze the binary quadratic nonlinear regression fitting equation: The regression coefficients of air temperature and radiation are both positive, which indicates that increasing temperature and radiation alone in summer will increase the test photovoltaic power generation capacity; the regression coefficient \( p(0.3213) \) of air temperature is greater than 0.25, and the regression coefficient \( p(0.0004) \) of solar radiation term is far less than 0.25, which indicates that the influence of solar radiation on photovoltaic power generation capacity is far more significant than that of air temperature. The regression coefficient of the interaction term is negative and \( p(0.2633) \) is greater than 0.25, which indicates that the interaction between air temperature and solar radiation is not significant in summer; the quadratic regression coefficient of air temperature is negative and \( p(0.0488) \) is less than 0.25, which indicates that excessively high air temperature in summer has a very significant negative impact on photovoltaic power generation capacity; the quadratic regression coefficient of solar radiation is positive and \( p(0.0131) \) is less than 0.25, which indicates that excessive solar radiation in summer has a significant increase in photovoltaic power generation capacity.

### 3.2. Trend surface results and discussion

Take the hourly photovoltaic power generation capacity from 6 a.m. to 20 p.m. every day within a week as the dependent variable, air temperature and radiation as the independent variables. Based on the multiple nonlinear regression model, use the trend surface analysis function of DPS to fit the quadratic and cubic trend surfaces, as shown in Figure 4 and Figure 5.

| \( \beta_1 \) | 0.00003158 | 2.5751 | 0.0119 |
| \( \beta_2 \) | 0.0000000823 | 0.3893 | 0.6981 |

* Student’s t test; \( p \) Represents the smallest significance level that does not accept the null hypothesis

Figure 3 and Figure 4 use the same regression model as Table 1 and Table 2. Therefore, the fit degree of Figure 3 is 88.17%, and the fit degree of Figure 4 is 90.25%, which indicates that the fitting results of Figure 3 and Figure 4 are better.

Analyze the trend surface of Figure 3 and Figure 4: When the air temperature is 21~36°C and the solar radiation is 5~890W/m\(^2\), the power generation capacity is between 0~250W.h, which is consistent with the power generation capacity data measured by the photovoltaic system used in the test; in the low temperature high radiation area(\( T_{air} <24°C, G_s >520W/m^2 \)), high temperature high radiation area(\( T_{air} >30°C, G_s >520W/m^2 \)) and low radiation area(\( G_s <170 W/m^2 \)), the photovoltaic power generation capacity is less. It is especially obvious in the low radiation area, and it is hardly affected by the air temperature, and the power generation capacity is almost 0; from the perspective of low temperature and low radiation to high temperature and high radiation, the overall photovoltaic power generation capacity is an upward trend, which indicates that when the temperature and radiation are increased at the same time, it will help photovoltaic power generation capacity increase; from the perspective of low temperature and high radiation to high temperature and low radiation, the overall photovoltaic power generation capacity has experienced a process of first increasing and then
decreasing, which shows that when the temperature and radiation are "one increase and one decrease", the photovoltaic power generation capacity has a maximum; from the low-radiation area to the high-radiation area, the overall photovoltaic power generation capacity is increasing, which indicates that higher solar radiation can help increase photovoltaic power generation capacity; from the low temperature zone to the high temperature zone, the overall photovoltaic power generation capacity is in a decreasing trend, which indicates that the high ambient temperature weakens the photovoltaic power generation capacity.

4. Conclusion

Based on the experiment, this paper explores the changing law of photovoltaic power generation when the air temperature and solar radiation are considered at the same time, and it can be summarized as follows:

(1) When solar radiation and air temperature act on the photovoltaic power generation system at the same time, the former has a greater impact on the power generation than the latter.

(2) The increase in solar radiation and ambient temperature at the same time contributes to the increase in photovoltaic power generation.

(3) When solar radiation and ambient temperature "one increase and one decrease", photovoltaic power generation first increases and then decreases, that is, there is an optimal ambient temperature, solar radiation and maximum photovoltaic power generation.

(4) Low temperature and high radiation, high temperature and high radiation and low radiation conditions are not conducive to the operation of the photovoltaic system, and the photovoltaic power generation shows a decreasing trend, especially in the low radiation conditions, the power generation is basically not affected by the temperature and is in the extreme of less power generation.

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