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Regression analysis of climatic changes affecting the production efficiency of a solar photovoltaic plant

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ABSTRACT: The article presents the analysis of climate changes affecting the production efficiency of the solar photoelectric plant: outdoor temperature T(ºC), wind speed V(m/s), atmospheric pressure P(kPa) and humidity ϕ(%) using regression methods. It has been determined that the efficiency of solar photoelectric power generation is high when the external temperature is from +20 ºC to +35 ºC and the wind speed is equal to 2.5-3.0 m/s. Determination coefficients R^2_T=0.7 and R^2_W=0.55 were determined for external temperature T(ºC) and wind speed V(m/s). It is shown that the efficiency of the solar photoelectric plant in the climatic conditions of Uzbekistan is higher in the first six months of the year than in the second six months. The obtained scientific results will greatly help in increasing the efficiency of the solar photovoltaic power plant, as well as in connecting and managing solar photovoltaic power plants to the unified electricity grid.

KEYWORDS: solar panel, solar photoelectric plant, regression and correlation methods, coefficient of determination.

I. INTRODUCTION

Today, energy production using renewable energy sources is increasing day by day, especially the production of electricity using solar photovoltaic power plants has doubled compared to 2000, and the growth rate has exceeded 55%. In the last five years, among the Asian countries, China and Taiwan, the production of electricity through solar photovoltaic power plants accounts for 60% of the world production.

In recent years, the share of renewable energy sources (RES) in providing global energy demand has exceeded 20%, and by the end of 2023, the global production index will be 12.4% [1]. In 2022, the installed capacity of solar photovoltaic modules exceeded 240 GW. To date, the installed capacity of photovoltaic modules around the world is 1185 GW. The contribution of SO2 in the decarbonization of the energy balance of photovoltaic systems exceeds 1399 million tons per year [2].

Today, one of the strategic tasks facing the government of the Republic of Uzbekistan is to increase the share of electricity produced from renewable energy sources (RES). The main goal of these tasks is to ensure energy security of the country.

There are a number of advantages in the expansion of solar photovoltaic power plants (SPVPP) in the country, namely, the large number of sunny days, the laws and regulations issued by the government, and the incentives provided are widely developing. However, there are two important aspects of solar photoelectric power plants, namely, that the technical characteristics of the solar panels during their operation are variable, and that the production of electricity is dependent on seasonal climate changes.

Therefore, the study of climate changes affecting the process of electricity generation in solar photoelectric power plants is one of the current issues.

In this article, climate changes, external temperature T(ºC), wind speed V(m/s), atmospheric pressure P(kPa) and humidity ϕ(%) affecting electricity produced by Namangan-Pop solar photoelectric power plant in 2018 data was analyzed using regression methods. The dynamics of changes in the electricity produced by the solar photoelectric power plant are given in terms of these quantities.

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II. MATERIALS AND METHODS

The research facility, a 130 kW solar photovoltaic power plant in Pop district, Namangan region, is equipped with polycrystalline solar panels of the following companies HANHWA, JSPV, S-ENERGY and TOPSUN, which are members of the Photoelectric Industry Association of the Republic of Korea.

Namangan-Pop Solar Photoelectric Power Station is located at 70º57'39" east longitude, 40º51'28" north latitude and 472 m above sea level.

Each company's solar panels are equipped with separate inverters. The solar photovoltaic power plant is connected in parallel with the power grid, and the produced electricity is directly transmitted to the power grid. The produced electricity is transferred to the electric network through the DTS-541 U#530230 type electronic meter. These data were obtained through an electronic counter, and climate change data were obtained from gismeteo.ru.

In the article, the results of the scientific research conducted in 2018 of the 130 kW Namangan-Pop solar photoelectric power station, that is, the data of the electricity produced month by month and the external temperature T(ºS), wind speed V(m/s), atmospheric pressure during this period P (kPa) and humidity ϕ(%) were analyzed using correlation and regression methods. The dynamics of change for the year 2018 of the relationship between the values of electric energy produced at SPVPP W(Y) and the external temperature T(X_1) and wind speed V(m/s) are given. Analyzes were carried out in Excel programs.

III. RESEARCH RESULTS

In the study, the dependence of the electricity produced by the Namangan-Pop solar photoelectric plant on climate change was considered in 2015-2021. In the previous article [3], in 2020, the maximum value of electricity produced by solar photovoltaic power plant was 143872 kWh, and in 2018, it reached its minimum value, i.e. 127468 kWh. Let's take a look at the electricity produced at this solar photovoltaic plant in 2018 and the climate change factors affecting production. Table 1 shows the values of electricity produced in 2018 in months W (kWh), during this period the external temperature T (ºS), wind speed V (m/s) and atmospheric humidity ϕ (%) and pressure P (kPa) is provided month by month.

Table 1.

	Y	X_1	X_2	X_3	X_4
	W (kWh)	T (ºC)	P (kPa)	V (m/s)	ϕ (%)
January	1590	2	97,04	1,3	72
February	8336	7	97,04	1,6	61
March	11410	17	96,51	1,9	61
April	15402	21	96,51	2,0	55
May	18560	26	96,24	2,4	48
June	16288	31	95,84	2,5	43
July	17125	36	95,31	2,3	32
August	14621	33	95,71	2,0	39
September	8363	27	96,38	2,2	43
October	6349	17	97,04	2,3	55
November	5002	9	97,31	1,8	69
December	4422	4	97,18	1,4	73

From table 1, we will see how the change of 4 unknown variables depends on the produced electricity. This is expressed by the following function.

$$W(Y) = f(X_1(T), X_2(P), X_3(V), X_4(\phi)) \quad (1)$$

In this case, the linear regression equation with 4 unknowns is as follows.

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 \quad (2)$$

Here, a_0; a_1; a_2; a_3; and a_4 - unknown numbers, X_1 - external temperature T (ºC); X_2- atmospheric pressure P, (kPa); X_3- wind speed V (m/s); X_4 - atmospheric humidity ϕ (%). Using the data in Table 1, correlation and regression analysis of multivariate data was performed. Table 2 shows the correlation matrix for 4 unknown arguments.

ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 10, Issue 9, September 2023

Table 2.

	Y	X_1	X_2	X_3	X_4
Y	1				
X_1	0,84217953	1			
X_2	-0,8320329	-0,92913718	1		
X_3	0,74367343	0,849660192	-0,655301843	1	
X_4	-0,785083	-0,9702715	0,916249715	-0,80796544	1

From Table 2, it is known that the correlation coefficient of the relationship between the produced electric energy values W(Y) and the external temperature (X_1) is equal to 0,8422, which indicates that the numerical values are highly correlated. Similarly, the correlation coefficient of the electric energy values W(Y) with the wind speed (X_3) is 0,7437, which shows that these quantities are also highly correlated.

Figure 1 shows the regression model showing the relationship between the electric energy values W(Y) and the outdoor temperature T(X_1) produced in 2018.

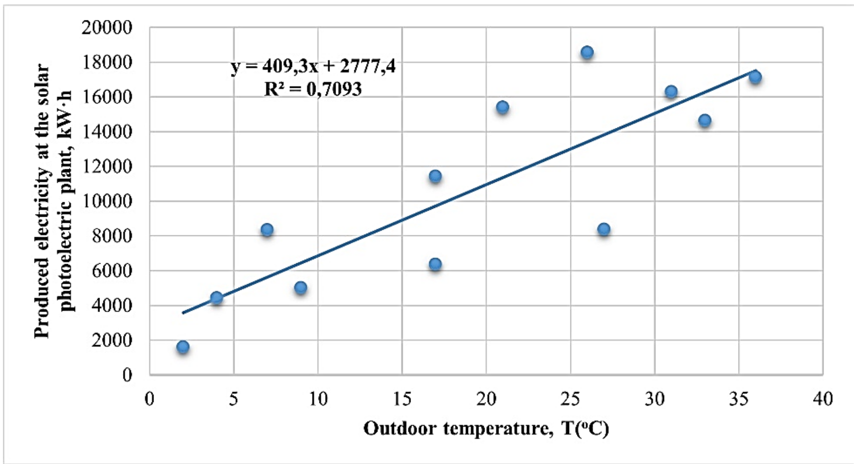

Figure 1. 2018 Regression model showing the relationship between the electric energy values W(Y) and the outdoor temperature T(X_1) produced at the solar photoelectric plant.

From Figure 1, it is known that the equation of a straight line with one unknown is $y=409.3 \cdot x + 2777.4$ and the coefficient of determination is $R^2=0.7093$. If the coefficient of determination $R^2 \approx 1$ is equal to or close to one, the dependence of the produced electric energy values W(Y) and the external temperature T(X_1) is high. The points above the straight line in Figure 1 indicate that the solar photoelectric plant worked effectively in that month, while the points below the straight line indicate that it worked inefficiently in those months.

Figure 2 shows the dynamics of changes in the relationship between the values of electricity produced at solar photoelectric plant W(Y) and the temperature of the external environment T(X_1) for 2018.

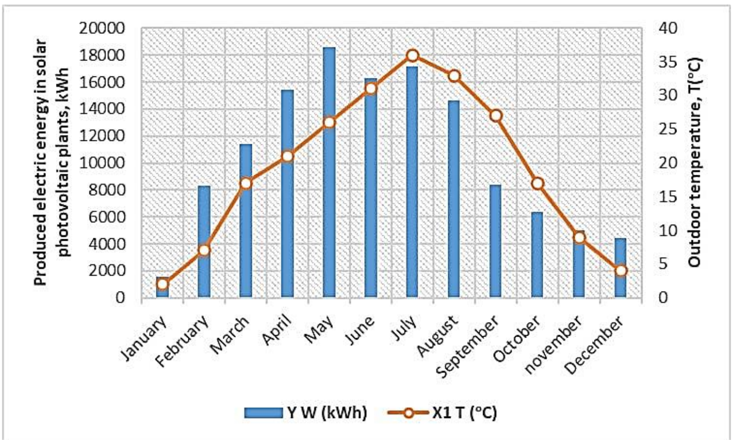

Figure 2. The dynamics of changes in the values of electric energy W(Y) and outdoor temperature T(X_1) produced by the solar photoelectric plant during 2018y.

Figure 2 shows that in the first half of 2018y, i.e., from February to May, the efficiency of the solar photovoltaic power plant was high, while in the second half of the year, the solar photovoltaic power plant worked inefficiently at the same outdoor temperatures. In 2018y, the maximum temperature corresponded to July, that is, it was +35 °C on average. The maximum production value of the solar photoelectric plant corresponded to the month of May, that is, it was 18,560 kW·s. These scientific results obtained are confirmed in the experimental results obtained in the following scientific articles [4,5,6]. Here is a general regression report analysis to test the regression model and regression equation in Figure 1. (Table 3).

Table 3.

Regression statistics						
Multiple R	0,842179528					
R-squared	**0,709266357**					
Normalized R-squared	0,680192992					
Standard error	3221,921472					
Observations	12					
Analysis of variance						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	253246803	253246803	**24,3957441**	0,000587863	
Balance	10	103807779,7	10380777,97			
Total	11	357054582,7				
	Coefficients	Standard error	*t- statistics*	*P- Value*	*Lower 95%*	*Upper 95%*
Y-intersection	**2777,376516**	1840,590445	1,508959543	0,162237374	-1323,714565	6878,467597
Variable X_1	**409,3020948**	82,86801439	4,939204805	0,000587863	224,6606524	593,9435373

So, if there is one unknown variable in the regression equation (2), it will be equal to a_0 =2777,38, a_1 = 409,30 through the following coefficients and will be in the following form.

$$Y = 2777{,}38 + 409{,}30X_1 \quad (3)$$

It is known that the coefficient of determination is equal to R^2=0.7093, if this coefficient is closer to one, the correlation between the function and the unknown argument is higher. If $R^2 < 5$, the correlation between the function and the unknown argument is not very close. In this case, the Fisher coefficient is F= 24.39. Fisher's criterion for a regression model reflects how well the model explains the total variance of the dependent variables. Fisher's criterion is calculated using the following equation.

$$F = \frac{R^2}{1-R^2} \cdot \frac{f_2}{f_1} \quad (4)$$

Here, R is the correlation coefficient; f_1 and f_2 are the number of degrees of freedom. For a linear equation, f_1=1. F_2=N-k-1; N is the number of measurements, k=1.

ISSN: 2350-0328
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Vol. 10, Issue 9, September 2023

It is known from Table 2 that X_2 and X_4 are unknown variables, i.e., atmospheric pressure P (kPa) and humidity ϕ (%), which are inversely proportional to the efficiency of the solar photovoltaic power plant, so we do not analyze these variables separately. We also conduct a regression analysis on the efficiency of the solar photovoltaic power plant, since the unknown variable X_3, that is, the wind speed V (m/s), is significant (Fig. 3).

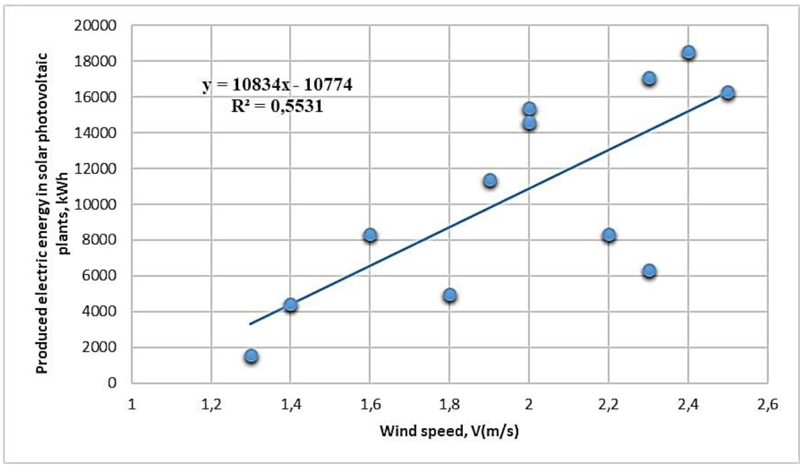

Figure 3. Regression model showing the relationship between the values of electricity W(Y) produced by solar photovoltaic power plant in 2018 and wind speed V (m/s).

Figure 3 shows that the equation of a straight line with one unknown is y=1083x-10774 and the coefficient of determination is R^2=0.55. The points above the straight line in Figure 3 indicate that the solar PV plant was efficient in that month, while the points below the straight line was inefficient. It was determined that the efficiency of the solar photovoltaic power station depends to a certain extent on the wind speed V (m/s).

The dynamics of the change between the values of electric energy W(Y) and wind speed V (m/s) produced at the solar photovoltaic power plant in 2018y is presented in Figure 4.

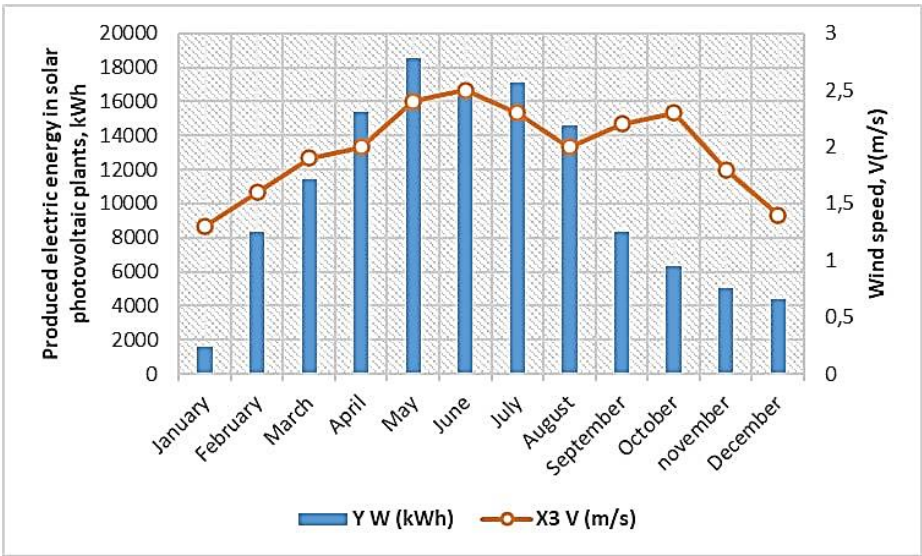

Figure 4. The dynamics of the change between the values of electric energy W(Y) produced by the solar photovoltaic plant during 2018 and the wind speed V (m/s).

Figure 4 shows that in the first half of 2018, i.e. from February to August, the efficiency of the solar photovoltaic power plant was high, and it was found that the solar photovoltaic power plant worked inefficiently in the second half of the year even with the same wind speed. The maximum production value of the solar photoelectric plant corresponded to the month of May, that is, it was 18560 kW·s. The wind speed corresponded to the month

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Vol. 10, Issue 9, September 2023

of June, that is, it was 2.4 m/s. The obtained scientific results were confirmed in the experimental results obtained in the following scientific articles [7,8,9].

Here is (Table 4) a general regression report analysis to test the regression model and regression equation in Figure 3.

Table 4.

Regression statistics						
Multiple R	0,743673429					
R-squared	**0,553050169**					
Normalized R-squared	0,508355186					
Standard error	3994,815207					
Observations	12					
Analysis of variance						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	197469097,3	197469097,3	**12,37387579**	0,005560177	
Balance	10	159585485,3	15958548,53			
Total	11	357054582,7				
	Coefficients	Standard error	*t- statistics*	*P- Value*	*Lower 95%*	*Upper 95%*
Y-intersection	**-10773,9891**	6190,911945	-1,740291123	0,112431728	-24568,20054	3020,22233
Variable X_1	**10833,58098**	3079,776196	3,517652028	0,005560177	3971,411983	17695,74998

So, (2) - when the regression equation is one unknown variable, it is equal to a_0 = -10773.99, a_1 = 10833.58 through the following coefficients and has the following form

$$Y= 10833.58X_1 -10773.99 \qquad (4)$$

Figure 3 shows that the coefficient of determination is equal to R^2=0.55. In this case $R^2 > 5$, the correlation between the function and the unknown argument is significant.

We will conduct a regression analysis of the dependence of the electric energy values produced by the solar photoelectric plant in 2018y on climate changes, i.e. external temperature T (ºC), wind speed V(m/s) and atmospheric pressure P (kPa) and humidity ϕ(%). a_0 in formula (2); a_1; a_2; a_3; and a_4 - unknown numbers and make formula (2) into a complete equation. Table 5 presents the statistics of the regression report.

Table 5.

Regression statistics						
Multiple R	0,889166255					
R-squared	**0,79061663**					
Normalized R-squared	0,670968989					
Standard error	3268,055165					
Observations	12					
Analysis of variance						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	4	282293290,7	70573322,68	**6,607874823**	0,015823826	
Balance	7	74761291,95	10680184,56			
Total	11	357054582,7				
	Coefficients	Standard error	*t- statistics*	*P- Value*	*Lower 95%*	*Upper 95%*
Y-intersection	**780695,5165**	551486,7203	1,415619792	0,199804183	-523363,3567	2084754,39
Variable X_1	**74,56974896**	548,1726909	0,136033316	0,895624411	-1221,65269	1370,792188
Variable X_2	**-1106,318175**	765,5559636	-1,44511731	0,19165979	-2916,570372	703,934023
Variable X_3	**7506,066714**	6585,516323	1,139784088	0,291870757	-8066,204894	23078,33832
Variable X_4	**269,998893**	306,4805692	0,880965778	0,407564626	-454,7124936	994,7102795

From Table 5, we determine the unknown numbers a_0, a_1, a_2, a_3, and a_4, a_0=780695.52; a_1=74.57; a_2=1106.32; a_3=7506.07 and a_4=269.99. Then the linear regression equation with 4 unknowns from equation (2) will look like this.

$$Y= 780695.52 + 74.57X1 + 1106.32X2 + 7506.07X3 + 269.99X4 \qquad (5)$$

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Vol. 10, Issue 9, September 2023

In this case, the coefficient of determination is equal to R^2=0.79, and Fisher's coefficient F= 6.61.

Therefore, it is known from the coefficient of determination R^2 that the external temperature and wind speed are highly dependent on the production efficiency of the solar photoelectric plant, and the atmospheric pressure and humidity are inversely proportional.

IV. DISCUSSION OF RESULTS

To study climate changes *(outdoor temperature T(ºS), wind speed V(m/s), atmospheric pressure P(kPa) and humidity ϕ(%))* affecting the production efficiency of the solar photovoltaic power plant, its optimal use and management serves to monitor opportunities and changes that occur under these influences, to determine patterns of seasonal change. Using the regression model showing the relationship between the produced electric energy values W(Y) and the outdoor temperature T(X_1), it is possible to determine at which temperatures of the outdoor environment the production efficiency of the solar photovoltaic plant is high. These obtained results have been proven in the following scientific articles [10,11,12]. According to the results of the regression model, the effect of the wind speed on the efficiency of the solar photovoltaic power plant is highly dependent. It was found that the efficiency of the solar photovoltaic power plant is especially high when the external temperature exceeds 33ºC and the wind speed is 2.5 m/s.

Atmospheric pressure P(kPa) and humidity ϕ(%) are highly dependent on the efficiency of solar photovoltaic power plant, but it is inversely related, that is, inversely proportional. For example: in July 2018y, the atmospheric pressure P (kPa) and humidity ϕ(%) reached the minimum value, the efficiency of the solar photovoltaic power plant was high in this month, i.e. close to the maximum.

Determination coefficients R^2_T=0.7 and R^2_W=0.55 were determined for external temperature T(ºC) and wind speed V(m/s).

The agreement of scientific results obtained by regression and correlation methods with experimental results proved once again that the conducted scientific work is correct.

V. CONCLUSION

Regression and correlation simulations of the corelation between the values of electricity produced in the Namangan-Pop solar photoelectric plant in 2015-2021 and climate changes showed that the efficiency of the solar photoelectric plant: solar radiation, ambient temperature and wind speed are linearly dependent and inversely dependent on atmospheric pressure and humidity. found the proof.

It has been proven that the efficiency of the solar photoelectric plant in the climatic conditions of Uzbekistan is higher in the first six months of the year than in the second six months. The obtained scientific results will greatly help in increasing the efficiency of the solar photoelectric power plant, as well as in connecting and managing solar photoelectric power plants to the unified electricity grid.

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