




Application of Mathematical Modeling for Long-term Forecasting of Electricity Generation by Solar Power Plants in the Republic of Uzbekistan

Ivan Bedritskiy^{1,2}¹, Kamila Jurayeva^{1,2}², Mirjahonkhuja Umarov^{3,4}³

¹*“Power Supply” Department, Tashkent State Transport University, Tashkent, Uzbekistan*

²*Tashkent State Transport University, Tashkent, Uzbekistan*

³*Head of Department of JSC “Uzbekistan Railways”, Tashkent, Uzbekistan*

⁴*JSC “Uzbekistan Railways”, Tashkent, Uzbekistan*

kaktus00@list.ru, lade00@bk.ru

Keywords: solar radiation, solar power plants, forecasting of electricity generation, mathematical modeling, approximation by a third-degree polynomial, seasonal climatic factors, monthly curve of electricity generation.

Abstract: The article provides a critical analysis of existing methods for predicting electricity generation by solar power plants and identifies the advantages and disadvantages of each of the methods used. A simple method for predicting electricity generation by solar power plants is proposed, regardless of the installed capacity of solar panels. The method consists in applying a third-degree polynomial approximation of the curve of monthly electricity generation as a percentage of the theoretically possible output. The method considers the intensity of solar radiation depending on the season, as well as seasonal climatic factors such as gloomy and sunny days and ambient temperature. Taking these factors into account allowed us to obtain a deviation in determining the annual amount of electricity, not exceeding 12% of the real amount. The application of the method makes it possible to evaluate the efficiency of solar power plants of any capacity, depending on the season, which simplifies the connection of solar power plants to the general energy system of the country.


1 INTRODUCTION


Solar power plants have become part of the energy systems of many countries, as solar energy is widely available, environmentally friendly, and has virtually inexhaustible resources. The use of solar power plants allows not only to meet the growing demand for energy, but also to reduce dependence on fossil fuels (Allaev, 2006; Kenzhaev, 2017).


Solar energy is an important component of “green” energy, which in turn is included as an important element in the concept of sustainable development of human society. In addition, the use of solar energy allows not only to use clean energy, but also to reduce carbon emissions, which is also part of the concept of sustainable development. Solar energy also contributes to increasing the energy independence of the country.

The initial investment in solar energy is very significant, but the operating costs of solar power plants are minimal, which makes it possible to obtain economic benefits from the use of solar energy in the future. The development of solar energy also contributes to the creation of new jobs (Zhandos, Yerkin, 2019), which is especially important for regions with high unemployment.

The Republic of Uzbekistan has a particularly significant potential in the development of solar energy. High levels of solar insolation, large areas of desert and semi-desert lands, and growing demand for electricity make solar energy a strategically important area for Uzbekistan. Figure 1 shows a map of the intensity of direct solar radiation on a normal surface in Uzbekistan.

¹ <https://orcid.org/0009-0009-8156-0811>

² <https://orcid.org/0000-0001-6015-5029>

³ <https://orcid.org/0009-4608-6015-4344>

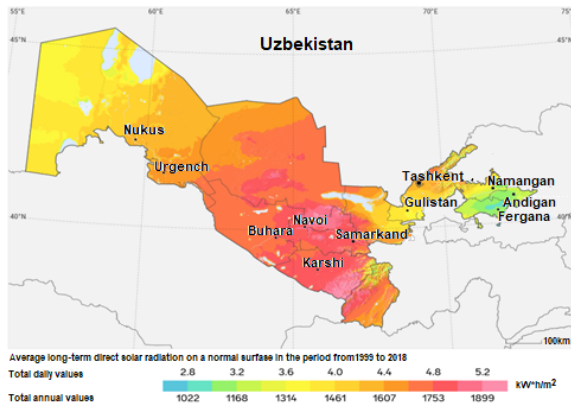


Figure 1: Map of direct solar radiation on a normal surface in Uzbekistan.

Figure 1 shows that the central and western regions of Uzbekistan, such as Navoi, Bukhara and Karshi regions, Khorezm region, as well as the Republic of Karakalpakstan receive an annual amount of solar energy comparable to countries such as Spain and China.

Electricity generation from solar power plants depends on weather conditions, and the inability to accurately predict power generation leads to an imbalance in the energy system. For this reason, forecasting electricity generation is an important task not only from the point of view of operational management of the energy system, but also for strategic planning. Accurate forecasts simplify the work, as they allow you to optimize the following functions:

- planning the distribution of electricity and the loading of certain types of power plants;
- increase the stability of the energy supply by optimizing the load;
- optimization of the power system as a whole;
- reducing the cost of capacity redundancy.

For these reasons, the research topic is very relevant, and the practical significance of the study lies in the possibility of accurately assessing the energy potential of solar installation and integrating solar power plants with the general energy system and other energy sources.

2 LITERATURE REVIEW

The works (Polovko, Butusov, 2005) systematize well-known methods for constructing short-term forecast of electricity consumption. The disadvantages of the methods are the short-term

nature of the forecasts and the subjective assessment of the results by one expert.

In (Kiseleva, Lisitskaya, Fried, 2020; Klyuev, Morgoev, Morgoeva, Gavrina, Martyushev, Efremkov, Mengxu, 2022; Rodríguez, Fleetwood, Galarza, Fontán, 2018), methods for constructing forecasts of power consumption using mathematical models, support vectors, and artificial neural networks are considered. These methods relate to multifactorial models and are applicable when there is a large amount of retrospective data.

In (Djaafari, Ibrahim, Bailek, Bouhouicha, Hassan, Kuriqi, Al-Ansari, El-kenawy, 2022; Wood, 2019), methods for predicting power consumption based on learning neural networks are considered. The disadvantages of the methods are that the solutions obtained with its help are not obvious, since for experts the network is something like a black box with unknown inputs and outputs.

Forecasting methods using expert knowledge are considered in (Abrukov, Kochakov, Abrukov, Anufrieva, Vasiliev, Smirnov, 2017; Terukov, Andronikov, Malevsky, Zainutdinov, Klyucharev, Bratyshev, Ilyichev, 2019; Visser, Al Skaif, Hu, Louwen, Sark, 2023; Rodríguez, Fleetwood, Galarza, Fontán, 2018). The disadvantage of these methods is the fact that the result of forecasting depends on the qualifications of experts.

The articles (Azhmukhamedov, Loba, Machueva, 2024; Engel, Engel, 2023) are devoted to machine methods of forecasting, which require specialized software.

3 MATERIALS AND METHODS

The aim of the study is to simplify the process of forecasting the electricity generation of solar power plants using mathematical modeling.

The hypothesis of the study is that to predict annual electricity generation by month, it is sufficient to know the installed capacity of solar panels, and for mathematical modeling of the forecast of electricity generation, it is necessary to know the approximating function of the curve of electricity generation by month.

To simulate an electric station using solar cells for the purpose of long-term forecasting of electric energy generation, Jinko Tiger Neo 66HL5 BDV (Chin) type solar panels were used in the amount of 3 units with a total installed capacity of 2,100 watts according to Standard Test Conditions (STC).

The installation scheme of the panels is shown in Figure 2.

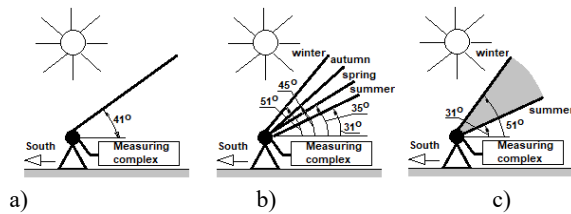


Figure 2: Panel installation scheme for simulating the operation of a solar power plant.

The first panel (Fig. 2, a) is fixed, set exactly to the south at an angle to the horizon equal to the latitude of the area (Tashkent), that is, 41 degrees. The second and third panels (Fig. 2, b, c) are also installed exactly in the south direction but could change the angle of inclination relative to the horizon. For the second panel (Fig. 2, c), the angle of inclination changed four times a year: in winter, the angle of inclination was 51°, in summer -31°, in spring and autumn – 45° and 35°, respectively, which is approximately equal to the optimal angles of inclination indicated in (https://termoteh.in.ua/article/effektivnost-ot-izmeneniya-ugla-naklona-solnechnogo-massiva/). For the third panel (Fig. 2, c) it is possible to change the angle of inclination monthly, that is, 12 times a year in the range from -10° to +10° during the year in which the experiment was conducted.

A measuring system is connected to each panel, which includes a switching device (circuit breaker), a BYM600 microinverter, a digital AC electricity meter and a load in the form of phase number converters (Bedritskiy, Jurayeva, Bazarov, Mirasadov, 2025; Bedritskiy, Jurayeva, Bazarov, 2020) to simulate a three-phase load and additional resistive elements, the value of which was selected so that each panel operated in a mode close to generation. maximum power at a rated panel voltage of approximately 40.5 V.

Due to the high efficiency of microinverters, internal losses in them are less than 4% and were not considered in further calculations. The installation operated continuously for two years with occasional stops for maintenance and adjustment of the load resistive elements, and was regularly cleaned of dust, snow and other contaminants. For each of the panel's operating modes, the amount of electricity generated per month was multiplied by three, which made it possible to calculate the installed capacity of the power plant at 2100W and save on the cost of installed electrical equipment.

The graph of annual electricity generation by a solar power plant is shown in Fig. 3. The solid lines indicate the graphs for 2021/2022, and the dotted

lines indicate the 2022/2023 observation years. The graphs show that the amount of electricity generated does not depend much on the year of testing and the method of installing solar panels.

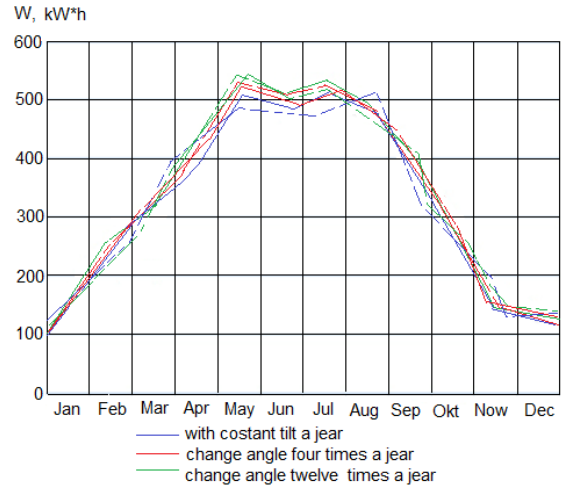


Figure 3: Power generation by a solar power plant with unregulated and adjustable guide structures.

The decrease in electricity generation in May-July is due to a decrease in the efficiency of photovoltaic conversion due to an increase in the temperature of solar panels. The results obtained correlate well with the data previously obtained by other authors and presented in (Azhmukhamedov, Loba, Machueva, 2024; Kiseleva, Lisitskaya, Fried, 2020).

3 RESULTS AND DISCUSSION

To build a model for predicting electricity generation, the obtained curve of the amount of electricity from the month number was generalized in the following way. It was calculated in % of the amount of electricity generated from the theoretically possible for the month using the expression

$$W_{\%} = \frac{W}{30 \cdot P_i \cdot n} \cdot 100\%,$$

where $W_{\%}$ - is the ratio of the actually generated electricity to the theoretically possible output at a given installed capacity in %;

W - is the actual electricity generated in kWh, taken for a certain month from the graph in Fig. 3 (solid blue line of the graph);

30 - is the number of days in the month;

P_i - is the installed capacity of solar panels, kW, in this installation it is equal to 2.100 watts or 2.1 kW;

n - is the number of hours of sunshine per day of a certain month.

Figure 4 shows a graph of the dependence $W_{\%}=f$ (month number) for the simplest case of installing solar panels – with a constant annual tilt angle, shown as a blue polyline reflecting the course of electricity generation in 2021/2022.

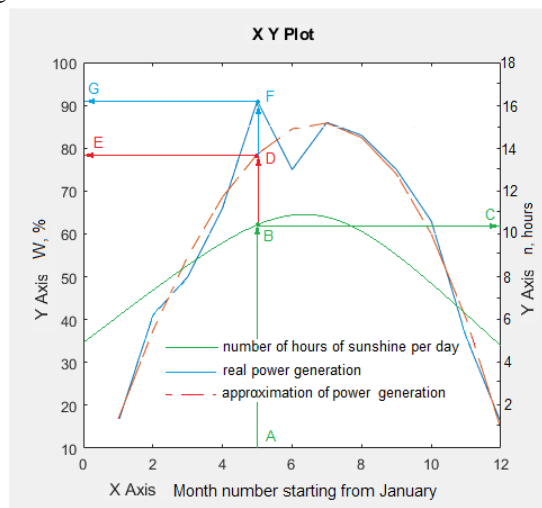


Figure 4: Electricity generation by a solar power plant depending on the month of the year.

To model the forecast of electricity generation, the curves $W_{\%}=f$ (month number) of the graphs in Fig. 3 were approximated by a third-degree polynomial, which is due to the sufficient accuracy of the approximation while simplifying the approximating expressions (Klyuev, Morgoev, Morgoeva, Gavrina, Martyushev, Efremkov, Mengxu, 2022). The coefficients of the approximating polynomial of the third degree and the plotting of the approximating function were calculated using the MATLAB program, a fragment of the program is shown in Fig. 5.

```
>> x=[1 2 3 4 5 6 7 8 9 10 11 12]; y=[16 41 50 66 91 75 86 83 75 63 36 16];
polyfit(x,y,3)
ans =
    -0.0528    -1.2874    24.8284    -6.6970
>> x=[1 2 3 4 5 6 7 8 9 10 11 12]; y=[16 41 50 66 91 75 86 83 75 63 36 16];
polyfit(x,y,3); z=-0.0528*x.^3-1.2874*x.^2+24.828*x-6.69; plot(x,y,x,z)
```

Figure 5: A fragment of a program for modeling the process of real electricity generation and plotting an approximating function for predicting annual electricity generation by a solar electric power plant.

The graph of the approximating modeling function for predicting annual electricity generation by a solar power plant, having an equation of the form $z = -0.0528x^3 - 1.2874x^2 + 24.8284x - 6.6970$ is shown in Fig. 4 (red dashed line), where z is the ratio of the actual electricity generated to the

theoretically possible output at a given installed capacity in %, denoted below $W_{\%}$; x – is the number of the month starting from January. The green continuous line in Fig. 4 shows a graph of the dependence of the number of hours of sunshine on the number of the selected month, that is, it is a graph of the form $n=f$ (month number). The number of hours of sunshine is read on the right vertical axis of the coordinate plane.

The calculation of the projected power generation was carried out in the following order:

- the x -axis selects the month number for which the amount of electricity is projected to be generated;
- draw a vertical line up to the intersection with the green line (line AB), and then draw a horizontal line to the right (line BC) to the intersection with the right vertical coordinate axis, on which we find the average number of hours of sunshine n in this month;
- draw a vertical line above to the point of intersection with the red dashed line (BD line), from this point we draw a horizontal line to the left (DE line) and along the vertical axis, we determine $W_{\%}$, that is, the ratio of the generated energy compared to the theoretically possible one, expressed in %;
- the predicted amount of energy generated can be calculated using the expression

$$W_f = \frac{30 \cdot P_i \cdot n \cdot W_{\%}}{100} (kW \cdot h).$$

Since the greatest difference in the generated and projected amount of electricity is observed in May, we calculate the maximum modeling error for this case. For the predicted output, we have: $P_i = 2.1 kW$; $n = 11$; $W_{\%} = 78\%$, we get $W_f = \frac{30 \cdot 2.1 \cdot 11 \cdot 78}{100} = 540 (kW \cdot h)$. Data for real production: $P_i = 2.1 kW$; $n = 10$; $W_{\%} = 92\%$ (we determine by the lines DF and FG, the blue graph in Fig.4).

We calculate the actual power generation $W_f = \frac{30 \cdot 2.1 \cdot 10 \cdot 92}{100} = 579.6 (kW \cdot h)$.

Considering the actual output as exemplary, we calculate the modeling error δ :

$$\delta = \left| \frac{540.5 - 579.6}{579.6} \right| \cdot 100 = 6.7\%.$$

The error obtained in this model is about 7%, but when all losses are considered, it increases to 10-14%. Let's compare the received errors with the errors of other known methods given in table 1 (Kenzhaev, 2017; Kiseleva, Lisitskaya, Fried, 2020; Klyuev, Morgoev, Morgoeva, Gavrina, Martyushev, Efremkov, Mengxu, 2022).

Table 1: Errors in forecasting models for electricity generated by solar power plants.

Model	Average forecast error
-------	------------------------

Physical	21-26%
Statistical	20-24%
Adaptive	7-15%
Hybrid	19-24%
The proposed methodology (statistical using mathematical modeling)	10-14%

From a comparison of the results, the proposed model for predicting electricity generation by solar power plants has an accuracy close to the most accurate adaptive model, but it does not require a large amount of statistical data and the availability of special software.

4 CONCLUSION

1. The amount of electricity generated depends little on the year of testing and the method of installing solar panels.

2. During the hot summer months, the amount of electricity generated by solar power plants decreases by 15-20% due to the high ambient temperature.

3. The proposed method of modeling the forecast of electricity generation by solar power plants does not require a large amount of statistical data and special software.

4. The use of the method of modeling electricity generation using a third-degree polynomial approximation makes it possible to indirectly consider seasonal climatic factors and at the same time does not depend on the installed panel capacity.

The use of mathematical modeling by approximating the monthly electricity generation curve with a third-degree polynomial to predict electricity generation by solar power plants has sufficient accuracy, makes it possible to evaluate the efficiency of solar power plants of any capacity and simplifies their integration into the general energy system of the Republic of Uzbekistan.

REFERENCES

- Abrukov, V.S., Kochakov, V.D., Abrukov, S.V., Anufrieva, D.A., Vasiliev, A.I., Smirnov, A.V., 2017. INTELLIGENT FORECASTING SYSTEM FOR SOLAR POWER PLANTS. *Alternative Energy and Ecology (ISJAEE)*.(16-18):30-42.
- Allaev, K. R., 2006. The state and prospects of energy development in the world and Uzbekistan. *Problems of energy and resource conservation*. Tashkent, No. 3. pp.26-44.
- Azhmukhamedov, I.M., Loba, I.S., Machueva, D.A., 2024. Forecasting and evaluation of energy generation at solar power plants: current problems and development trends. *Modeling, optimization, and information technology*. 12(1).
- Kenzhaev, Z.T., 2017. The state and prospects of solar energy development. №37(171). P.6-7.
- Kiseleva, S.V., Lisitskaya, N.V., Fried, S.E., 2020. Forecasting the generation of solar power plants and photovoltaic installations: basic approaches and effectiveness. *International Scientific Journal Alternative Energy and Ecology (ISJAEE)*. № 7 (18). pp. 24-43.
- Review of energy generation forecasting methods. (<https://cyberleninka.ru/article/n/obzor-metodov-prognozirovaniya-generatsii-energii/viewer>).
- Polovko, A.M. Butusov, P.N., 2005. MATLAB for students. St. Petersburg: BHV-Petersburg, 320 p., ill.
- Tyunkov, D.A., Sapilova, A.A., Gritsai, A.S., Alekseenko, D.A., Khamitov, R.N., 2020. Methods of short-term forecasting of electric energy generation by solar power plants and their classification. *Electrical engineering systems and complexes*.;48(3):4–10.
- Terukov, E.I., Andronikov, D.A., Malevsky, D.A., Zainutdinov, R.A., Klyucharev, A.Yu., Bratyshev, S.N., Ilyichev, V.G., 2019. An experimental study of the influence of meteorological factors on the generation of electricity by solar modules in the climatic conditions of the Astrakhan region. *Caspian Journal: Management and High Technologies*.№ 2 (46). Pp. 180-193.
- Engel, E.A., Engel, N.E., 2023. Machine learning methods for forecasting and maximizing solar power generation, *Bulletin of the VSU. Series: System Analysis and Information Technology*: No. 2
- Bedritskiy, I., Jurayeva, K., Bazarov, L., Mirasadov, M., 2025. Chan hysteresis models and magnetization curve models for cores made of soft magnetic amorphous alloys. *AIP Conference Proceedings Open source preview*, 3256(1), 030015
- Bedritskiy, I., Jurayeva, K., Bazarov, L., 2020. Evaluation of the stability of the parametric phase number converter. *E3S Web of Conferences Open source preview*, 216, 01092
- Djaafari, A., Ibrahim, A., Bailek, N., Bouchouicha, K., Hassan, M.A., Kuriqi, A., Al-Ansari, N., El-kenawy, E.M., 2022. Hourly predictions of direct normal irradiation using an innovative hybrid LSTM model for concentrating solar power projects in hyper-arid regions. *Energy Reports*. V. 8. P. 15548–1556
- Renewable Energy Statistics 2023. – Abu Dhabi: International Renewable Energy Agency, 2023. – URL: <https://www.irena.org>
- Klyuev, R.V., Morgoev, I.D., Morgoeva, A.D., Gavrina, O.A., Martyushev, N.V., Efremenkov, E.A., Mengxu, Q., 2022. Methods of forecasting electric energy consumption: a literature review. *Energies*. V. 15. № 15:8919.
- Visser, L., Al Skaif, T., Hu, J., Louwen, A., Sark, W.V., 2023. On the value of expert knowledge in estimation

- and forecasting of solar photovoltaic power generation. *Solar Energy*. V. 251. P. 86–105.
- Rodríguez, F., Fleetwood, A., Galarza, A., Fontán, L., 2018. Predicting solar energy generation through artificial neural networks using weather forecasts for microgrid control. *Renewable Energy*. V. 126. P. 855–864.
- Wood, D.A., 2019. German solar power generation data mining and prediction with transparent open box learning network integrating weather, environmental and market variables. *Energy Conversion and Management*. V. 196. P. 354–369.
- Zhandos, O., Yerkin, Kh., 2019. «Forecasting the electricity generation of solar power plants» International Satbayev Conference, №2(2).
<https://solargis.com/maps-and-gis-data/download/uzbekistan/>
- <https://termoteh.in.ua/article/effectivnost-ot-izmeneniya-ugla-naklona-solnechnogo-massiva/>