The efficiency of the on-grid solar power plant in the Chechen Republic

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Abstract. The paper presents the analysis’ results of the generation and economic efficiency of a solar power station functioning in the private sector in conjunction with a centralized power grid. Based on data analysis of the generation of a test solar power plant with a capacity of 1.86 kW, a comparative analysis of the calculated and actual characteristics in real functioning conditions is carried out. The estimated power generation capacity of the station during 5 months (December 2019 - April 2020) was 680.1 kWh, and the actual generation for the same period was 525.86 kWh. Using data on the solar radiation's level on the Chechen Republic territory, as well as data on electricity tariffs in the region, the economic effect of using a grid solar power plant is predicted. Taking into account the electricity tariff for private consumers, the estimated payback period of the system was 25 years. At a rate for commercial consumers - 12 years. Based on the analysis, it was concluded that the use of grid solar power plants is economically feasible only for electricity consumers in the Chechen Republic who purchase electricity at a commercial rate.

1 Introduction

Renewable energy is actively developing in the world and is being introduced in various areas, including the private sector. The most promising type of renewable energy is solar energy. This is due to the fact that the total power of the solar radiation flux entering the land's surface is much higher than the power of all functioning power plants in the world. To assess the economic efficiency of power plants based on renewable energy sources, it is necessary to have the following data: current electricity tariffs, power plant capacity and the amount of electricity generated, the durability of the system components and, of course, the amount of initial capital and maintenance costs [1]. In addition, it is necessary to take into account the possibility of selling electricity to the grid and the tariff in which energy is purchased by the power grid organization. It should be taken into consideration that grid-type solar power plants make a profit only with a sufficiently large capacity and subject to the sale of electricity at a "green tariff". The technical and regulatory framework for the sale of electricity by private owners of micro-generation facilities based on renewable energy

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sources in Russia is not sufficiently developed. This paper discusses an on-grid solar power plant used to reduce energy costs without supplying energy to the grid. The purpose of this work is to provide the features of predicting the efficiency of a grid solar power plant in the Chechen Republic through a retrospective analysis of the data on the power plant's output in real functioning conditions. The Chechen Republic is located in the south of Russia, in the eastern part of the North Caucasus and has all the transitional types of climate: from arid, temperate continental to cold and humid highlands, as well as six altitude zones from semi-desert to alpine.

2 Methods

The main research methods: statistical analysis of data on the generation of an on-grid solar power plant with a capacity of 1.86 kWh located in the Chechen Republic for the period from December 01, 2019 to April 30, 2020, forecasting efficiency of using solar radiation level data from the SolarGIS platform, processing data in computer programs MatLab and Excel.

3 Results and Discussion

In the structure of capital expenditures for a grid solar power plant, a significant part is occupied by photovoltaic modules and an installation system. In the grid solar power plant considered in this work, the cost of photovoltaic modules is about 50% of the total system cost (Table 1). It should be noted that this table does not show logistics and other associated costs. Installation costs typically account for about 20% of the total system cost.

Table 1. The initial capital cost of components of a grid solar power plant

| Name                        | Qty | Price (USD) | Amount  |
|-----------------------------|-----|-------------|---------|
| PV modules                  | 6   | 163,21      | 979,26  |
| Mounting system             | 1   | 161,74      | 161,74  |
| Inverter                    | 1   | 534,87      | 534,87  |
| Switching and protection devices | 1  | 70,55      | 70,55  |
| Installation costs          | 1   | 349,28      | 349,28  |
| **Total:**                  |     | **2095,7**  |         |

The main characteristics of the investigated grid solar installation are shown in Table 2. The total rated power of the photovoltaic system is 1.86 kWh. It must be borne in mind that the rated power of photovoltaic modules indicated by the manufacturer in the technical data sheet is the power due to standard test conditions. The standard test conditions for testing the power of a photovoltaic module used by manufacturers are a temperature of 25°C, a solar flux density of 1000 Wh/m². We could conclude that the power in real functioning conditions will differ significantly.

The object is a private house with energy consumption above the average. The average monthly energy consumption is about 1.9 MWh. Average power - 2628.58 Wh, the peak power reaches up to 8 kWh. At the same time, in the case of using an on-grid solar inverter, the peak power does not matter. The main characteristic of the inverter is the maximum permissible power of the connected PV modules. According to the data of the State Committee for Prices and Tariffs of the Chechen Republic, the tariff for private consumers is $0,038/kWh [2].
Table 2. Main characteristics of the studied on-grid solar power plant

| Characteristic            | Value                                      |
|---------------------------|--------------------------------------------|
| PV module type            | Monocrystalline silicon, PERC              |
| The efficiency of photovoltaic modules | 21.32%                                    |
| Temperature coefficient of power | -0.470%                                   |
| Total rated power         | 1,86 kWh (310 Wh * 6)                      |
| Area                      | 9.8 m2                                     |
| Azimuth                   | 173°                                       |
| Tilt angle                | 33.4°                                      |
| Coordinates              | 43.147388, 45.876701                       |

The average value of direct solar radiation on the territory of the Chechen Republic is 3,010 kWh/m² per day [3]. Average total radiation – 3,558 kWh/m² per day. Scattered radiation - 1.722 kWh/m² per day. Radiation incident on an optimally oriented surface - 4,037 kWh/m² per day. The optimal direction for photovoltaic modules in the Chechen Republic is azimuth 180°, the optimal tilt angle relative to the ground is 32°. Each latitude has its own optimal tilt angle for PV modules. Different sources provide different data. For example, on the SolarGIS platform for the Chechen Republic, an angle of exactly 32° is given, but in some sources an angle of 43° is also given. This issue needs to be further researched to accurately determine the optimal angle in the given area. To predict the production of photovoltaic modules, it is necessary to take into account various factors, such as module degradation, solar energy flux density in the given area, temperature, etc. The power of one photovoltaic module [Wh] is calculated according to the following formula [4-6]:

\[
P_{PV} = Y_{PV} f_{PV} \left( \frac{G_T}{G_{T,STC}} \right) \left[ 1 + \alpha_p \left( T_e - T_{c,STC} \right) \right]
\]  

(1)

where \( Y_{PV} \) – the rated power of the photovoltaic module due to standard test conditions (STC - Standard Test Conditions) [Wh]; \( f_{PV} \) – coefficient of decrease in overall efficiency as a result of photovoltaic cells degradation; \( G_T \) – total energy flux density of solar radiation at the land's surface, incident on an inclined surface [W/m²]; \( G_{T,STC} \) – energy flux density of solar radiation due to standard test conditions [1000 Wh/m²]; \( \alpha_p \) – temperature coefficient of the photovoltaic module power [%]; \( T_e \) – PV module temperature [K]; \( T_{c,STC} \) – temperature of the photovoltaic module due to standard test conditions (298 K).

The total energy flux density of solar radiation at the Earth’s surface incident on an inclined surface is calculated by the following formula [7, 8]:

\[
G_T = G_b \cdot R_b + G_d \cdot R_d \cdot \frac{1 - \cos \beta}{2} + G_d \cdot A_t \cdot R_b \cdot (1 - A) \cdot \frac{1 + \cos \beta}{2} \left[ 1 + \sin \left( \frac{\beta}{2} \right) \right]
\]  

(2)

where \( G_b \) – the direct solar radiation on the Earth’s surface, consisting of the difference between the total and scattered radiation [kW/m²]; \( R_b \) – the average ratio of the flow falling...
on the horizontal and inclined surfaces; \( R_g \) — albedo of the Earth’s surface; \( \beta \) — tilt angle of the photovoltaic module [deg]; \( A_i \) — coefficient of the atmosphere anisotropy.

The above-given formulas (1) and (2) allows to predict the production of one photovoltaic module. However, solar power systems often use a large number of modules connected in various ways. In the on-grid solar power plant researched within this work, 6 photovoltaic modules are used, connected in series. The total power of the photovoltaic system is calculated using the following formula [9-11]:

\[
P_a = P_{pv} \cdot n_p \cdot n_s
\]

where \( P_a \) — is the power of the photovoltaic system [Wh]; \( n_p \) — number of PV modules connected in parallel in the system; \( n_s \) — the number of PV modules connected in series in the system.

When predicting generation, it is also necessary to take into account the efficiency of the inverter and losses during energy conversion [12, 13]. The forecast results of the production of photovoltaic modules with a nominal capacity of 1.86 kWh in the Chechen Republic using the SolarGIS platform, as well as the actual generation of the power plant, are shown in Figure 1. The maximum energy value, as expected, decreases in July - 256.3 kWh. The minimum value in December is 85.3 kWh. The actual peak power is 1.96 kWh.

![Fig. 1. Estimated and actual values of the photovoltaic modules’ production.](image)

The projected and actual production values at the beginning of the year differ significantly, but in April the actual production was 208.1 kWh, while the predicted value was 208.7 kWh. The deviation from the forecast is about 0.3%. However, in January the deviation was 57.8%. This is due to the fact that the production is influenced by meteorological conditions [14, 15]. For more accurate forecasting, it is necessary to take into account data from meteorological stations located in the immediate vicinity of the installation [16]. Figure 2 (a) shows a graph of weekly production. As we could see, at the beginning of the week, the production level is significantly lower due to weather conditions, but at the end of the week, April 8 (Fig. 2 (b)), we see a perfectly smooth production schedule, which indicates that the weather was favourable on that day.
Fig. 2. Weekly and daily output of the system: a - output for the period from April 2 to 8, 2020; b - daily production for April 8, 2020.

The economic effect of a grid-connected solar power plant is calculated basing on the system's generation values and electricity tariffs [17, 18]. As it was said in the beginning, the tariff for electricity in the Chechen Republic for private consumers is $0.038/kWh. The actual generation of the system for 5 months (December 2019 - April 2020) is 525.86 kWh. Taking into account the tariff, the cost of the actual generated electricity is $19.66. Moreover, the forecasted cost for the same period is $25.43. Thus, the predicted annual output of the system is 2150.3 kWh, or $80.39. Taking into account the cost of the system presented in Table 1, the payback period for this grid-connected solar system is over 25 years. However, it should be borne in mind that electricity tariffs are growing by about 3-4% per year. At the same time, the durability of the used photovoltaic modules is 30 years (degradation is not less than 80%) [19, 20].

4 Conclusions

Basing on the analysis, it was found out that on-grid stations are the most affordable among the main types of solar energy systems for the private sector. This is due to the fact that there is no need to use energy storage systems in such installations. However, an important condition for the economic efficiency of such installations is the electricity tariff of at least $0.081/kW. Taking into account the tariff for private electricity consumers, the payback period of the researched on-grid solar power plant was more than 25 years. If electricity is consumed from the grid with commercial tariff, the payback period of the system would have been 12 years rather than 25, which is already more acceptable for the final consumer. Based on this, it could be concluded that the use of grid solar power plants is economically feasible in enterprises of the Chechen Republic, which pay for electricity at a commercial rate. For the private sector, it is necessary to determine mechanisms of state support for the purchase of power plants based on renewable energy sources. And also it is necessary to work out in detail the regulatory legal regulation on the part of micro-generation and the "green tariff" to stimulate private homeowners. The research has shown that some initial data require
additional elaboration. For example, the optimal angle of inclination of photovoltaic modules for the Chechen Republic is different in different sources – from 31° to 43°. Forecasting algorithms based on data on the level of insolation from the Solar GIS platform showed good results with an acceptable deviation. However, for more accurate forecasting, it is necessary to measure the level of insolation in the area, as well as use data from meteorological stations located in close proximity to the solar power plant.

References

1. T. Beck, H. Kondziella, G. Huard, and T. Bruckner, Applied Energy 173, 331-342 (2019)
2. Global Solar Atlas [Electronic resource] // Global Solar Atlas URL: https://globalsolaratlas.info/map?c=43.316436,45.699863,11&s=43.316436,45.699863
   &m=site&pv=small,173,33,1.86 (2020)
3. A. John, and A. William Beckman, Solar Engineering of Thermal Processes (2013)
4. M.N. Akhter, S. Mekhilef, H. Mokhlis, and N.M. Shah, IET Renewable Power Generation 13(7), 1009-1023 (2019)
5. Solar battery SilaSolar 310W PERC (5BB). Technoline URL: https://esolarpower.ru/solar/solar-panels/mono-panel/solnechnaya-batareya-silasolar-310w-perc-5bb/ (2020)
6. H. Chiou-Jye, H. Mao-Ting and C. Chung-Cheng, International Journal of Smart Grid and Clean Energy 2, 139-147 (2013)
7. W. Van Deventer, E. Jamei, G. S. Thirunavukkarasu, M. Seyedmahmoudian, T. K. Soon, B. Horan, and S. Mekhilef, Renewable Energy 140, 367-379 (2019)
8. M. M. Fouad, L.A. Shihata and E.I. Morgan, Renewable and Sustainable Energy Reviews 80, 1499-1511 (2017)
9. T. Beck, H. Kondziella, G. Huard and T. Bruckner, Applied Energy 173, 331-342 (2016)
10. D.A. Bogdanov, A.V. Bobyl, E.I. Terukov, and V.N. Verbitskii, Technical Physics Letters 41(2), 113–116 (2015)
11. A.M. Humada, S.Y. Darweesh, K.G. Mohammed, M. Kamil, S.F. Mohammed, N.K. Kasim, T.A. Tahseen, O.I. Awad, and S. Mekhilef, Solar Energy 199, 742–760 (2020)
12. D.A. Bogdanov, G.A. Gorbatovskii, V.N. Verbitskii, A.V. Bobyl, and E.I. Terukov, Semiconductors 51(9), 1180–1185 (2017)
13. F.A. Salem, M. Ahmed, S. Ghoneim, M.M. Al-Harthi, B. ALamri, S. Mekhilef, and M. Orabi, International Journal of Engineering Research and Technology 12(10), 1687-1695 (2019)
14. M.D. Rozmi, G.S. Thirunavukkarasu, E. Jamei, M. Seyedmahmoudian, S. Mekhilef, A. Stojcevski, and B. Horan, Renewable and Sustainable Energy Reviews 115, 109363 (2019)
15. N. Chintapalli, M. K. Sharma, and J. Bhattacharya, Solar Energy 208, 115-123 (2020)
16. H. Takeda, Solar Energy 149, 176-187 (2017)
17. R. K. Akikur, R. Saidur, H. W. Ping, and K. R. Ullah, Renewable and Sustainable Energy Reviews 27, 738-752 (2015)
18. J. Wang, R. Ran, Z. Song, and J. Sun, J. Electr. Eng. Technol. 12, 64-71 (2017)
19. S. Leva, A. Dolara, F. Grimaccia, M. Mussetta, and E. Ogliari, Math. Comput. Simulat. 131, 88-100 (2017)
20. F.H. Gandoman, F. Raeisi, and A. Ahmadi, Renewable and Sustainable Energy Reviews 63, 579-592 (2016)