

Design and Equipment Selection for a Peak-Load Photovoltaic Power Plant

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Abstract: The research focuses on the analysis of the operational and economic efficiency of an autonomous photovoltaic (PV) power plant operating in combination with an auxiliary diesel generator. The study considers the performance of a selected PV panel configuration under real climatic conditions and evaluates its ability to meet household electrical demand throughout the year. At the initial stage, a literature review was conducted to identify the key factors influencing the efficiency and reliability of photovoltaic systems, including solar irradiance, system configuration, energy storage requirements, and seasonal variability. Particular attention is given to the differences between standalone and grid-connected PV systems, with an emphasis on design features, energy storage needs, and operating conditions relevant to autonomous installations. The study includes technical and economic calculations for the selected PV system, covering energy production, load coverage, battery charging and discharging behavior, and diesel fuel consumption during periods of insufficient solar generation. Capital investment and operational costs are evaluated, and the impact of seasonal variations in solar irradiance on system performance is analyzed. The scientific novelty of the work lies in the comprehensive assessment of current balance, seasonal correction factors, and hybrid operation modes, allowing a quantitative evaluation of the mismatch between nominal and actual PV output under real operating conditions. The obtained results provide practical guidance for optimizing autonomous photovoltaic systems, improving their reliability, and reducing dependence on fossil fuel-based backup generation. Overall, the study combines technical performance indicators with economic feasibility considerations, contributing to the development and practical implementation of efficient and sustainable off-grid power supply systems.

1 INTRODUCTION

Off-grid solar and micro-grids are developing in Africa, where only 30 percent of the sub-Saharan region has access to energy sources. Africa, like other regions with powerful extractive industries, is developing solar energy as an alternative to diesel power plants or as a backup source for unreliable power grids. It should be borne in mind that the price of a kilowatt of solar energy is halving every 2.5 years and has decreased 100 times since 1977,

and there is no obvious reason for changing this trend in the future [1]-[4].

Calculations show that 1% of the world's deserts can provide all the energy that the world currently uses, and 25% of the world's deserts can supply 25 times more energy than we currently use [5]-[8].

The number of hours in a day during which the sun shines in a given place is also essential. This value is very different for different regions. Moreover, it is influenced not only by the geographical latitude of the area, but also by other

factors, for example, location in a mountainous area or simply the presence of a nearby mountain ridge that blocks the sun in the morning or evening hours. It is a basic diagram of a network solar power plant with the addition of a battery bank (ACB), a charge controller and replacement of a network inverter with a hybrid one. A distinctive feature is the ability to store part of the electricity generated during the solar period in the battery (Fig. 1).



Figure 1: Scheme of an autonomous, grid-connected (hybrid) solar power plant.

Due to the presence of a battery bank, they are less dependent on the source of central power supply [9]. Such SES is used mainly as part of an uninterruptible power supply system where the central power supply is insufficient or unstable [10].

The disadvantages include the high cost of the system, due to the battery bank and the power of the inverter, which should be the more, the more time required for uninterrupted operation and connected loads, respectively.

SES operating without connecting to an external power grid are called autonomous (Fig. 2).

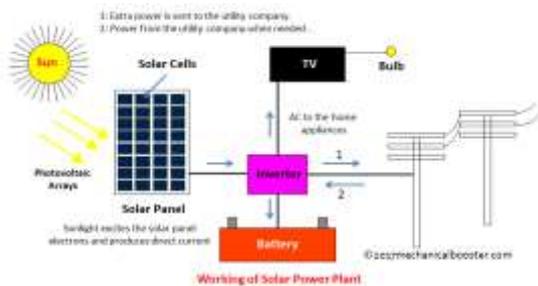


Figure 2: Scheme of an autonomous, not connected to the grid (autonomous) solar power station.

An autonomous photovoltaic power plant, in addition to solar panels, usually contains batteries

and a charge controller. If it is necessary to supply power to consumers requiring a standard voltage of 220 / 380V AC, an inverter must be included in the photovoltaic power plant. The only drawback of a photovoltaic power plant is the loss of energy at low loads [11]-[13].

2 THEORETICAL PART OF A SCIENTIFIC PROBLEM

In this configuration, the average power rating typically reaches 10 kW. The following variations are also possible:

- Each panel is served by a small integrated inverter providing hundreds of watts of power.
- Separate DC / DC converters are used in each photovoltaic cell section, DC / DC converter outputs are connected in parallel to one DC / AC inverter. This topology is the most efficient, with a power rating of up to 100 kW.

The main function of an inverter is to convert DC currents from photovoltaic panels or batteries at different voltage levels into AC at a specific voltage level and frequency to power devices or transfer to a power system. The frequency and voltage depends on the region, in Europe it is 50 Hz and 220 V, in the USA

- 60 Hz and 110 V. Depending on the application, there are phase requirements, so inverters are available in single, two and three phase. DC / DC converter raises or lowers the input voltage level, adjusts its output for maximum efficiency in the DC / AC conversion stage.
- The capacitor performs the function of voltage buffering.
- MOSFETs in the bridge are switched at a frequency of about 20 kHz to convert DC to AC.
- Inductors "smooth" the signal after the keys to obtain a sine wave.

2.1 Mathematical Apparatus for Autonomous Photovoltaic Power Plants

To ensure accurate design and performance evaluation of autonomous photovoltaic (PV) systems, a set of fundamental equations was applied in this study.

2.2 Photovoltaic Panel Output Power

The instantaneous electrical power generated by a PV module is calculated as:

$$P = E \times A \times \eta$$

where:

- P – output power (W);
- E – solar irradiance on the module surface (W/m²);
- A – active area of the panel (m²);
- η – panel efficiency (%), including temperature and wiring losses.

2.3 Sizing of Battery Storage for Autonomous Operation

The required battery capacity is determined using:

$$C_{bat} = \frac{E_{load} \times N_{days}}{V_{bat} \times DOD \times \eta_{bat}}$$

where:

- E_{load} – daily energy consumption (Wh);
- N_{days} – desired autonomy period (days);
- V_{bat} – nominal battery voltage (V);
- DOD – depth of discharge (%);
- η_{bat} – battery round-trip efficiency.

2.4 Economic Assessment Metrics

For evaluating the financial feasibility of PV systems, the Levelized Cost of Energy (LCOE) is applied:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + O_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

Where:

- I_t – investment cost in year ttt;
- O_t – operational cost;
- M_t – maintenance cost;
- E_t – annual energy production (kWh);
- r – discount rate;
- n – system lifetime (years).

These equations enable a rigorous technical and economic analysis and support informed decision-making when selecting PV technologies for autonomous applications.

In some cases, the voltage level at the input of the DC/AC converter must be higher than at the

output of the DC/DC converter. For this purpose, a transformer is used after the inductors. Despite the fact that the transformer increases the weight, size, and cost of the device and reduces efficiency by an average of 2%, it improves device protection and user safety by providing galvanic isolation between the DC and AC parts of the circuit. A similar function can also be performed by a DC/DC converter with zero-voltage switching (transformer equivalent).

Table 1 presents an estimate of the solar energy potential and shows the total (direct and scattered) solar insolation on a horizontal surface under cloudy conditions, expressed in kW × h / m² [14].

Based on the analysis of the data presented in Table 1, it becomes possible to design a PV system, since information on solar insolation in the selected region and the electricity consumption of a country house is available. As the design objective is to develop an autonomous solar power plant, calculations and equipment selection are carried out for a photovoltaic–diesel power plant, which operates during peak household consumption hours, as determined in Table 1.

Using the data on total solar radiation and the power of the selected solar panels (SP), the monthly energy generation of a single module for the given region was calculated using the following expression:

$$W_m = S_m \times E \times k \times \eta, \text{ kW} \times \text{h}.$$

Where:

- S_m is the area of the joint venture, W;
- E - insolation value for the selected period, kW×h / m²;
- η is the PV module efficiency;
- k is a correction coefficient accounting for power losses due to solar cell heating and the oblique incidence of solar radiation during the year [15].

The coefficient k is taken as 0.5 for summer and 0.7 for winter, which reflects reduced heating of the PV elements during the winter period.

The required number of PV modules to fully cover the monthly electrical energy demand is calculated as:

$$N = W_{mons} / W_m.$$

The results of all calculations are summarized in Table 2.

Table 1: Monthly solar insolation data for Kolpashevo locality.

Locality	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Kolpashevo	63	138	339	447	523	578	615	440	264	121	63	38
MJ/m ²	17,5	38,3	94,2	124,2	145,3	160,6	170,8	122,2	73,3	33,6	17,5	10,6

Table 2: Monthly solar panel energy production and quantity calculation.

Month	W, kWt×h	E, kWt×h/m ²	W _m , kWt×h	N, things
January	412,3	17,5	5,94125	70
February	377	38,3	13,00285	29
March	368,9	94,2	31,9809	12
April	330	124,2	42,1659	8
May	319,3	145,3	35,23525	10
June	279	160,6	38,9455	8
July	257,3	170,8	41,419	7
August	249	122,2	29,6335	9
September	387,5	73,3	17,77525	22
October	396,8	33,6	8,148	49
November	399	17,5	5,94125	68
December	443,3	10,6	3,5987	124

W_{cons} denotes the average annual energy consumption, where winter–autumn consumption exceeds spring–summer consumption. The number of selected photovoltaic panels in Table 2 is rounded up to the nearest integer. Analysis of Table 2 shows that the minimum number of panels required for year-round power supply is 124. However, from an economic perspective, it is more reasonable to install 12 PV modules in combination with a diesel power plant [16]–[19].

3 EXPERIMENTAL PART OF THE STUDY

Using the solar calculator [17], the power generation of photovoltaic panels was calculated for the selected design site located in the Tashkent region, Parkent district, near the village of Pskent. The installation includes 94 solar panels with a rated capacity of 280 W and 12 panels installed at a zenith angle of 45° (0° – horizontal, 90° – vertical) and an azimuth angle of 180° (180° – south, 0° – north).

The monthly distribution of power generation together with the load is shown in Figure 3. Figure 4

illustrates the configuration of the 12-panel system used for household power supply.

To visually determine the periods of maximum efficiency of the solar power plant (SPP), monthly solar insolation values were calculated using reference data. The sums of direct solar radiation on a horizontal surface under average cloudiness conditions are given in Table 3. These values were converted into kW·h, after which the electricity generation of the SPP and the actual load for the summer period (July) were determined [20]–[26].

The calculated values of direct solar radiation incident on the PV surface for July are summarized in Table 4.

Figure 5 and Table 5 present a comparison between photovoltaic panel output and the actual electrical load for July. The energy balance of the system is illustrated in Figure 6, while Fig. 7 shows the monthly PV coverage and diesel fuel consumption.

Table 6 presents the hourly values of battery discharge and charge currents.

From the graph in Figure 6, it can be seen that the PV system alone cannot provide stable power supply to the cottage during peak load periods. In such cases, the energy deficit is compensated by the battery storage system.

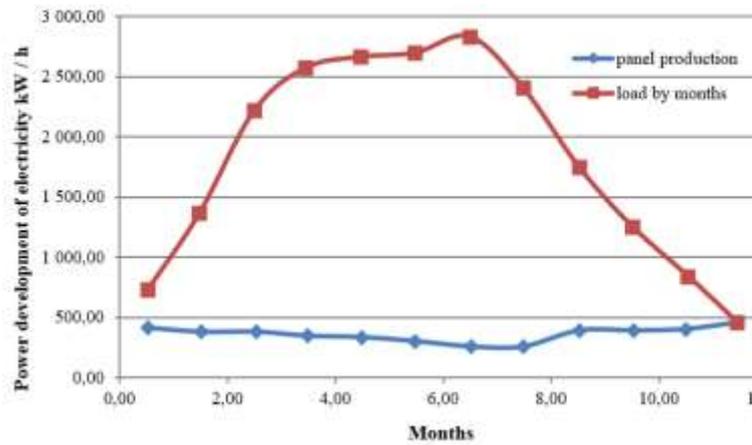


Figure 3: Production of 94 solar panels for year-round electricity supply.

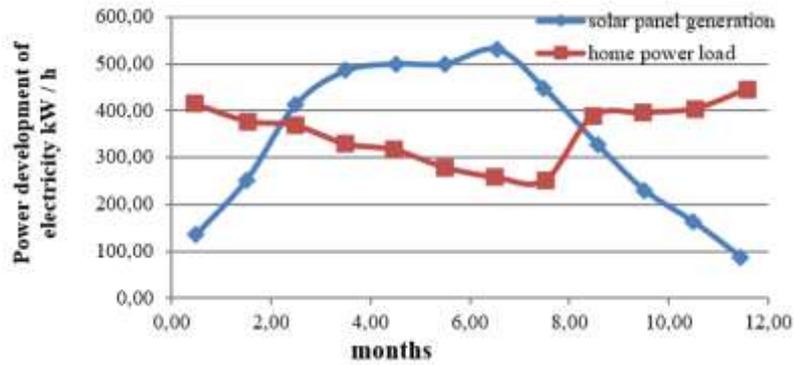


Figure 4: Development of solar panels for power supply of the house in the amount of 12 pcs.

Table 3: Monthly direct solar radiation sums under average cloud conditions (kW×h/m²).

t,(h)	1	2	3	4	5	6	7	8	9	10	11	12
MJ/m²	-	0,00	0,04	0,13	0,25	0,47	0,64	0,85	1,02	1,15	1,23	1,23
t,(h)	13	14	15	16	17	18	19	20	21	22	23	24
MJ/m²	1,19	1,07	0,85	0,64	0,47	0,25	0,08	0,04	0,00	-	-	-

Table 4: Sum of direct solar radiation on the SP surface under average cloudiness conditions (July).

t,(h)	1	2	3	4	5	6	7	8	9	10	11	12
MJ	-	0	0,19	0,61	1,16	2,19	2,98	3,96	4,75	5,35	5,73	5,73
t,(h)	13	14	15	16	17	18	19	20	21	22	23	24
MJ	5,54	4,98	3,95	2,98	2,19	1,16	0,37	0,19	0	-	-	-

Table 5: The sum of the production of solar radiation by the SP in power under average cloud conditions (July).

t, (h)	1	2	3	4	5	6	7	8	9	10	11	12
kWt×h	-	0	0,052	0,17	0,32	0,61	0,83	1,096	1,32	1,48	1,59	1,59
t, (h)	13	14	15	16	17	18	19	20	21	22	23	24
kWt×h	1,53	1,38	1,09	0,83	0,61	0,32	0,103	0,05	0	-	-	-

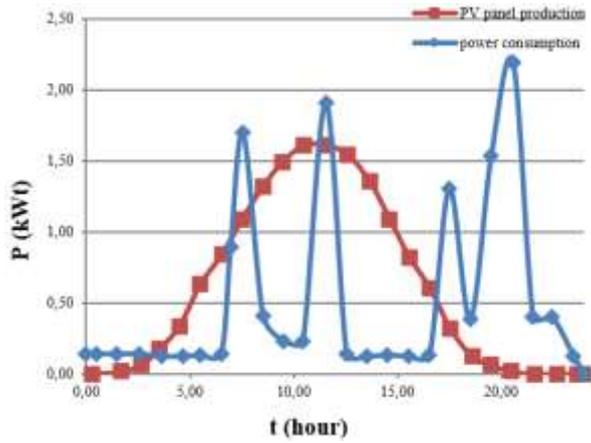


Figure 5: Comparison of the output of photovoltaic panels (July) and real load.

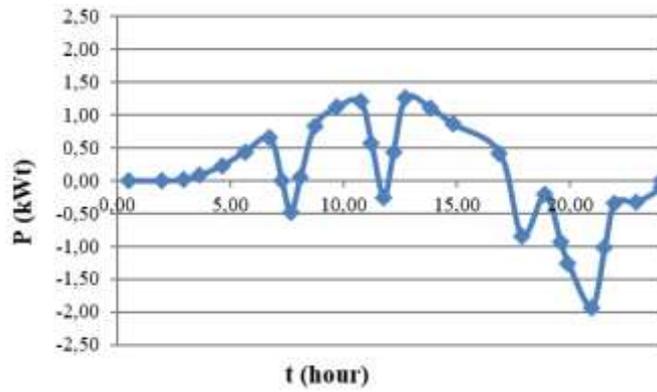


Figure 6: Energy balance.

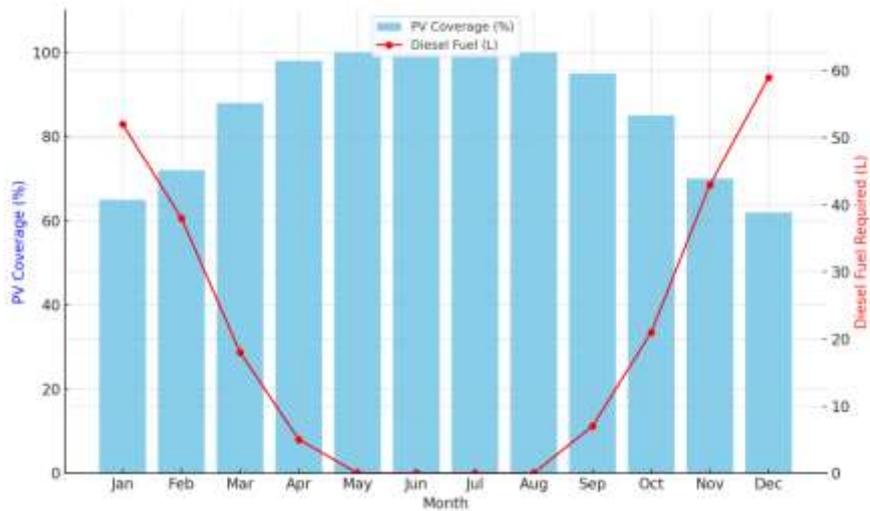


Figure 7: Monthly PV coverage and diesel fuel consumption.

Table 6: The value of the discharge / charge current by hours.

I ₁	I ₂	I ₃	I ₄	I ₅	I ₆	I ₇	I ₈	I ₉	I ₁₀	I ₁₁	I ₁₂
-5,4	-5,4	-3,33	1,67	7,92	20	28,75	-24,58	26,25	52,08	56,67	-12,5
I ₁₃	I ₁₄	I ₁₅	I ₁₆	I ₁₇	I ₁₈	I ₁₉	I ₂₀	I ₂₁	I ₂₂	I ₂₃	I ₂₄
58,33	52,08	40,42	29,2	20	-40,42	-12,08	-61,67	-91,25	-16,25	16,25	-5,4

4 BRIEF ACCOUNT

The battery discharge/charge current is calculated as:

$$I = \frac{P}{U} = \frac{-0,13 \times 10^3}{24} = 5,4 \text{ A} \times h$$

where I is the discharge (-) / charge (-) current of the battery P is the power consumption U - battery voltage.

Summing the discharge current from 18:00 to 03:00 gives a total discharge of: I_{time} = -257.4 A × h.

This operating mode does not lead to excessive battery wear, since six batteries are used: two are connected in series, forming three pairs, which are then connected in parallel. This configuration provides a total capacity of 300 A·h. Dividing the total discharge by three yields 85.8 A·h for each battery pair over a 12-hour period.

5 CONCLUSIONS

A complete performance analysis of the autonomous photovoltaic (PV) power plant shows that the total net charging current during 04:00–17:00 is I_{char} = 356.3 A·h, obtained by integrating the charge and discharge currents and subtracting the discharge during peak load hours (18:00–22:00). The system operating period considered is from 08:00 to 12:00. The resulting value corresponds to a full-cycle discharge of the accumulator batteries (AB) of 150 A·h/day in total, with consumption approximately equally distributed between both battery pairs at 118.8 A·h/day.

Seasonal correction coefficients were used to adjust hourly loads so that system behavior is accurately reflected throughout the year. PV power supply meets the full household demand from May, without the need to operate the diesel generator, until August, as shown by the simulation results. In contrast, during the period from November to January, additional generation is required to compensate for reduced solar irradiance.

Monthly diesel fuel consumption was therefore calculated and varies from zero liters in summer to 59 liters in December, illustrating the strong seasonal dependence of the hybrid energy system.

This seasonal pattern is illustrated in Figure 7, which shows the percentage of PV coverage (blue bars) and diesel fuel consumption (red line) in liters. The figure clearly demonstrates an inverse relationship: with high PV penetration, diesel demand is low, while reduced PV output during winter months leads to increased diesel usage. Overall, the figure highlights the efficiency of the hybrid system and its near-zero fossil fuel consumption under favorable solar conditions.

The developed methodology, based on current balance analysis, seasonal adjustment, and fuel consumption modeling, can be used as both a technical and economic guideline for optimizing autonomous PV systems. It also improves system reliability while reducing operating costs and dependence on fossil fuels, making it suitable for sustainable off-grid power applications.

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