Determination of the optimal battery capacity for standalone solar power systems

Olimjon Toirov[1], Shokhrukh Azimov[1,a)], Ogabek Kholjayev[1], Bekzodbek Pulatov[1], Nilufar Esanaliyeva[2], Islomjon Toshpulatov[3]

[1] Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
[2]Fergana state technical university, Fergana, Uzbekistan
[3]Kokand state university, Fergana, Uzbekistan

[a)] Corresponding author: azimovshohruh@mail.ru

Abstract. This article is devoted to the problem of determining the optimal battery capacity in standalone photovoltaic (PV–battery) systems in order to ensure their reliable operation. In the study, a 24-hour load profile for residential consumers was developed, and the daily electrical energy consumption was calculated. In addition, based on solar radiation and ambient temperature data corresponding to local climatic conditions, the real power output of photovoltaic modules was mathematically modeled while taking into account temperature effects. For the battery system, the energy balance and state-of-charge (SOC) dynamics were formulated considering charging and discharging efficiencies. The calculations were performed in the form of a 168-hour (one-week) simulation by repeating the 24-hour profile seven times, during which the battery capacity was varied in the range of $5-80\ kWh$ and thoroughly analyzed. The results show that as the battery capacity increases, the energy deficit decreases significantly, and a minimum optimal battery capacity is identified at which no power supply interruptions occur for the selected load and climatic conditions. This solution enables effective coverage of evening peak loads and efficient storage of surplus solar energy generated during daytime hours. The proposed mathematical model has practical significance for the design of standalone PV–battery systems under the conditions of Uzbekistan and provides a solid foundation for further comprehensive optimization incorporating economic performance indicators.

INTRODUCTION

Today, the use of renewable energy sources is developing rapidly on a global scale (Figure 1). China is the world leader in solar energy, ranking first in both photovoltaic production and installed capacity [1]. In 2024 alone, China successfully connected 329 GW of new installed capacity to the electricity supply system. According to Solar Power Europe, this country accounted for 55% of the total installed capacity of solar power plants worldwide [2]. According to Carbon Brief, in 2024, China installed more domestic solar capacity than it exported. The total installed capacity of solar energy in the world in 2024 reached 597 GW, with new capacity additions of 148 GW [3]. Autonomous solar photovoltaic (PV) plants are widely used as an important energy source, especially in areas that are not connected to central power grids or where connection is economically inefficient. Such systems play an important role in meeting the need for electricity in settlements, farms, greenhouses, and remote areas. Although the main advantage of autonomous PV systems is their environmental friendliness and the fact that they are based on a renewable source, their stable and reliable operation depends on many technical factors [4]. In an autonomous solar power supply system, energy production directly depends on solar radiation and is unevenly distributed throughout the day and by season. Therefore, the task of covering the consumer load during periods of lack of sunlight or low radiation falls on the battery. The battery system is one of the most important and expensive elements of an autonomous PV plant, and the correct selection of its capacity determines the technical reliability and economic efficiency of the system. Insufficient battery capacity leads to power outages, incomplete load coverage, and inconvenience to the consumer. Conversely, if an excessively large capacity is selected, initial capital costs increase sharply, the payback period of the investment is extended, and the overall economic efficiency of the system decreases [5]. Therefore, the optimal determination of battery capacity is one of the most urgent scientific and practical issues in the design of autonomous PV systems. In practice, in many projects, battery capacity is selected based on simplified rules or ready-made software tools. However, such approaches often do not sufficiently take into account the local load profile, climatic conditions, and reliability requirements. Despite the high solar resources in Uzbekistan, there is a need for open and understandable mathematical models based on realistic load regimes and climatic parameters [6]. Therefore, this article develops a mathematical model aimed at optimally determining the battery capacity for autonomous solar photovoltaic power plants based on the load profile and climatic parameters. The study uses the Loss of Power Supply Probability (LPSP) indicator as a criterion for energy balance, state of charge (SOC), and system reliability, and conducts simulations based on real data. The results obtained allow for the scientific design of autonomous PV-battery systems and ensuring the continuity of energy supply [7-8].

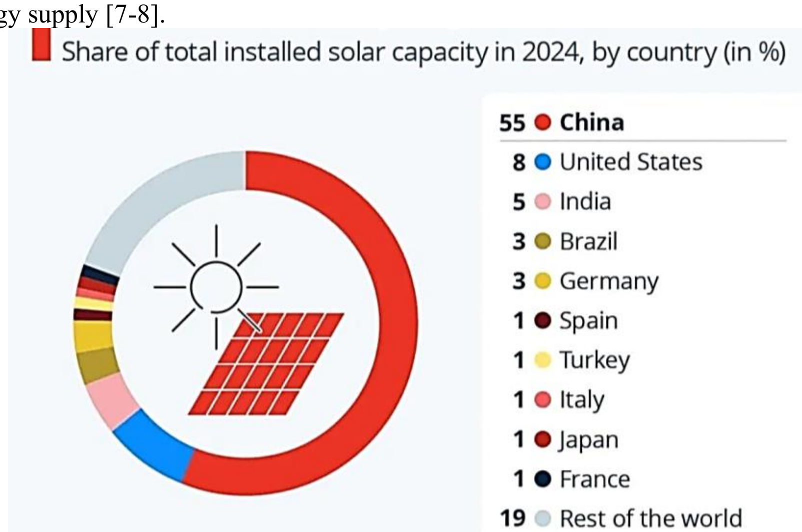

FIGURE 1. Leading countries in the installation of solar panels (as a percentage of the world capacity)

EXPERIMENTAL RESEARCH

In this study, experimental calculations and simulation studies were conducted based on real load and climate data to assess the practical effectiveness of the mathematical model developed for an autonomous PV-battery system [9-10]. A typical autonomous household suitable for the conditions of Uzbekistan was selected as the experimental object, and the consumer's demand for electricity was formulated in the form of a 24-hour load profile.

TABLE 1. Parameters of household appliance loads for autonomous household supply

Consumer list		Number [pcs]	P_{nom} [kW]	Daily energy consumption [kWh]	Working hours per day [h]	Cyclic mode coefficient k_i	Operating mode and operating times
1.	Refrigerator	2	0.150	3.24	24	0.45	Constant, compressor cyclical
2.	Condenser	2	1.20	10.92	7	0.65	12:00–17:00 and 21:00–23:00
3.	Television	3	0.100	1.2	4	1	19:00–23:00
4.	Washer	1	0.500	0.5	1	1	3 times a week (average 0.4 h/day)
5.	Electric oven	2	2.00	8	2	1	Evening 17:00–19:00
6.	Lamps (LED)	30	0.020	3.6	6	1	18:00-24:00
7.	Computer/laptop	3	0.070	1.05	5	1	09:00–12:00, 20:00–22:00
8.	Phone/tablet	5	0.015	0.15	2	1	Various times
9.	Boiler water heater	1	2.00	3.3	3	0.55	06:00–08:00 and 20:00–21:00
10.	Microwave oven	1	1.00	1	1	1	08:00–08:30 and 18:00–18:30
11.	Water pump	1	0.750	1.0125	3	0.45	06:00–08:00 and 20:00–21:00
12.	Fan	2	0.075	1.5	10	1	Summer 12:00–22:00

The daily energy consumption of each device, calculated using this formula, is given in Table 1:

$$E_i = N_i \cdot P_{nom,i} \cdot h_i \cdot k_i \ \text{[kWh/day]} \quad (1)$$

In the first stage of the experimental study, an hourly load graph was drawn up based on the nominal capacities, operating times and cycle coefficients of household electrical appliances (refrigerator, air conditioner, lighting, water pump, electric oven, etc.) [11-12]. As a result, the total daily electricity consumption was determined to be $35.47\ kWh/day$. The highest load values mainly fell on the period from 17:00 to 22:00, and this period served as a decisive factor in choosing the battery capacity. In the second stage, the production capacity of solar photovoltaic modules was determined based on real climate data. Hourly values of solar radiation $G(t)$ and ambient temperature T_{amb}(t) were adopted, and the module surface temperature was calculated using the Nominal Operating Cell Temperature (NOCT) model [13-14]. The PV system output was determined as a function P_{pv}(t) taking into account the temperature coefficient, inverter and cable losses, and it was observed that it could partially or fully cover the load during the daytime hours, and the output approached zero during the evening and night hours [15]. In the third stage, the operation of the battery system was modeled. The battery state of charge $SOC(t)$ was updated hourly based on the charging and discharging efficiencies ($\eta_{ch}(t) = \eta_{dis}(t) = 0.95$) and the constraints $SOC_{min} = 20\%$, $SOC_{max} = 80\%$.

TABLE 2. 24-hour climate, production, and load parameters for an autonomous PV–battery system

t/r	Time	G(t) [W/m²]	T_amb(t) [°C]	T_cell(t) [°C]	P_{pv}(t) [kW]	P_{yuk}(t) [kW]	P_{net}(t) [kW]
1.	00:00-01:00	0	18	18	0	0.135	-0.135
2.	01:00-02:00	0	17	17	0	0.135	-0.135
3.	02:00-03:00	0	16	16	0	0.135	-0.135
4.	03:00-04:00	0	15	15	0	0.135	-0.135
5.	04:00-05:00	0	15	15	0	0.135	-0.135
6.	05:00-06:00	0	16	16	0	0.21	-0.210
7.	06:00-07:00	80	18	20.5	0.054	1.5724	-1.518
8.	07:00-08:00	150	22	26.687	0.099	2.5724	-2.473
9.	08:00-09:00	300	26	35.375	0.192	0.635	-0.442
10.	09:00-10:00	450	29	43.062	0.280	0.345	-0.064
11.	10:00-11:00	600	31	49.750	0.364	0.345	0.019
12.	11:00-12:00	800	33	58	0.470	0.345	0.125
13.	12:00-13:00	950	40	69.687	0.532	1.845	-1.312
15.	13:00-14:00	900	35	63.125	0.518	1.845	-1.326
16.	14:00-15:00	750	33	56.437	0.443	1.845	-1.401
17.	15:00-16:00	550	30	47.187	0.337	1.845	-1.507
18.	16:00-17:00	350	28	38.937	0.221	1.845	-1.623
19.	17:00-18:00	250	25	32.812	0.161	4.285	-4.123
20.	18:00-19:00	0	23	26.125	0.066	4.885	-4.818
21.	19:00-20:00	0	22	22	0	1.26	-1.260
22.	20:00-21:00	0	21	21	0	2.8324	-2.832
23.	21:00-22:00	0	20	20	0	2.955	-2.955
24.	22:00-23:00	0	19	19	0	2.595	-2.595
25.	23:00-00:00	0	18	18	0	0.735	-0.735

The 24-hour profile was repeated 7 times, and a 168-hour (1-week) simulation was performed. In the experimental study, the battery capacity was changed stepwise from 5 kWh to 80 kWh, and the system reliability for each case was evaluated using the Loss of Power Supply Probability (LPSP) criterion. The results showed that at small capacities the evening load is not fully covered and LPSP has large values. With increasing capacity, $LPSP$ decreases sharply, and $LPSP = 0$ is observed around $C_{batt} \approx 35\ kWh$. The experimental results obtained confirm the practical applicability of the developed mathematical model and allow for a scientific selection of battery capacity in autonomous PV–battery systems [16-18].

RESEARCH RESULTS

In an off-grid solar power system, the battery plays an important role as an energy storage device [19-22]. Solar energy production is uneven throughout the day, and at night and during periods of low solar radiation, the battery covers the consumer load [23-26]. Therefore, the correct selection of the battery capacity ensures uninterrupted operation of the system and has a significant impact on the overall economic efficiency. The battery model is developed based on the following basic principles. Energy balance between PV production and load.

$$P_{net}(t) = P_{pv}(t) - P_{yuk}(t)\ kW \tag{2}$$

If $P_{net}(t) > 0$ the excess PV power will charge the battery. $P_{net}(t) < 0$ the battery will be discharged. All values of $P_{net}(t)$ are given in Table 2 above. In this section, practical calculations were performed based on a mathematical model of photovoltaic (PV) system generation and battery energy exchange [27-32]. The following technical and operational parameters were adopted for the calculations.

Number of PV panels: $N = 16$

Power of one panel according to STC: $\mathrm{P} = 0.665$ kW, System efficiency (inverter + losses): $\eta_{sys} = 0.92$

Temperature coefficient: $\gamma = -0.0035$ 1/°C Charge efficiency: $\eta_{char} = 0.95$ Discharge efficiency: $\eta_{dis} = 0.95$

In order to extend the battery life and prevent deep discharge, the following limits for SOC were adopted:

Minimum permissible level: $SOC_{min} = 20$ % Maximum permissible level: $SOC_{max} = 80$ %

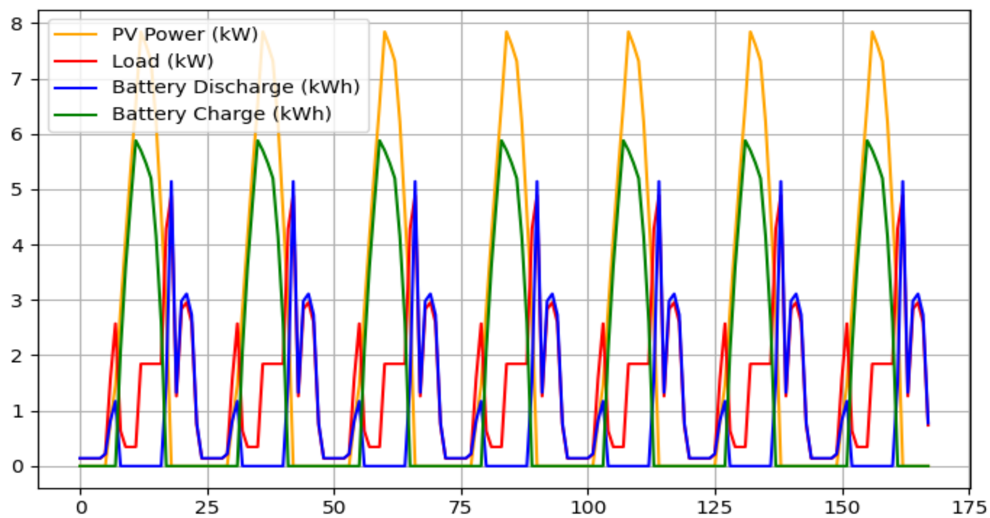

FIGURE 2. Dynamics of PV power, load and battery status in an autonomous solar system

The nominal power of each panel is 665 W, and the number and total nominal power we need are determined as follows:

$$N_{pv} = \frac{E_{day}}{P_{STC} * PSH * \eta_{sys}} = \frac{35.47}{0.665 * 6.23 * 0.92} = 9.306 \approx 10 \tag{3}$$

Here, we actually need 10 PV modules, but we have assumed 16 to account for cloudy days and smaller battery capacity.

$$PSH = \frac{1}{1000} \sum_{t=1}^{24} G(t) = \frac{6230}{1000} = 6.23 \tag{4}$$

$$P_{pv,nom} = N_{pv} * P_{STC} = 16 * 0.665 = 10.64\ kW \tag{5}$$

We have determined the temperature of the panel surface for each hour based on formula (10) above, as well as the real-time production capacity of the PV modules based on this temperature, and these values are listed in Table 2.

Determination of the optimal battery capacity based on the LPSP criterion. To evaluate system reliability, the LPSP criterion – also referred to as the loss of power supply probability (or the cumulative energy deficit) – was applied:

$$LPSP = \frac{\sum P_{def}(t) * \Delta t}{\sum P_{yuk}(t) * \Delta t} \tag{6}$$

Simulation results. The Cbatt capacity was changed from 5 $kWh\ to$ 80 kWh, and a 168-hour model was run for each capacity. The results showed the following. In the range of 20–28 kWh, the LPSP is too large → the evening load is not covered. Around 30–35 kWh, the LPSP decreases sharply. At 35 kWh and above, LPSP = 0 - no energy deficit is observed at any hour during the week. The graph below shows how the LPSP decreases as the capacity increases.

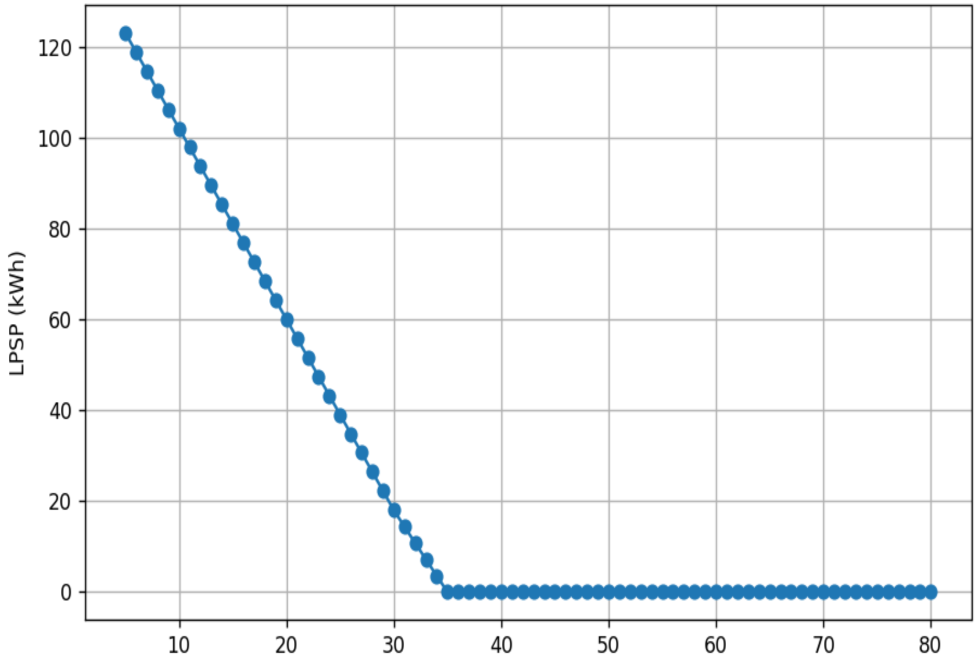

FIGURE 3. Insufficient energy compared to battery capacity

CONCLUSIONS

1. This article scientifically studies the issue of optimal battery capacity determination in terms of ensuring the reliability of energy supply in autonomous solar photovoltaic power plants and increasing the overall economic efficiency of the system. During the study, the energy balance and state of charge (SOC) for the "PV–battery" system were studied, taking into account the real load profile, solar radiation and climatic parameters such as ambient temperature. The hourly operation of the system and the battery charge and discharge modes were analyzed in depth. The results showed that it is not enough to select the battery capacity based on daily energy consumption alone, but the time distribution of the load and the unevenness of solar energy production are also decisive factors. It was found that ensuring energy continuity in conditions where PV production is zero in the evening and night hours is completely dependent on the battery system.

2. The LPSP (Loss of Power Supply Probability) criterion was used to assess the system reliability, and 168-hour (one-week) simulations were conducted for different battery capacities. The calculation results showed that energy deficits occur in batteries with small capacities, a certain part of the load is not supplied, and the LPSP value is high. It was observed that with increasing battery capacity, LPSP decreases sharply and becomes zero after a certain limit. According to the results of the study, a battery with a capacity of about 35 kWh was evaluated as the optimal solution for the selected load and climatic conditions, since in this case the system operated continuously for a week and the SOC never fell below the minimum permissible limit.

At the same time, it was found that increasing the capacity further would lead to an increase in capital costs without significantly improving energy reliability. In conclusion, the proposed mathematical model and LPSP-based evaluation method are effective tools for scientifically selecting battery capacity in autonomous PV systems, which will provide a solid foundation for further optimization studies integrated with economic indicators in the future.

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