EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972

ANALYSIS OF SOLAR BATTERY BEHAVIOR USING MATHEMATICAL MODELING

Abidova G.Sh.
Kurbanov I.B.
Tashkent State Transport University (Tashkent, Uzbekistan)

Abstract

This paper presents a mathematical model of a solar battery designed for analyzing energy processes in autonomous power supply systems. The model is based on the current-voltage (I–V) characteristic of a photovoltaic converter and takes into account the influence of key internal and external factors, including illumination, temperature, and the angle of incidence of solar radiation. Using computer simulation methods, the characteristics of a single solar cell as well as solar batteries formed by series, parallel, and series-parallel connections are investigated. The obtained simulation results confirm the adequacy of the developed model and its applicability for evaluating energy balance and designing power supply systems.

Keywords: solar battery, photovoltaic converter, mathematical model, current-voltage characteristic, computer simulation, illumination, temperature, autonomous power supply systems, energy balance, solar energy

Introduction

A rigorous mathematical representation of a solar battery has been formulated, grounded in contemporary approaches to the analysis of energy conversion processes within autonomous power supply systems. The proposed methodology relies on advanced computational modeling and simulation environments, enabling a detailed investigation of the dynamic and steady-state behavior of photovoltaic energy sources under varying external conditions.

Photovoltaic generators, which ensure the direct transformation of solar radiation into electrical energy, are structurally composed of numerous interconnected photovoltaic elements-solar cells. When these elements are electrically integrated, predominantly through series and parallel configurations, they form a unified energy-converting system commonly referred to as a solar battery. Such systems are capable of

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972

producing considerable electrical power under sufficient irradiance levels, which makes them indispensable both in aerospace applications—particularly for spacecraft power systems-and in terrestrial contexts, including autonomous and distributed energy supply units for industrial, residential, and remote installations [1].

From a structural standpoint, solar batteries may incorporate tens or even hundreds of thousands of individual photovoltaic cells. The specific topology of their interconnection is determined by the necessity to achieve prescribed electrical parameters, namely the required output voltage and current [2]. Series connections primarily increase the voltage level, whereas parallel configurations enhance the current-carrying capability, thus allowing for flexible adaptation of the system to diverse operational demands.

The present study focuses on the development and analysis of a mathematical model of a solar battery that adequately captures its electrical characteristics. Central to this model is the volt-ampere characteristic (VAC), which describes the functional dependence between output current and voltage under fixed environmental conditions, such as solar irradiance and temperature. This characteristic serves as a fundamental tool for evaluating the performance and energy efficiency of photovoltaic systems [3].

In addition to the classical VAC-based description, the model incorporates the influence of key physical parameters, including semiconductor material properties, internal resistive losses, recombination mechanisms, and temperature-dependent effects. Such an extended formulation allows for a more accurate prediction of the solar battery's behavior in real operating conditions, including partial shading, non-uniform illumination, and thermal fluctuations.

Furthermore, the application of numerical simulation techniques facilitates the optimization of system design and control strategies. By employing iterative computational methods, it becomes possible to identify optimal operating points-such as the maximum power point (MPP)-and to assess the impact of external disturbances on energy output [4]. This, in turn, contributes to improving the overall efficiency and reliability of solar power systems.

Thus, the developed mathematical model not only provides a comprehensive description of the electrical behavior of solar batteries but also serves as a practical instrument for their design, analysis, and optimization in both spaceborne and terrestrial energy applications [5].

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972

At the present stage of development of autonomous power supply systems, the application of computer-based modeling and simulation methods has become a fundamentally important tool for analyzing energy conversion and distribution processes [6]. The complexity and variability of operating conditions, especially for systems incorporating renewable energy sources, necessitate the use of numerical approaches capable of reproducing both transient and steady-state regimes with high accuracy.

The use of simulation techniques provides broad analytical capabilities. In particular, it enables the evaluation of the energy balance within an autonomous system when the energy parameters of primary and auxiliary (buffer) sources are predefined, and when the temporal profile of load consumption is specified. Such an approach allows for a comprehensive assessment of whether the generated and stored energy is sufficient to meet demand over a given time horizon [7].

In addition, computational modeling makes it possible to investigate the sensitivity of the system's energy balance to variations in the characteristics of its components [8]. This includes analyzing how fluctuations in the output parameters of energy sources-caused by environmental or operational factors-affect the overall stability and efficiency of the power supply system. Of particular importance is the ability to account for time-dependent changes in source behavior, which are typical for renewable energy technologies.

A further critical aspect of the analysis is the study of external influences on system performance. Parameters such as solar irradiance, ambient temperature, seasonal variations, and geographic conditions have a direct and often nonlinear impact on the energy characteristics of the system, especially when photovoltaic generation is involved. Accurate consideration of these factors is essential for predicting real-world performance and ensuring reliable system operation [9].

To address these challenges, it is necessary to construct an adequate mathematical model of a solar battery that reflects its physical and electrical properties under varying environmental conditions. Such a model serves as a core component of the overall simulation framework, enabling quantitative analysis, optimization of system parameters, and validation of design solutions for autonomous energy supply systems.

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972

Solar Battery Model

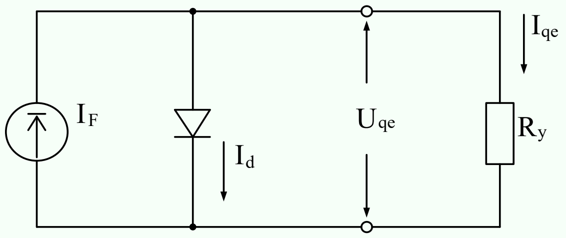


Fig. 1. Equivalent circuit of a solar cell

Fig. 1. Shows the equivalent replacement circuit of a solar cell (SC). It is described by the following expression:

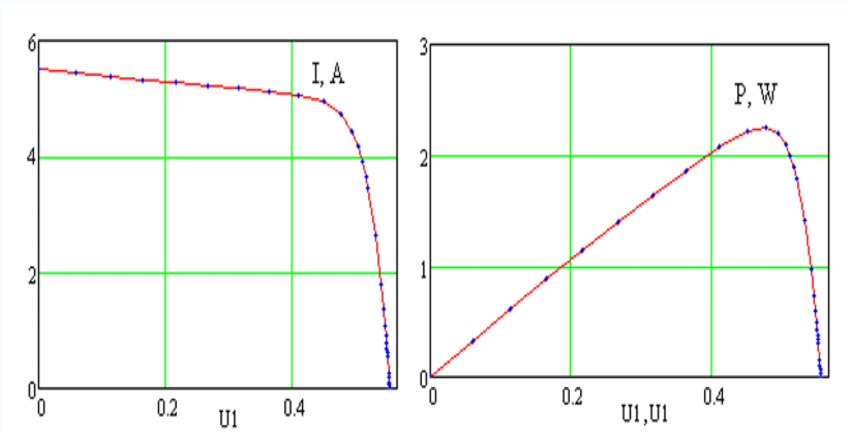
$$I_{\text{ÑÝ}} = I_{\text{Ô}}(W) - I_0 \cdot \left[\exp\frac{qU_{\text{ÑÝ}}}{kT} - 1\right] \Leftrightarrow U_{\text{ÑÝ}} = \frac{k\cdot T}{q}\ln\left[\frac{I_{\text{Ô}}(W) - I_{\text{ÑÝ}}}{I_0} + 1\right] \quad (1)$$

where $I_{\text{ÑÝ}}$ is the current through the external load, I_0 is the reverse saturation current, q is the electron charge, T is the absolute temperature, K, k is the Boltzmann constant, $U_{\text{ÑÝ}}$ is the output voltage of the cell, and $I_{\text{Ô}}$ is the current of minority carriers generated by light (photocurrent).
The influence of the illumination of the SC on the value of $U_{\text{ÑÝ}}$ is expressed by the formula

$$I_{\text{Ô}}(W) = W \cdot I_{\text{Ô}} \quad (2),$$

where W is the illumination of the SC.
Let us implement the mathematical model of the SC. As an example, let us choose a SC with the following characteristics: Uxx = 0,55 B, Ikz = 5,5 A. => 9 0 2,061 10^{-9} I A.
The circuit implementing the VAC of the solar cell described by expression (1) is shown in Figure 2. It allows one to assess the influence on the operation of the SC of such parameters as the illumination level of the SC (nominal value W = 1360 W/m²), ambient temperature (nominal value K = 298 K), as well as the angle of incidence of the light flux (nominal value α = 90° = π/2 rad).

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972



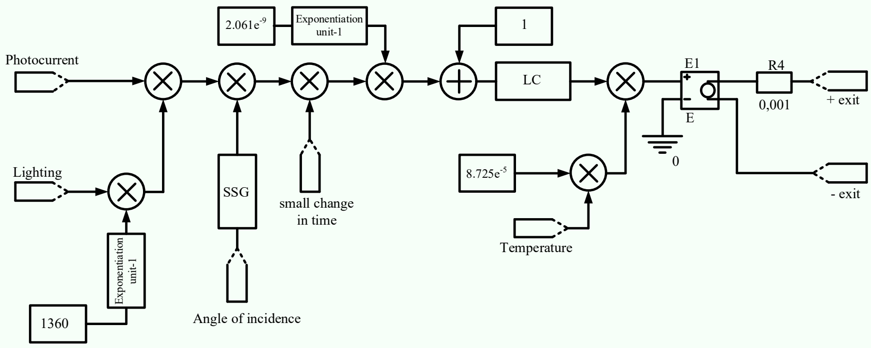


Fig. 2. Mathematical model of the SC

a - current-voltage characteristic, b - power-voltage characteristic

Fig. 3. Characteristics of the SC described by equation (2)

Let us test a solar battery consisting of 3 cells connected in series. In this case, the output voltage of the SB U_SB is determined by the formula $U_{\text{ÑÁ}} = U_{\text{ÝÊÂ}} = U_{\text{ÑÝ}} \times N$, where N is the number of solar cells connected in series;

$I_{\text{ÑÁ}} = I_{\text{ÝÊÂ}} = I_{\text{ÑÝ}}$ figure 4 shows a model of the SB consisting of 3 SCs connected in series.

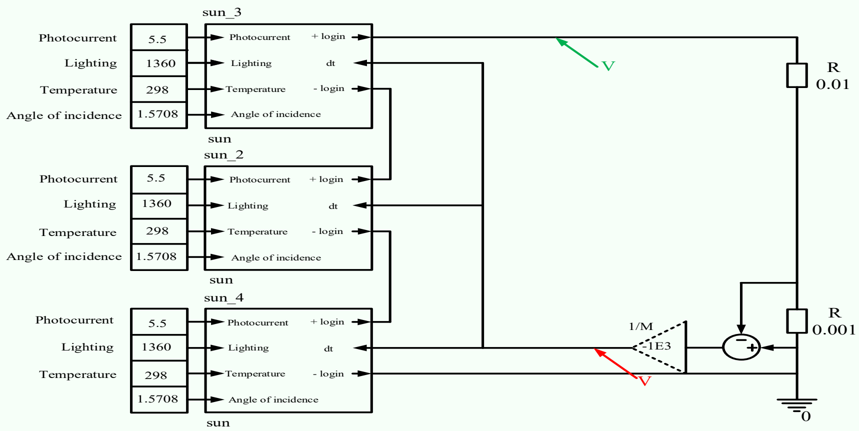
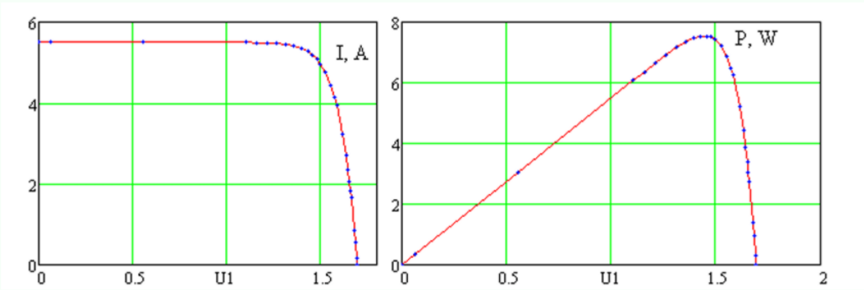


Fig. 4. Model of a solar battery consisting of 3 solar cells connected in series

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972



a b

a - current-voltage characteristic, b - power-voltage characteristic

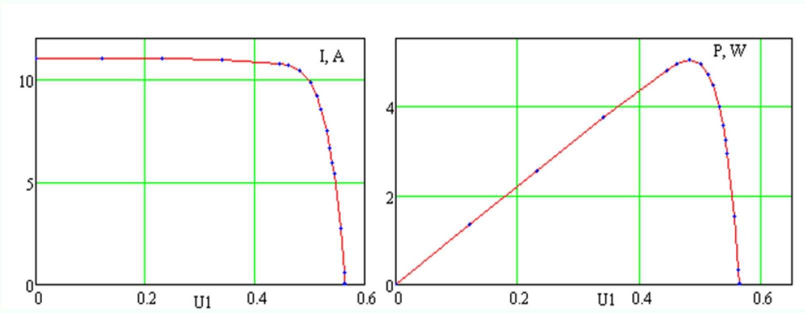
Fig. 5. Characteristics of the circuit shown in Figure 4

As can be seen from Figure 5, the open-circuit voltage of the SB is 3 times greater than the open-circuit voltage of the SC (see Figure 3) => the model has been constructed correctly [10].

Let us test a solar battery consisting of 2 cells connected in parallel. In this case, the output voltage of the SB $U_{ÑÁ}$ is determined by the formula

$$U_{ÑÁ} = U_{ÝÊÂ} = U_{ÑÝ} \times N, \qquad I_{ÑÁ} = I_{ÝÊÂ} = I_{ÑÝ} \times M,$$

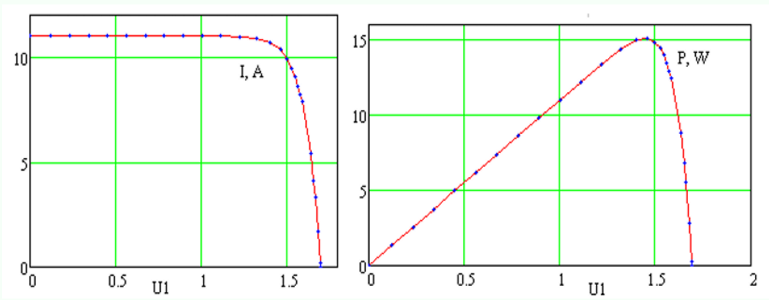
where M is the number of solar cells connected in parallel.



a b

a - current-voltage characteristic, b - power-voltage characteristic

Fig.6. Characteristics of a circuit consisting of 2 solar cells



a b

a - current-voltage characteristic, b - power-voltage characteristic

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972

Fig. 7. Characteristics of a circuit consisting of 6 cells connected in series-parallel

As can be seen from Figure 6, the short-circuit current of the SB is 2 times greater than the short-circuit current of the SC (see Figure 3) => the model has been constructed correctly.

Let us consider a model of a solar battery consisting of 6 solar cells connected in series-parallel.

In this case, the output voltage of the SB $U_{\text{ÑÁ}}$ is determined by the formula $U_{\text{ÑÁ}} = U_{\text{ÝÊÂ}} = U_{\text{ÑÝ}} \times N$, where N is the number of solar cells connected in series $I_{\text{ÑÁ}} = I_{\text{ÝÊÂ}} = I_{\text{ÑÝ}} \times M$, where M is the number of solar cells connected in parallel.

Conclusion

In the course of this study, a comprehensive mathematical model of a solar battery has been developed, providing an adequate and physically substantiated representation of its energy and electrical characteristics. The proposed approach, based on modern methods of computer simulation, makes it possible to analyze in detail the processes of generation, conversion, and distribution of energy within autonomous power supply systems.

It has been demonstrated that the use of simulation modeling significantly expands the possibilities for evaluating the energy balance of such systems under both steady-state and dynamically changing operating conditions. Particular attention has been given to the influence of external factors—such as solar irradiance, temperature, and seasonal variations—which have a decisive impact on the performance and efficiency of photovoltaic sources.

The constructed model, based on the volt-ampere characteristic of the solar battery, allows not only for accurate prediction of output parameters but also for the investigation of system behavior under non-ideal and time-varying conditions. This creates a foundation for optimizing system configuration, improving energy efficiency, and ensuring reliable operation of autonomous power supply systems.

Thus, the results obtained confirm the effectiveness of the proposed modeling methodology and its practical relevance for the design, analysis, and optimization of modern photovoltaic energy systems in both terrestrial and aerospace applications.

EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 4, April 2026
brightmindpublishing.com
ISSN (E): 3061-6972

References

1. International Energy Agency, Renewables 2021: Analysis and Forecast to 2026 (IEA, Paris, 2021).
2. International Renewable Energy Agency, World Energy Transitions Outlook 2022: 1.5°C Pathway (IRENA, Abu Dhabi, 2022).
3. T. Markvart and L. Castañer, Practical Handbook of Photovoltaics: Fundamentals and Applications, 2nd ed. (Elsevier, Oxford, 2012).
4. G. N. Tiwari and R. K. Mishra, Advanced Renewable Energy Sources (Royal Society of Chemistry, Cambridge, 2012).
5. A. Luque and S. Hegedus, Handbook of Photovoltaic Science and Engineering, 2nd ed. (Wiley, Chichester, 2011).
6. D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed," Prog. Photovolt: Res. Appl. **11**, 47–62 (2003).
7. F. Amirov, A. Kh. Sulliev, A. T. Sanbetova, and I. Kurbonov, "Study on the biparametrical transudations circuits with distributed parameters," *IOP Conf. Ser.: Earth Environ. Sci.* 939, 012008 (2021). doi:10.1088/1755-1315/939/1/012008
8. O. T. Boltayev, F. A. Akhmedova, and I. B. Kurbanov, "Consideration of the nonlinearity of the magnetization curve in the calculation of magnetic chains with a moving electromagnetic screen," *Unitech Trans.* 95, 13086 (2022). doi:10.32743/UniTech.2022.95.2.13086
9. G. Sh. Abidova, G. R. Qahharova, and I. B. Kurbanov, "Analysis and selection of the type of analogue-digital converter used in the processing of informational data," *Proc. 66th Int. Sci. Conf. Astrakhan State Tech. Univ.*, Astrakhan, Russia, 367–370 (2022).
10. G. Abidova, "Calculation and development of measuring amplifier with automatable and digital comparator of ensuring switching of amplification coefficients," *AIP Conf. Proc.* 3152, 050003 (2024). doi:10.1063/5.0218847