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QUALIMETRIC METHOD FOR ASSESSING QUANTITATIVE AND QUALITATIVE PARAMETERS OF A SOLAR CELL

The article considers the qualimetric method of evaluating a solar cell, which describes its main electrophysical characteristics and the processes that occur in it during the conversion of solar energy into electricity.

The dependence of the photovoltaic characteristics of a solar cell on various parameters is analyzed. It is shown that an increase in temperature leads to a decrease in the main characteristics of a solar cell, in particular the efficiency, short-circuit current, fill factor and other indicators that characterize the current-voltage characteristic. This decrease occurs due to changes in the electrophysical properties of the materials from which solar cells are made, as well as due to the influence of temperature changes in the material. A method for calculating the main electrophysical parameters, such as short-circuit current and open-circuit voltage, has been developed, which takes into account the detailed structure of the materials used to manufacture solar cells, which increases the accuracy of calculations of the output power and efficiency, and also increases the stability of the current-voltage characteristics of solar cells in real operating conditions. It is emphasized that an important aspect is the analysis of the impact of changes in lighting conditions, which have a significant effect on the conversion of solar energy. The models show how changes in the intensity and spectrum of lighting can change the behavior of a solar cell, in particular, affect the current and voltage under variable lighting conditions during the day or in conditions of unstable solar radiation. It is shown that existing approaches to modeling solar cells require further improvement, in particular, taking into account the structure of materials, temperature and lighting conditions, which will increase the accuracy of calculations and the stability of solar cell operation in real conditions.

KEYWORDS: *solar cell, qualimetric evaluation method, quality and quantity system, information and measurement system, control method, photovoltaic module*.

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Statement of the problem

Solar energy is one of the most promising renewable energy sources. However, to maximize the use of all the capabilities of this energy source, it is necessary to develop photovoltaic technologies , which have great potential. Today, the main task of photovoltaics is to reduce the cost of electricity generated by solar cells (SC). To achieve this goal, it is necessary to increase the efficiency and reduce the cost of SC.

Statement of the task

The aim of the article is to model the quantitative and qualitative parameters of a photovoltaic module for stabilization and accuracy of current-voltage characteristics using qualimetry models.

In accordance with the specified goal, the work solves the problem of modeling the quantitative and qualitative parameters of the photovoltaic module for stabilization and accuracy of the current-voltage characteristics of the photovoltaic module.

Presentation of the main study

Modeling of solar energy parameters is a key element for increasing its efficiency, reliability, and economic feasibility, which contributes to a wider practical application of photovoltaic modules.

The features of modeling quantitative and qualitative parameters of the SE are:

- design optimization, which helps to improve their design and materials to achieve maximum performance;

- improving efficiency by analyzing parameters such as: short-circuit current, open-circuit voltage and internal resistance;

- identification of defects in the production process and deviations from calculated values, which may signal the presence of contaminants;

- forecasting of performance, SC under the influence of various external factors (e.g. temperature, lighting level), which is important for their operation in real conditions;

- comparative analysis of different types of SC, allowing to explore their advantages and disadvantages and choose effective solutions for specific applications;

- adaptation to new materials;

- reducing production and operating costs, making solar energy more affordable and competitive;

- development of new technologies, allowing faster and more efficient conduct of experiments and analysis of their results;

The features of constructing current-voltage (I-V) characteristics of SE are:

- accurate prediction of SC parameters under different operating conditions, which is critically important for optimizing design and materials, and also directly affects output power and efficiency;

- detection of defects in materials and production technology, deviations from calculated values, which may signal problems such as insufficient photoconductivity or inefficient light absorption;

- taking into account the influence of external factors, such as temperature, lighting level and angle of incidence of sunlight, as well as forecasting the operation of solar power plants in real conditions, which is especially important for the design of solar power plants;

- conducting a comparative analysis of different types of solar cells (e.g., monocrystalline, polycrystalline, thin-film), which helps to determine the most effective solutions for specific conditions.

Using I-V models in a quality management system helps to set standards and conduct regular inspections, which helps to increase the reliability and durability of SC.

The work considered the relationship between the SE model and its key electrical characteristics. The SE model is a critically important tool for studying and optimizing electrical characteristics, such as: short-circuit current (I_{sc}), open-circuit voltage (U_{os}), internal resistance (R_{in} .), photocurrent (I_f) , output power (P_{out}), and efficiency (efficiency).

In works [1-3] the modeling of short-circuit current is considered. Short-circuit current is the maximum current that the SE can deliver under no-load conditions , i.e. at zero voltage. High short-circuit current indicates good optical properties of the SE material and efficient light absorption. Short-circuit current is an indicator of the ability of the SE to generate electricity and is directly related to the photocurrent. The SE model allows you to predict the short-circuit current based on the photocurrent generated by illumination. In mathematical models, such as the model of a single-type diode, the short-circuit current is calculated as a function of solar radiation intensity and temperature.

When comparing theoretical values of short-circuit current with experimentally obtained data, discrepancies can be found that indicate defects in the SC material. If the actual short-circuit current is lower than expected, this may indicate the presence of contaminants on the semiconductor surface, which is confirmed by laboratory tests.

When comparing the same type of SE, the critical parameter is the diffusion length and surface passivation. In SE, with uniform generation, the short-circuit current can be written, according to expression (1):

$$I_{SC} = q \cdot G \left(L_n + L_p\right), \qquad (1)$$

where I_{sc} - short-circuit current; G - generation rate; q - electron charge; L_n and L_p - are the diffusion lengths of electrons and holes, respectively.

Although expression (1) uses some assumptions, it shows that the short-circuit current strongly depends on the generation rate and diffusion length.

The short-circuit current is determined by the number of photons absorbed by the semiconductor material SC. When a photon with sufficient energy interacts with the atoms of the material, it can knock an electron out of its orbit, creating an "electron-hole" pair. These free electrons and holes begin to move under the influence of the internal electric field created by the p - n junction, which ultimately leads to the occurrence of a current.

For silicon-based power supplies, the short-circuit current largely depends on:

- intensity of solar radiation (for example, the more solar energy falls on the element, the more photons interact with the material, and, accordingly, the higher short circuit current);

- the spectrum of solar radiation , different wavelengths of light interact with a semiconductor differently (for example, ultraviolet and visible radiation can generate more free carriers than infrared);

- temperature (for example, as the temperature increases, the number of thermally activated charge carriers increases, which can have both a positive and negative effect on short circuit current);

For prediction short-circuit current is calculated using various mathematical models, among which the most common are [3, 4]:

- model of a single-type diode , this model is based on the diode equation and allows you to calculate short-circuit current as a function of light intensity and temperature conditions;

- models based on numerical simulations that use numerical methods (e.g., the finite element method) and allow for the geometry of the solar cell to be taken into account.

Comparison of calculated values short-circuit current with experimentally obtained data, allows you to assess the accuracy of the models, and identify potential problems in the production process. For example, if the actual The short-circuit current is significantly lower than expected, this may indicate:

- surface contamination (e.g. dust, dirt or organic contaminants);

- incorrect manufacturing technology (for example, crystal structure defects or poor-quality materials);

- inefficient light supply (for example, incorrect installation angle of the photovoltaic module), which can lead to a decrease in the intensity of solar radiation on the surface of the solar cell.

The main factors that affect the value of the short-circuit current are:

- temperature fluctuations;

- the use of anti-reflective coatings , which can significantly increase short-circuit current due to reduced reflectivity of the SC and increased light absorption;

- the structure of the semiconductor layer (for example, the use of thin-film technologies can increase the short-circuit current by optimizing the conditions for the generation of charge carriers).

Models describing short-circuit current can be useful for assessing the long-term reliability of ESS. Predicting changes short-circuit current as a result of material degradation over time, allows the development of reliable photovoltaic modules, which is critical for ensuring their durability and high performance.

Short-circuit current is an important parameter that affects the overall efficiency of a solar power system. The solar power system model allows both to predict the short-circuit current and to identify the causes of possible deviations from the expected values. This makes the model an important tool for optimizing and increasing the efficiency of solar technologies.

Open circuit voltage (U_{oc}) is the maximum voltage that the SE can develop in the absence of load [5,6]. To predict the no-load voltage in SE models, the following parameters are used: temperature, internal resistance, illumination level,. In mathematical models based on thermodynamic principles, open circuit voltage, can be expressed in terms of temperature and light level according to expression (2):

$$U_{oc} = \frac{k \cdot T}{e} \ln \left(\frac{I_F}{I_0} + 1 \right), \qquad (2)$$

where U_{os} - open circuit voltage k - Boltzmann constant , T - absolute temperature, e - electron charge, I_F - photocurrent, A, I_0 - reverse diode saturation current **.**

In case of deviations of the open-circuit voltage from the calculated values, models can be used to analyze the causes of these deviations (for example, if the open-circuit voltage decreases with increasing temperature, this may indicate problems with the material).

The open circuit voltage is determined by the balance between the generation and recombination of charge carriers in the semiconductor material. When the SC is illuminated, the photon energy leads to the formation of electron-hole pairs. The internal electric field created by the pn junction promotes the separation of these pairs, directing electrons to the anode and holes to the cathode. In the absence of a load, carriers continue to be generated, but recombination also continues. The open-circuit voltage reaches its maximum value when the charge flows of the device are in equilibrium, that is, the rate of generation of charge carriers is equal to the rate of their recombination.

There are different models for calculating open circuit voltage , namely:

- thermodynamic models , which are based on the principles of thermodynamics and allow us to express open circuit voltage due to temperature and light level;

- models based on numerical simulations , which can take into account effects such as temperature gradients, inhomogeneities in the material structure and other factors affecting the open circuit voltage. These models can use finite element methods or other numerical techniques to simulate the behavior of the SE under different conditions.

Open circuit voltage depends on the following factors: temperature; illumination level ; surface condition . With increasing temperature the open circuit voltage decreases. This is due to increased recombination of charge carriers, which is associated with increased thermal energy. Such models help predict how a change in temperature will affect open circuit voltage. Increasing the lighting level increases open circuit voltage as the short circuit current increases. In conditions where the light level becomes excessively high, saturation effects may occur, which also need to be taken into account in the models. Contamination and defects on the surface of a semiconductor can reduce open circuit voltage. The presence of microcracks or contamination can lead to increased recombination, which will be seen when comparing experimental and calculated values.

Deviation analysis open circuit voltage from the calculated values , allows you to identify potential problems, namely:

- decrease open circuit voltage with increasing temperature may indicate that the material cannot withstand thermal loads;

- differences between experimental data and models may indicate the presence of defects in the structure or inefficiencies in the production technology.

Models describing the open-circuit voltage can be used to design more efficient SE, and can also be useful for predicting the durability of SEs. If the study shows that The open circuit voltage drops sharply under certain conditions, indicating the need for durability and reliability tests of the SC.

Open circuit voltage is an important indicator of the efficiency of the SE. Models describing open circuit voltage, allow not only to predict its value, but also to identify the causes of deviations, which is an important step towards optimizing solar technologies. This makes modeling Open circuit voltage is an important tool for researchers and manufacturers seeking to improve the efficiency and reliability of photovoltaic modules.

The internal resistance of a power supply is a key parameter that determines its performance, especially in real-world conditions when the elements are operating under load [7,8] . This parameter reflects the resistance that the current experiences when passing through the power supply, and it directly affects the output power and efficiency. Power supply models can include the calculation of the internal resistance, which allows you to evaluate how this internal resistance affects the output power and efficiency. By measuring the voltage and current on the load, you can use a model to determine the internal resistance, which is important for optimizing the power supply parameters.

By analyzing data on internal resistance and its dependence on operating conditions, it is possible to predict how changes in temperature, humidity, and other factors may affect the performance of the SC (for example, an increase in the internal resistance of the SC may indicate material degradation, which can be corrected by improving production technologies).

The internal resistance of a SC can be defined as the ratio of the voltage change to the current change under the operating conditions of the element. It is important to consider that the internal resistance can vary depending on the environmental conditions and the state of the element itself.

Internal resistance is directly related to the output power of a power supply. When internal resistance increases, some of the output power is lost as heat, which leads to a decrease in the effective voltage and current at the output. This, in turn, reduces the overall efficiency of the system.

SC models can include the calculation of internal resistance based on parameters such as temperature, light level and material characteristics. Mathematical models can use open circuit voltage and short circuit current data to estimate internal resistance. When comparing theoretical values of internal resistance with experimentally obtained data, deviations can be detected that indicate problems in the design or production of the SE. Factors that affect internal resistance: temperature ; humidity ; degradation of materials .

With increasing temperature, the internal resistance of the SE increases. This is due to the increase in thermal vibrations of atoms in the semiconductor material, which causes a decrease in the mobility of charge carriers and, consequently, an increase in resistance.

High humidity can affect internal resistance, especially in conditions where moisture penetrates the structure of the SC. This can lead to corrosion of the connections and an increase in resistance.

Over time, SC materials can degrade, which also leads to an increase in internal resistance. In the event of increased recombination of charge carriers or the appearance of cracks in the semiconductor structure, the internal resistance can increase significantly.

Analysis of internal resistance data and its dependence on operating conditions allows us to predict how environmental changes will affect the performance of the SC. If the internal resistance increases sharply at a certain temperature, this may be an indicator that the element materials are not sufficiently resistant to thermal loads.

Understanding the impact of internal resistance on power output allows you to optimize your SC system. For example, if the analysis shows that high internal resistance reduces overall performance, you can consider opportunities to improve the manufacturing technology, such as:

- optimization of the design of the SC ;
- the use of new semiconductor materials with lower internal resistance, which can significantly increase the efficiency of solar cells.

Thus, internal resistance is an important parameter that significantly affects the performance of solar cells. Models that take into account internal resistance allow not only to estimate the current efficiency, but also to predict the impact of various factors on performance, which is critical for the development and optimization of solar technologies.

Photocurrent is the current generated by a semiconductor as a result of light absorption, which leads to the generation of free electrons and holes in the semiconductor material [9-11]. The photocurrent model, based on the principles of photovoltaics , allows the prediction of photocurrent based on the intensity of solar radiation and the spectrum of light. The models can take into account various parameters, such as the angle of incidence of light, which allows for a more accurate assessment of photocurrents under different conditions.

Comparing model and experimental photocurrent data helps to identify factors that affect the efficiency of the SC. For example, if the photocurrent is lower than expected, this may indicate problems with the optical properties of the material, which requires additional analysis and correction of the models.

Photocurrent is defined according to expression (3), as the number of electric charges created per unit time under the influence of light:

$$I_F = \frac{E}{E_0}\left[I_{sc} + k_{I_{sc}}\left(T - T_0 \right) \right] \quad (3)$$

where I_F - is the photocurrent, A, E - is the energy illuminance, W/m ^{2}, E_0 =1000 W/m ^{2} is the energy illuminance under standard conditions, I_{sc} - is the short-circuit current, A, k_{Isc} - is the temperature coefficient of the short-circuit current, T - is the absolute temperature, T_0 - is the current temperature.

The photocurrent is proportional to the intensity of solar radiation incident on the surface of the SC. It is important to note that the photocurrent may depend on the spectrum of solar radiation, since different materials respond differently to different wavelengths of light.

Modern solar cell models take into account the following factors that affect the photocurrent: solar radiation intensity; light spectrum; angle of incidence of light .

Models can use solar radiation data under different conditions, including different seasons and climate zones, allowing them to predict photocurrent values for specific conditions. Different semiconductor materials have different absorption spectra. Models can include information about the interaction of different wavelengths of light with the material, allowing for more accurate predictions of photocurrent.

As the angle of incidence changes, the effective area on which light falls changes, and therefore the number of photons absorbed. Models can take these changes into account to accurately calculate the photocurrent.

Comparing model-predicted photocurrent values with experimentally measured data plays an important role in optimizing solar cells.

Factors affecting SC efficiency: optical properties of the material; surface quality; temperature. If the measured photocurrent is lower than expected, this may indicate problems with the optical properties of the material, such as reflection or scattering of light. The presence of impurities or insufficient transparency of the upper layers can lead to losses of light energy.

Irregularities and defects on the surface of the SC can prevent normal light penetration. Examination of the surface using microscopy methods will help to identify such defects.

As the temperature increases, the effective carrier mobility decreases, which can lead to a decrease in the photocurrent. Models that take into account thermal effects allow for a more accurate prediction of this parameter.

The following factors can be identified that allow increasing the photocurrent: optimization of materials; development of anti-reflective coatings ; adaptive sun tracking systems.

Different materials interact with light differently, which allows for the development of new semiconductors that better absorb light over a wide range of wavelengths.

The use of special anti-reflective coatings reduces light reflection, which can significantly increase photocurrent. Models help predict how such coatings will affect the performance of SC.

Systems that automatically change the tilt angle of photovoltaic modules to optimally receive sunlight throughout the day can significantly increase photocurrent and power output.

Continuous monitoring of photocurrent under different operating conditions is also important for assessing the durability and reliability of SC. Collecting photocurrent data over time allows for the detection of potential problems such as material degradation or changes in the environment.

Thus, photocurrent is one of the key parameters determining the efficiency of solar cells. Models that take into account various factors affecting photocurrent play an important role in predicting the performance of solar systems.

In works [5-7], modeling of output power (P_{out}) was considered. The output power of a solar power system is the product of current and voltage, making it critical for assessing its overall efficiency. Maximum output power of a solar power system P_{max} is determined according to expression (4):

$$P_{max} = U_{oc} \cdot I_{sc} \cdot F_Z \quad (4)$$

where P_{max} – maximum output power of the SC, I_{sc} - short-circuit current, U_{oc} - open-circuit voltage, F_Z - fill factor of the I-V characteristic of the SC.

models allow you to predict the output power depending on short-circuit current, open-circuit voltage, internal resistance, temperature changes, and illumination, which allows you to more accurately assess performance in real-world conditions.

Analysis of experimental power output data, combined with models, allows us to identify optimal operating conditions, as well as determine how improvements in materials or technologies can increase the efficiency of solar energy conversion.

Thus, the output power depends not only on the maximum current and voltage values, but also on the actual operating conditions of the element.

SC models can take into account the effect of the following external factors on the output power: temperature; illumination level. Temperature changes can affect the output power. Increasing temperature generally reduces open circuit voltage and, therefore, output power. Models that take into account thermodynamic effects allow us to predict how output power will change under different temperature conditions.

Different levels of solar radiation affect the short-circuit current and therefore the power output. Models that take into account the variation of light levels throughout the day and in different seasons allow for more accurate predictions of SC performance.

Comparison of model and experimental data on output power allows us to identify the optimal operating conditions for photovoltaic modules .

In Tab.1 ,Fig. 1 and Fig. 2 shows the results of modeling the dependence of the no-load voltage and photocurrent on the internal resistance of the SC.

Table 1.

Results of modeling the dependence of the no-load voltage and photocurrent on the internal resistance of the CE

R,Ом	U,B	I, mA
6,5	0,80	1240
22,7	2,72	1200
44,7	5,2	1165
110	9,85	891
230	12,81	560
252	12,86	510
274	12,9	470
340	13,07	382
477	13,2	280
922	13,6	150

From the graph in Fig. 1, it can be seen that the voltage increases from 0 to 13 V, upon reaching a resistance of 110 Ohms, the voltage stabilizes and increases to 14 V.

It can be seen from the graph in Fig. 2 that the photocurrent decreases with the increase of the internal resistance of the SE to the value of 922 Ohms.

Studying the effect of different materials on the output power helps to determine which semiconductor materials are most efficient and significantly increase the output power of the SC. Analysis of different design solutions, such as the use of multilayer SC or different types of anti-reflection coatings , can help in increasing the output power. A decrease in output power over a long service life may be a sign of degradation of the materials from which the SC is made.

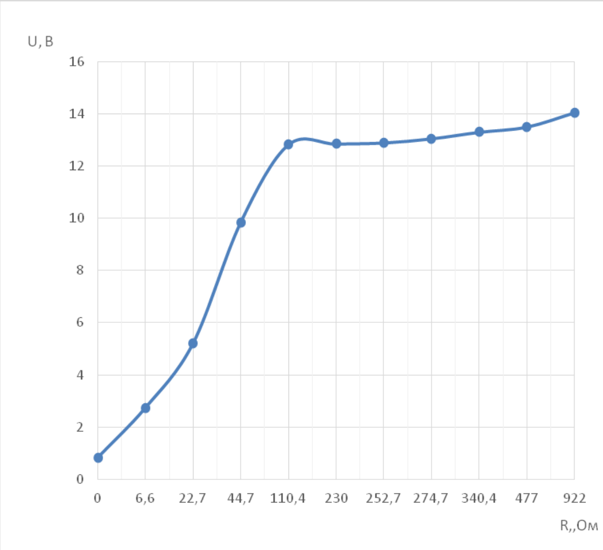

Fig. 1. - Graph of the change in the no-load voltage from the internal resistance of the CE

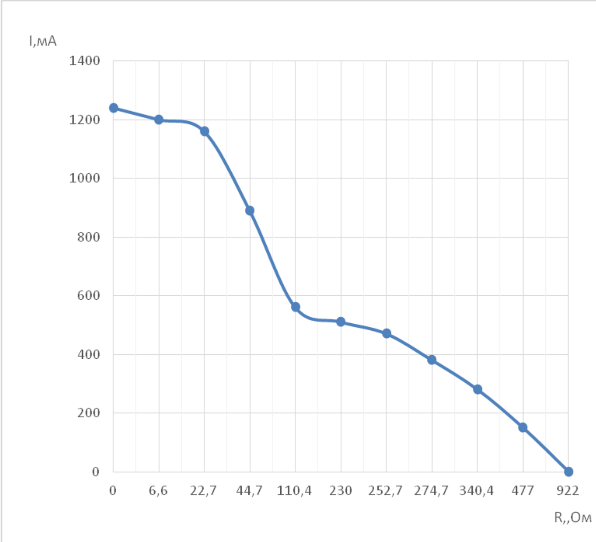

Fig.2 - Graph of the change of the photocurrent from the internal resistance of the CE

The dependence of output power on various factors has several practical applications. Optimizing output power allows designing photovoltaic modules with high efficiency through the use of sun tracking systems that change the angle of inclination of the panels to maximize sunlight reception.

Data on the output power of solar plants helps in the planning of power systems based on renewable energy sources. This is important for ensuring the reliability of power supply and load management.

Estimating output power allows investors and companies to make more informed decisions about investing in solar technologies, choosing those that have demonstrated high efficiency and reliability.

Modeling and experimental analysis allow for optimization of power output by providing a better understanding of the factors affecting solar PV performance, which contributes to the development of efficient solar technologies and systems for a sustainable energy future.

In works [5,6], the modeling of efficiency, which is an important characteristic that shows what fraction of solar energy the element converts into electrical energy, is considered. The efficiency is calculated, according to expression (5), as the ratio of the output power (P_{out}) to the power of solar radiation falling on the SE P_p .

$$\eta_{KPD} = \frac{P_{out}}{P_p} = \frac{I_m \cdot U_m}{P_p} , \qquad (5)$$

where η - is the efficiency of the SC, I_m and U_m – current and voltage corresponding to the point of maximum power P_{max} , P_p - the radiation power incident on the SC.

The SC model allows for the calculation of efficiency based on power output and illumination level. Optimization of the models based on experimental data allows for the prediction of how various changes in design and materials may affect efficiency. If the efficiency is lower than the calculated one, this may indicate the need to optimize the design, improve the quality of materials, or apply new technologies.

Thus, the SC model serves as an important tool for analyzing and optimizing its key characteristics, namely: short-circuit current, open-circuit voltage, internal resistance, photocurrent, output power and efficiency. The SC model allows not only to predict the behavior of the cell under different conditions, but also to identify potential problems, which is critical for improving the efficiency and reliability of solar systems.

High efficiency means that the element is able to efficiently use available solar radiation, making it more attractive from an economic point of view.

SC models allow us to calculate the efficiency based on the output power and the level of sunlight. It is important to note that the efficiency depends on a number of factors: the type of materials, the temperature value ,

Different semiconductor materials have different absorption and recombination coefficients, which affect efficiency. Models that take into account material properties help predict how changes in design or the use of new technologies may affect efficiency.

Models that take into account thermodynamic effects can predict how the efficiency will change with temperature. As the temperature increases, the efficiency of charge carrier recombination can decrease, leading to a drop in efficiency. Comparing model and actual efficiency values allows us to identify directions for its increase. If the actual efficiency is lower than the calculated one, this may indicate the need to optimize the design of the element, for example, changing the thickness of the active layer or using special coatings to increase light absorption .

Improving the quality of semiconductors and other materials used can increase efficiency. Models that incorporate data on material quality can predict how their improvement might affect the efficiency of the SC.

The introduction of new technologies, such as perovskite solar cells or multilayer structures, can significantly improve efficiency. Models that take such technologies into account allow for the prediction of their impact on efficiency.

The value of efficiency is important for a number of practical tasks:

- Efficiency helps to select the most efficient technologies for use in solar systems, which is important for minimizing production and installation costs;

- the value of the efficiency of various solar energy systems helps to plan energy strategies, ensuring reliable and efficient use of solar energy;

- high efficiency makes solar technologies more attractive for investment, which can contribute to the development of the energy industry and lower prices for solar energy.

Efficiency is an important indicator of the effectiveness of solar energy. Efficiency modeling, combined with experimental data, allows identifying opportunities for optimization and improvement of technologies, which is critical for the further development of solar energy and increasing its competitiveness in the market.

Thus, the following results were obtained using models of quantitative and qualitative indicators of SE parameters:

- development and improvement of SC models, leading to a deeper understanding of the physical processes occurring in SC;

- modeling of solar energy parameters allows us to quantitatively assess how different conditions (temperature, illumination, angle of incidence of light) affect the main parameters (short-circuit current, open-circuit voltage, output power), which contributes to accurate prediction of the performance of photovoltaic modules in real operating conditions;

- SC models allow you to detect defects in materials or production technologies, which can be used to improve processes, reduce defects and improve the quality of photovoltaic modules ;

- scientific results obtained in the modeling process can be implemented in production, which leads to cost reduction and increased efficiency of production processes;

- modeling of SC, helps in research of new photoconductive materials, such as perovskites , which can lead to the creation of efficient SC with the best characteristics;

- SC models allow predicting the service life of SC, taking into account degradation factors, which may affect maintenance strategies and management of their installations;

- studying and optimizing efficiency through modeling helps reduce the cost of electricity production and increase the share of solar energy in the overall energy balance;

- SC models allow for rapid adaptation of existing technologies to new challenges and opportunities, providing an innovative approach to industry development.

The use of models of quantitative and qualitative indicators of solar energy parameters contributes to obtaining scientific results that increase the efficiency, quality, and reliability of solar technologies, which supports the development of sustainable energy solutions and promotes the transition to environmentally friendly energy sources.

Solar SC modeling helps optimize the design of photovoltaic modules , which increases their efficiency. This will allow for the efficient use of solar energy and reduce the costs of its production.

Research in photovoltaics is leading to the creation of new high-performance materials, such as perovskites or organic compounds. Models can help predict their behavior and characteristics.

Solar SC models can be adapted to predict the performance of solar PV systems in different climates, which will allow the development of more versatile solutions for solar systems. Solar PV models will provide a better understanding of how solar PV can work effectively in combination with other renewable energy sources, such as wind or hydropower, creating flexible power systems. Solar PV models can be used to predict the service life of solar PV and identify potential problems, which will ensure effective maintenance and management in information and measurement systems.

Models will allow you to create information and measuring systems that will automatically adapt the operation of solar installations depending on current conditions, increasing overall efficiency. Optimization of production processes using models will help reduce material costs, which will make solar technologies affordable. Modeling allows you to identify and eliminate weaknesses in the design and materials of solar energy systems, which leads to the creation of reliable and durable solar energy systems. The use of solar energy models in educational institutions contributes to the development of scientific research in the field of renewable energy sources and the formation of new specialists in this field.

Conclusions

CE models are an indispensable tool for scientists, engineers, and manufacturers seeking to create efficient and reliable solar technologies through the use of:

- taking into account external factors in the model, under various external conditions, such as: temperature, light level and humidity, which allows for accurate prediction of the performance of the solar energy system in real operating conditions;

- performance optimization, comparing theoretical values obtained from models with experimental data helps to identify deviations and determine the causes of their occurrence, which in turn contributes to the optimization of designs, materials and production technologies, and can also significantly increase output power and efficiency;

- predicting the degradation of the CE model, which is important for planning the operation and assessing the service life of photovoltaic modules .

Further development of SE models may include taking into account detailed characteristics of materials, in particular their electrophysical properties at different temperature regimes and operating conditions, which will significantly increase the accuracy of predicting the efficiency of SE operation in real conditions, taking into account not only general parameters, but also microstructural features of materials.

Thus, further development and improvement of SE models is an important step towards increasing the efficiency of solar energy in the context of global climate change and increasing demand for renewable energy sources. With the help of SE models, it is possible to achieve more accurate predictions of the generation of electrical energy by photovoltaic modules at solar stations, which will ensure economic benefits and environmental sustainability in the use of solar energy in the future.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of the manuscript. In addition, the authors fully complied with ethical standards, including plagiarism, data falsification, and double publication.

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КВАЛІМЕТРИЧНИЙ МЕТОД ДЛЯ ОЦІНКИ КІЛЬКІСНИХ ТА ЯКІСНИХ ПАРАМЕТРІВ СОНЯЧНОГО ЕЛЕМЕНТА

У статті розглянуті кваліметричний метод оцінки сонячного елемента, що описує його основні електрофізичні характеристики та процеси, які відбуваються в ньому під час перетворення сонячної енергії на електричну.

Проаналізовано залежність фотоелектричних характеристик сонячного елемента в залежності від різних параметрів. Показано, що підвищення температури веде до зниження основних характеристик сонячного елемента, зокрема коефіцієнта корисної дії, струму короткого замикання, коефіцієнта заповнення та інших показників, що характеризують вольт-амперну характеристику. Це зниження відбувається через зміни в електрофізичних властивостях матеріалів, з яких виготовлені сонячні елементи, а також через вплив температурних змін в матеріалі. Розроблена методика розрахунків основних електрофізичних параметрів, таких як струм короткого замикання та напруга холостого ходу, яка враховує детальну структуру матеріалів, що використані для виготовлення сонячних елементів, що підвищує точність розрахунків вихідної потужності та коефіцієнта корисної дії, а також підвищує стабільність вольт-амперних характеристик сонячних елементів у реальних умовах експлуатації. Акцентовано, що важливим аспектом є аналіз впливу змін умов освітленості, які мають значний ефект на перетворення сонячної енергії. Моделі показують, як зміни в інтенсивності та спектрі освітлення можуть змінювати поведінку сонячного елемента, зокрема впливати на струм та напругу при змінному освітленні впродовж дня або в умовах непостійного сонячного випромінювання. Показано, що наявні підходи до моделювання сонячних елементів потребують подальшого удосконалення, зокрема з урахуванням структури матеріалів, температурних і освітлювальних умов, що підвищить точність розрахунків та стабільність роботи сонячних елементів в реальних умовах.

КЛЮЧОВІ СЛОВА: *сонячний елемент, кваліметричний метод оцінки, система якості і кількості, інформаційно-вимірювальна система, метод контролю, фотоелектричний модуль*.

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