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ACTUAL PATHWAYS FOR SOLAR ENERGY DEVELOPMENT BASED ON THE MATERIALS OF THE SCIENTIFIC AND PRACTICAL CONFERENCE «RENEWABLE ENERGY AND ENERGY EFFICIENCY IN THE 21ST CENTURY» 2025

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The main results of the reports in the section "Solar Energy" were considered and summarized. Specialists from Ukraine, the Republic of Uzbekistan, the Czech Republic and the United States of America took part in the work of the section. A total of 39 reports were presented, most of which concerned issues of increasing the efficiency and ensuring the stability, reliability and uninterrupted operation of solar power plants. Several reports were devoted to research in solar thermal energy, in particular, technologies of solar passive thermal power.

Keywords: *solar power plant, photovoltaic module, photovoltaic technologies, energy efficiency, solar heat power engineering, passive solar technologies*

СУЧАСНІ ШЛЯХИ РОЗВИТКУ СОНЯЧНОЇ ЕНЕРГЕТИКИ ЗА МАТЕРІАЛАМИ НАУКОВО-ПРАКТИЧНОЇ КОНФЕРЕНЦІЇ «ВІДНОВЛЮВАНА ЕНЕРГЕТИКА ТА ЕНЕРГОЕФЕКТИВНІСТЬ У ХХІ СТОЛІТТІ» 2025

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Розглянуто та узагальнено основні результати доповідей на секції «Сонячна енергетика». У роботі секції взяли участь фахівці з України, Республіки Узбекистан, Чеської республіки та Сполучених Штатів Америки. Всього було представлено 39 доповідей, здебільшого вони стосувалися питань підвищення ефективності та забезпечення стабільності, надійності й безперебійності функціонування сонячних електричних станцій. Декілька доповідей були присвячені дослідженням у сонячний теплоенергетиці, зокрема технологіям сонячної пасивної теплоенергетики.

Ключові слова: *сонячна електростанція, фотоелектричний модуль, фотоелектричні технології, енергоефективність, сонячна теплоенергетика, пасивні сонячні технології.*

Introduction. During the work of the XXVI International Scientific and Practical Conference "Renewable Energy and Energy Efficiency in the XXI Century" (Ukraine, Kyiv, May 21–23, 2025), the "Solar Energy" section covered a range of issues related to the further development of solar energy in Ukraine, the Republic of Uzbekistan, the Czech Republic, and the United States of America [1]. The conference featured 39 reports on solar energy, the majority focusing on enhancing efficiency as well as ensuring the stability, reliability, and uninterrupted operation of solar power plants. Several reports were devoted to research in solar thermal energy, in particular, passive solar thermal energy technologies.

The purpose of the publication is to summarize the research materials presented in the reports and highlight the trends in the development of solar energy as one of the areas of renewable energy.

Analysis of the content of the reports. In recent years, renewable energy sources, in particular, solar generation, have played a key role in the development of energy systems around the world, increasing their share and presence every year. In 2024, approximately 800-850 MW of solar power plants for businesses and households were built in Ukraine. As of 2024, the number of solar power plants (SPPs) reached about 75% of all renewable energy facilities in Ukraine [2, 3]. Solar energy can solve many problems. Ukraine has approved a National Renewable Energy Plan, which envisages achieving a 27% share of renewable sources in gross final energy consumption by 2030, in particular in electricity, heat supply and transport [4]. Attracting investments, introducing state-of-the-art technologies, and supporting the state will help increase the share of renewable energy sources in the country's energy balance and improve its energy independence.

The main trends in the development of solar energy in Ukraine include [5, 6]:

- focus on decentralization – modernization of the energy sector with a focus on the active development of small and medium-sized energy projects in Ukraine, which will reduce dependence on centralized energy sources;
- improvement of energy storage infrastructure – one of the key areas for investment in solar energy;
- introduction of new technologies in solar energy – use of more efficient photovoltaic cells, panels with double-sided generation (bifacial panels) and technologies for concentrating electricity.
- The results of research by solar energy experts reflected in the conference reports were aimed at solving many issues that correspond to current trends. They covered both the research into improving the efficiency of solar cells for creating solar energy systems, and issues of ensuring the stability, reliability, uninterrupted operation and durability of these systems.

Photovoltaics. Photovoltaic (PV) modules. Increasing the efficiency of solar energy conversion occurs by improving the efficiency of photovoltaic cells through the search for new materials and methods of their processing; developing new designs; using panels with double-sided generation and solar energy concentrators; creating cogeneration plants for more efficient use of solar energy.

A number of reports considered the issues of increasing the energy efficiency of silicon solar cells, which are the most common type of solar cells in the world. Currently, the efficiency of existing monocrystalline silicon solar cells has reached 18%-23% on an industrial scale [7], while research aimed at increasing their efficiency is ongoing. The report [8] considered the use of the technology of diffusion doping of the surface layer of silicon with impurity germanium atoms, which leads to a change in the bandgap width of the original silicon due to the formation of heterostructures GexSi1-x-Si, which is one of the fundamental parameters of the material. This, in turn, leads to an expansion of the spectral sensitivity range, which is typical for the development of efficient solar cells with a wide range of solar radiation absorption. The report [9] was devoted to the issue of increasing the absorption of sunlight by the surface layers of solar cells that generate electricity by treating their smooth surfaces with texturing. Comparisons show that a silicon cell with surface treatment achieved a short-circuit current 1.2 times higher than a conventional solar cell. In studies, report [10], using the technology of multi-stage low-temperature diffusion doping, nanoclusters of impurity atoms of gadolinium in silicon were obtained, which form the so-called "hidden Schottky barriers" in the volume, the electrophysical properties of which can be used to create new materials with improved characteristics, as well as new optoelectronic elements. According to the authors, this opens up great opportunities for the use of such materials in the creation of new, highly efficient solar cells with a high degree of integration.

The studies into perovskite solar cells, which have made significant progress over the past decade, but still face a number of obstacles that need to be addressed before they can be widely used, were covered in the reports [11, 12]. In the report [11], inverted perovskite solar cells were studied, which, due to the optical properties of the electron transport layer (ETL) and hole transport layer (HTL), can outperform traditional perovskite solar cells. Elements with NiOx/CH3NH3Pb3/ETL structures were studied (ETL as MoO3, TiO2, ZnO). Using TCAD modeling to determine the optimal geometric dimensions of the inverted perovskite solar cell, the thickness of the ETL and HTL layers was gradually changed, while the thickness of the perovskite absorber layer was adjusted. The results of the research determined the optimal NiOx thickness for all structures and the efficiency of inverted perovskite solar cells with ZnO, MoO3 and TiO2 as ETL with the optimal layer thickness. The report [12] presents an overview of the structural and fundamental aspects of perovskite solar cells that lead to significant performance improvements, as well as creative strategies to improve their stability in extreme environments such as high temperatures and prolonged illumination.

The report [13] presented the results of studies on dye-sensitized metal oxides, which are widely studied as an alternative to silicon solar cells. Analysis of the photoelectrochemical characteristics of the obtained electrodes based on ZnO and TiO2, which were sensitized to visible light with a cationic polymethine dye, showed that ZnO films in the wavelength range of 420–620 nm have twice the photocurrent quantum yield compared to TiO2. Thus, a hybrid structure “dye – ZnO”, sensitive to visible light, is formed, which can be used for photoelectrochemical cells for solar energy conversion.

The report [14] identified effective approaches to the use of solar energy. It was found that the temperature of a solar cell undergoes significant changes as a result of the light exposure on its surface, i.e. the heating effect has a significant impact on key electrophysical parameters, in particular, it leads to an increase in the recombination of charge carriers. Experimental studies conducted in the temperature range from 270 K to 390 K revealed a significant increase in the fraction of Shockley-Reed-Hall (SRH) recombination.

A number of reports were devoted to the development of new PV module designs. In report [15], the mechanical stability of silicon wafers for solar cells was analyzed using digital modeling on the COMSOL Multiphysics® platform. Based on the results of modeling and experimental studies, a new design of a flexible photovoltaic energy converter with a wide curvature range was developed to cover both convex and concave surfaces of various objects. In report [16], the practical development of optimal designs based on modeling of new technically adapted to the climate photovoltaic energy devices that can be cooled by rotating around their axis is presented. One of the critical problems for solar panels is excessive surface heating due to high ambient temperatures, which leads to a decrease in efficiency. A new 3D format of a photovoltaic energy device (PVED) with a vertically-axial pyramidal structure, characterized by self-cooling properties and technical adaptation to climatic conditions, is proposed. Due to its geometric characteristics, in particular, the three-dimensional structure and optimized heat transfer properties, the device was found to effectively reduce the temperature coefficient and ensure long-term stable operation. This innovative device was shown to improve the energy conversion efficiency by 33–40%. In the report [17], the relationship between the open-circuit voltage and light intensity for triangular and rectangular solar cells with the same surface area was investigated. It was found that at low light intensity, the open-circuit voltage of rectangular solar cells based on polycrystalline silicon is higher compared to triangular samples. In the report [18], factors affecting the efficiency of photovoltaic cells were considered, one of which is the deterioration of the main characteristics of the module (open-circuit voltage and power) with increasing temperature. To increase performance, it was proposed to use cooling of solar panels, which most often occurs using water or air. The use of air cooling is proposed as the simplest and most cost-effective method, using natural or forced air flow to remove heat. The report [19] analyzed the effect of mechanical loading on solar panels. It confirmed a significant negative impact on the performance of silicon-based solar panels, in particular, a deterioration in photovoltaic performance due to bending and breakage of the glass coating.

The research of specialists [20, 21] was aimed at increasing the efficiency of double-sided photosensitive solar cells, which are capable of providing an increase in generation efficiency by 15-20% [22]. In the report [20], research was carried out for single-sided and double-sided photosensitive solar cells by coating them with an anti-reflective layer with the application of SiO2 with a thickness of 100 nm on the surface of the sample as an anti-reflective layer for both types of solar cells. Calculations were carried out by modeling single-sided and double-sided photosensitive solar cells with a thickness of 20 μm using the Sentaurus TCAD software. According to the results, it was found that the current density reached 28 mA/cm^2 for a double-sided solar cell and 22 mA/cm^2 for a single-sided solar cell. The report [21] presents the results of the analysis of the reflective properties of materials that can be used to increase the efficiency of double-sided solar modules. It has been determined that to significantly increase the efficiency of two-sided PV modules, it is better to use white reflective surfaces of modules. The best among such materials is nanoPAN, which is comparable in reflective properties to natural white snow. Using nanoPAN as a reflector for two-sided PV modules allows to increase the open-circuit voltage of the module.

In the report [23], experts studied solar cells based on multi-junction heterostructures (GaInP/GaIn/Ge). This type of photovoltaic cells has the highest efficiency in concentrated solar radiation with a concentration coefficient of 100...1000. The basic principle of concentrating photovoltaic systems is to use optics to focus sunlight onto a small photovoltaic cell. For the research, an experimental device with a solar energy concentrator based on Fresnel lenses was developed. It was shown that the area of the solar cell can be reduced by a factor equal to the concentration coefficient, and the radiation intensity can be increased by the same factor. It is recommended to use thermal energy and an active cooling system to cool photovoltaic cells.

The practical application of combined photovoltaic modules was discussed in reports [24, 25]. In report [24], a design of a combined flat solar panel for simultaneous production of heat and electricity with a coolant moving in a glass channel on the front side of a classic polycrystalline solar panel was presented. A mathematical model of energy transfer in PV/T was developed. The photovoltaic panel was considered as a multilayer body with ideal thermal contacts between the layers. The conducted computer simulation showed broad prospects for the use of such energy systems. The report proposes [25] the use of a hybrid photovoltaic thermal collector [26] for hydrogen production In particular, for the most promising electrolyzer with a proton exchange membrane, for which heated water is used as a raw material, it is advisable to use the thermal part of the hybrid collector. Calculations and modeling of the system using electrical models are presented, as well as an electrical model of a hybrid photovoltaic thermal collector with an electrolyzer connected to it.

The report [27] reviewed and characterized individual types of combined modules manufactured in the world. Today, the improvement of the characteristics of combined modules is carried out by improving the design of the absorbing panel; searching for a suitable nanofluid circulating in the module; the possibility of convenient splitting of the light beam into certain wavelengths and subsequent adjustment of the corresponding type of solar cells to these waves. Variants of structural and technological solutions for combined solar modules were proposed, depending on the purposes of their application.

The issue of reflection of solar radiation rays by photovoltaic modules was considered in the report [28]. To reduce the negative impact of reflected rays, it was proposed to use masking, which can reduce the amount of electricity generated by PV modules. According to the results of experimental studies, it was found that the use of masking did not significantly reduce the amount of generation for low-power PV modules, but provided that the mask is installed directly on the panel. Masks with minimal impact on electricity generation are presented, made from available materials (red and green polyethylene film); one of the mask materials is agricultural canvas, which can be used in one, two or three layers.

Photovoltaics. Solar power plants. One of the problematic issues in the large-scale use of solar power plants is the daily and seasonal change in insolation. In addition, the discrepancy between the daily peak of photovoltaic generation and the periods of peak loads in the electrical network in the case of mass implementation of solar power plants leads to a surplus of generation during the day. Therefore, the issue of energy storage is one of the key areas of development of solar power. The report [29] considers ways to increase the efficiency of solar power plants within the general energy system by implementing electricity storage systems and optimizing the peak of solar power plant generation due to a change in orientation relative to the sun. It is shown that in the intra-daily cycle for short-term storage, it is advisable to use large-capacity storage clusters based on electric batteries together with generating photovoltaic capacities. In the annual cycle, given the rapid development of green hydrogen energy, it is possible to use the surplus of photovoltaic generation during the period of maximum insolation to obtain green hydrogen. Thus, the drop in solar generation in the winter period can be covered by using green hydrogen stored in storage. The report [30] presents the results of a review of the structures of energy complexes based on solar power plants and battery energy storage systems. Various types of connections of accumulators to solar power plants are analyzed. One of the possible solutions to this problem for SPPs is battery energy storage and storage systems (BESS, EESS technologies), especially for distributed energy systems. BESS provide a stable and reliable power supply due to high speed and density of energy storage, sufficient power, which allows them to be used to regulate the frequency and power of power systems. BESS makes it possible to store electricity generated by solar panels during peak hours of generation and use it during periods of low productivity or increased demand.

Planning of the power system development should be carried out taking into account the balance reliability. Therefore, the issue of increasing the accuracy of forecasting the generation schedules of solar power plants is extremely important, which will reduce the need for balancing capacities, and therefore, ensure the balance reliability of the power system of Ukraine in conditions of sharp fluctuations in the variable generation of solar power plants. The purpose of the research is to identify the optimal periods for the operation of solar power plants and assess their economic and energy potential. The report [31] presented the results of experimental studies of the change in the surface temperature of photovoltaic modules of a 2.4 MW solar power plant , which is located in the city of Merefa, Kharkiv region, depending on the air temperature and the average hourly power output of the plant. The results of the comprehensive analysis of the potential for using solar power generation in the city of Odesa are presented in the report [32]. The analysis is based on meteorological data obtained from the local weather station, in particular data on solar radiation, temperature and other parameters that affect the efficiency of solar power plants. Using modern data processing tools, graphs were constructed that demonstrate seasonal and daily fluctuations in parameters. The results obtained allow us to formulate practical recommendations for the placement and operation of solar power plants in the city of Odesa. The report [33] evaluates the efficiency and productivity of a 100 kW network solar photovoltaic system installed on the building of the Faculty of Electrical Engineering of the Andijan Machine-Building Institute. The results of research based on data collected from January to December 2024 are presented. The report [34] considers the prospects for the use of solar energy in Uzbekistan and Central Asia, a region that has the necessary solar resources and technological paths to become leaders in its implementation. It is shown that thanks to scientific research and innovative engineering solutions, problems with the implementation of photovoltaic systems caused by the harsh climate of the region can be solved.

Reports [35, 36] were devoted to the issues of determining the optimal approach in calculating a photovoltaic power plant or choosing a photovoltaic module. In the report [35], it was proposed to use multiple generation of synthetic daily insolation series in calculating photovoltaic power plants, which reproduce short-term autocorrelation processes of insolation changes in the real range of root-mean-square deviations from the averaged values. Usually, in contrast to this approach, averaged multi-year solar radiation data for a certain region are used in calculations. It is shown that synthetic series of peak solar hours PSH(n) are the most helpful tool in solving problems of optimizing the component composition of autonomous and backup power supply systems with high reliability. The report [36] proposed that when choosing a photovoltaic module model for tasks related to electricity generation, the method of simplifying the model based on the criterion of annual electricity generation should be applied, i.e., it is advisable to use the simplest model that provides sufficient accuracy.

The results of the study of the impact of partial shading on the performance of photovoltaic modules were presented in the report [37]. The analysis was carried out at the experimental photovoltaic station of Vinnytsia National Technical University. The results showed that losses occur only in current and power, while voltage showed a smaller impact in partial shade. The analysis and modeling conducted prove the need to take into account the shading of photovoltaic modules, since it directly affects the accuracy of the forecasts. The greatest impact on the forecast results is caused by shading in the autumn-winter period, when shading is observed by neighboring rows of panels.

The report [38] presents an analysis of literature sources and performs full-scale and mathematical modeling of the modes of photovoltaic stations and distribution electrical networks. This made it possible to explain the dependence of the reliability and uninterrupted operation of power transformers in distribution networks on the operating mode of networks and photovoltaic stations. The main processes that cause overheating of parts of power transformers and become the cause of their failure are highlighted. The analysis and modeling conducted prove the direct influence of the operating modes of photovoltaic stations, and accordingly, the modes of distribution electrical systems on the reliability and uninterrupted operation of power transformers used in these networks.

Since solar power plants play a substantial role in the power and electricity balance of electric power systems, it is crucial to know how much electricity and on what schedule in time SPPs can generate it. In addition to solar insolation, another reason for unstable generation of SPPs is their technical condition, in particular, the gradual degradation of photovoltaic modules. The effective functioning and durability of photovoltaic systems require regular maintenance and diagnostics. Identification of defects in photovoltaic systems at the early stages of development will help to avoid costly and long-term repairs. A number of conference reports were devoted to these problems. In report [39], a hardware-software complex was developed to solve the problem of forecasting SPP generation, which was shown for monitoring, classifying and detecting malfunctions (damages) in the operation of SPPs and identifying their technical condition taking into account retrospective data. The proposed method involves two stages: 1) modeling, during which a mathematical model of the process of functioning of solar power plants is created based on retrospective data on their operation with the determination of the dead zone and the formation of a neuro-fuzzy generation algorithm; 2) the monitoring and forecasting process to detect and diagnose the appearance of defects or malfunctions, in which the system operates in real time, controlling the technical condition of the PV modules. The report [40] presents a pilot autonomous system for determining the parameters of photovoltaic modules. This system is developed on the Raspberry Pi microcomputer platform and allows you to measure the V-I characteristic and determine the main PV module parameters in field conditions within a few seconds. These parameters are associated with a single-diode replacement scheme for photovoltaic cells and characterize the current operating characteristics of the PV modules: real maximum power, electrical losses and the degree of their degradation. The results of the study of methods for determining the degradation of photovoltaic modules, including electrochemical impedance spectroscopy (EIS), were discussed in a report [41]. In particular, the EIS method shows significant prospects as a non-destructive diagnostic method for assessing the degradation of solar panels. As recent studies show, EIS applies a small alternating voltage to the solar cell and measures the current response, calculating the impedance from the amplitude coefficient and the phase difference between the applied voltage and the resulting current. By changing the frequencies and analyzing the Nyquist and Bode diagrams, researchers successfully detected mechanical degradation in solar cells by comparing the values of the equivalent circuit elements in the normal and degraded states. An assessment of waste management problems in the solar energy sector of Ukraine was also conducted. The report [42] presents a thermal image-based defect detection technology that effectively reduces energy losses, especially in large photovoltaic systems. The problem was solved using general methods of theoretical analysis of the problem based on the study of the physical properties of photovoltaic systems and the features of their diagnostics. A methodology for selecting and combining various diagnostic technologies, in particular electroluminescent testing and the use of machine learning algorithms, was developed to increase the accuracy of fault detection and minimize operating costs. A theoretical model for determining the parameters of photovoltaic modules that vary depending on the load voltage was presented in the report [43]. It was shown that when calculating the current-voltage characteristics of photovoltaic modules, a single-diode model with variable parameters provides a good match between theoretical and experimental data, namely the normalized root mean square deviation is nRMSE ≈ 0.2%. But unlike conventional multi-diode models with fixed parameters, the proposed approach gives a more adequate idea of the recombination and resistive losses in photovoltaic cells.

Solar thermal energy. Several reports were devoted to research on improving solar thermal systems and on the use of passive solar thermal technologies in the southern regions of Ukraine.

The use of passive solar technologies for heat supply was proposed in the report [44]. A method of accelerated restoration of low-rise residential buildings destroyed in hostilities on the territory of Ukraine, using available building materials and passive solar technologies for their heat supply, is considered. An analytical study was conducted on the use of clay concrete with organic filler (straw) for the construction of low-rise solar passive houses in the territories of Ukraine, provided that these territories have organic raw materials (straw) and sufficient reserves of clay soils with a clay fraction content of 15%. Clay concrete with organic filler (straw) is an environmentally friendly organic building material that is made from local and relatively inexpensive raw materials: soils with a high content of clay matter, organic agricultural waste (wheat straw). The main requirements that building materials and products must meet have been determined.

The report [45] presents the development of an innovative technology for increasing the efficiency of a modern solar water heater by installing a reflective base between the base and the pipes. Using the Comsol Multiphysics program, an improved solar collector was studied, and the distribution of water velocity, density distribution, and temperature distribution in its pipe were analyzed. It was shown that due to its new optimal design, the improved solar collector is 8% more efficient than conventional collectors.

The results of the analysis of the energy balance of a solar installation operating in a free heat exchange mode using an electric stimulator of coolant circulation at the outlet are given in the report [46]. The influence of the main parameters, such as solar radiation intensity, ambient temperature and coolant circulation speed, on the efficiency of the system was studied. It was found that the use of an electric stimulator ensures the stability of the coolant movement and improves heat transfer.

The report [47] proposed the use of energy management system software when choosing a solar collector for heating social and administrative buildings, which is important for making a decision on the use of solar collectors in the construction sector and when considering energy management issues. As a result, a draft commercial offer is formed for the customer, which contains detailed information about the cost of the project, expected economic benefits and other important factors.

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