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# DEVELOPMENT TRENDS OF SOLAR POWER ENGINEERING BASED ON THE MATERIALS OF THE SCIENTIFIC AND PRACTICAL CONFERENCE «RENEWABLE ENERGY AND ENERGY EFFICIENCY IN THE 21st CENTURY» 2024

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**Bondarenko D.[1], Matiakh S.[2], Surzhyk T.[3], Sheiko I.[4], Kravchenko M.[5]**

Author for correspondence: Bondarenko Dmytro,
e-mail: dima7007bond@gmail.com

*The main results of the reports at the "Solar Energy" section were considered and summarized, in particular, one of the areas of solar energy engineering - solar power generation. Specialists from Ukraine and the Republic of Uzbekistan took part in the work of the section in this field. A total of 32 reports were presented, focusing on topics such as the implementation of distributed generation facilities based on photovoltaic systems, improving the energy efficiency of solar power plants, etc. The reports demonstrated the primary trends to highlight the issues of building and operation of energy-efficient solar power plants in today's realities.*

[1] PhD
https://orcid.org/0000-0002-5629-930X

[2] PhD
https://orcid.org/0000-0002-1707-3519

[3] Dr. of Science
https://orcid.org/0000-0002-1418-7748

[4] Junior Researcher
https://orcid.org/0000-0002-5770-3677

[5] PhD, Assoc. Prof.
https://orcid.org/0000-0003-0428-6440

[1, 2, 3, 4] Institute of Renewable Energy of NAS of Ukraine, Kyiv, Ukraine

[5] Kyiv National University of Construction and Architecture, Kyiv, Ukraine

**Key words:** *power, solar power plant, distributed generation, smart energy systems, energy efficiency, photovoltaic technologies.*

# ТЕНДЕНЦІЇ РОЗВИТКУ СОНЯЧНОЇ ЕЛЕКТРОЕНЕРГЕТИКИ ЗА МАТЕРІАЛАМИ НАУКОВО-ПРАКТИЧНОЇ КОНФЕРЕНЦІЇ «ВІДНОВЛЮВАНА ЕНЕРГЕТИКА ТА ЕНЕРГОЕФЕКТИВНІСТЬ У XXI СТОЛІТТІ» 2024

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**Бондаренко Д. В.[1], Матях С. В.[2], Суржик Т. В.[3], Шейко І. О.[4], Кравченко М. В.[5]**

Автор для кореспонденції: Бондаренко Дмитро,
e-mail: dima7007bond@gmail.com

*Розглянуто та узагальнено основні результати доповідей на секції «Сонячна енергетика», зокрема одного з напрямів сонячної енергетики – сонячної електроенергетики. В роботі секції з цього напряму взяли участь фахівці з України та Республіки Узбекистан. Всього було представлено 32 доповіді, які стосувалися питань впровадження об'єктів розподіленої генерації на основі фотоелектричних систем, підвищення енергоефективності роботи сонячних електростанцій тощо. Основні тенденції змістів доповідей полягали у висвітленні питань створення та функціонування енергоефективних сонячних електростанцій у сьогоднішніх реаліях.*

канд. техн. наук
https://orcid.org/0000-0002-5629-930X

[2] канд. техн. наук
https://orcid.org/0000-0002-1707-3519

[3] д-р. техн. наук
https://orcid.org/0000-0002-1418-7748

[4] мол. наук. співроб.
https://orcid.org/0000-0002-5770-3677

[5] канд. техн. наук, доц.
https://orcid.org/0000-0003-0428-6440

[1, 2, 3, 4] Інститут відновлюваної енергетики НАН України, м. Київ, Україна

[5] Київський національний університет будівництва і архітектури, м. Київ, Україна

**Ключові слова:** *електрична енергія, сонячна електростанція, розподілена генерація, інтелектуальні системи, енергоефективність, фотоелектричні технології.*

**Introduction.** During the XXV International Scientific and Practical Conference "Renewable Energy and Energy Efficiency in the 21st Century" (Ukraine, Kyiv, May 22-24, 2024), the "Solar Energy" section highlighted the trends in the further development of one of the areas of solar energy engineering - solar power industry in Ukraine and the Republic of Uzbekistan [1]. 32 reports were presented at the conference in the field of solar power, , which focused on the implementation of distributed generation facilities based on photovoltaic systems, improving the energy efficiency of solar power plants, etc. The main trends in the reports were the focus on highlighting the issues of building and operation of energy-efficient solar power plants in today's realities.

**The purpose** of the publication is to summarize the research materials that were presented in the reports and highlight the trends in the development of solar power as a component of one of renewable energy technologies.

**Analysis of the content of reports.** One of the goals of the Energy Strategy of Ukraine until 2050 [2], which provides for the development of the economy in accordance with the National Economic Strategy for the period until 2030 [3], and that of the fulfillment of international obligations within the framework of the Agreement on the Association of Ukraine with the EU [4] and the Paris Climate Agreement is the development of alternative energy. Today, the production of electricity by solar power plants (SPPs) of Ukraine does not meet its potential, because the territories promising for the placement of industrial SPPs are under occupation or in close proximity to the zone of active hostilities. In two years, about 13% of industrial SPPs have been destroyed or damaged [5]. Despite this, according to experts, solar power remains a strategically important area for renewable energy development in Ukraine. Today, solar power plants provide about 75% of the production of "green" energy, but the focus of the solar sector has transformed from a more ecological one to a security and economic one [5]. Over the past two years, there has been an increase in the number of solar power plants attributable to the growing number of residential SPPs: in 2022, 220 MW of solar power plant capacity was introduced, of which 206 MW were installed by households; in 2023, according to incomplete data – 115 MW of SPPs were installed [5].

The future energy strategy envisages decentralization of the system to reduce its vulnerability and increase its resistance to attacks and damage. After the several waves of destruction of thermal and hydro generation in recent months, when Ukraine lost more than 8 GW [6] of electricity generation capacity, the energy system needs not only restoration, but also renewal. Experts see the stability and efficiency of Ukraine's energy sector primarily in the development of both small and medium-sized distributed "green" energy [7].

Decentralized (distributed) generation is a system of energy production and transmission with the participation of a large number of consumers who are producers of electrical energy for their own needs and, at the same time, transmitters of excess energy produced to the general network - prosumers. The main feature of the decentralized model is the maximum approximation of energy production to the consumer. In 2023, Law No. 3220-IX "On the Restoration and Green Transformation of the Energy System of Ukraine" [8] was adopted, which amended 18 laws relating to many aspects of the functioning and development of the energy markets of Ukraine, aimed at the development of small distributed generation. One of the changes is the introduction of the self-production mechanism, which is analogous to the support mechanism widely used in the world for renewable energy facilities — NetEnergyBilling [9, 10]. Such actions will contribute not only to more efficient use of energy, but also to the achievement of decarbonization goals and the fight against climate change, that is, they will meet the European integration obligations and the strategically declared "green" transformations of Ukraine.

The research efforts of solar power specialists today are focused on creating **smart energy systems** that can ensure the flexibility and efficiency of generation, distribution, storage and consumption of electrical energy. Since solar generating capacity can be segmented, it is promising to move to the construction of generating power plants in the form of a cluster structure and the creation of unified generating modules. Such miniplants are quite typical and contain elements that are typical for their purpose and nominal parameters. The generating power plant proposed by the authors [11] can be used to create power generation miniclusters - local, small-capacity solar power plants to provide electricity for own needs and transfer surpluses to the general grid. The use of energy clusters will ensure decentralization of the energy system, modularity, universality and its resistance to external and internal factors. A minicluster is a self-sufficient energy connection, which, in turn, consists of typical unified units that generate, store and distribute electrical energy. The use of smart systems and algorithms in modules and clusters would enable controlling the processes of generation, accumulation and distribution in optimal modes, as well as quickly balancing the system in case of failure of an individual element of the cluster. It is noted that the use of an independent learning unit management algorithm is a step towards the introduction of artificial intelligence in cluster power systems. The use of microinverters for combining small energy systems is proposed in [12]. The cluster-block approach improves the stability and scalability of both the broad energy system as a whole and local areas, especially during outages. The main idea presented by the authors is the use of microinverters - equipment that converts direct current into alternating current - as devices that ensure decentralization within the solar power plant. The advantages of using microinverters locally, as well as the implementation of microinverters together with energy storage solutions, are shown. Systems with different types of battery placement are described. The report [13] considered the use of packet transmission of electrical energy as a powerful and flexible tool for managing the generation, distribution, and consumption of electrical energy, while electrical energy is transmitted in pulse packets containing an information component, that is, they are carriers of both information and energy. The transmission of electrical energy in packets of information pulses is a promising direction of research, since it does not require additional transmission lines and significant changes to the structured cable networks of already existing information systems. At the same time, targeted delivery of the necessary amounts of electrical energy is carried out. Batch transmission of energy under the conditions of limited and unstable generation enables rational distribution and use of energy resources. Two variants of the structural topology of such an information and electrical network are proposed. The necessary equipment and algorithms for its operation are shown, lines for the further development of such systems are highlighted.

**In a number of reports of the conference, topical issues related to the structural aspects of SPP were considered: choosing the optimal option of SPP, advantages and disadvantages of mechanisms for supporting and stimulating the installed SPP, etc.** Structural options of an SPP to provide energy to a private house are considered in the report [14]. A comparison is given for grid, hybrid and autonomous power plants. It is noted that today, when there are mass blackouts of consumers in the energy system, the grid power plant will not solve the problem of providing electricity, because in the absence of electricity generation, it will not be able to receive it from the network. The hybrid solar power plant allows you to ensure the autonomy of the house due to the accumulation of solar energy in the existing batteries of sufficient capacity in its composition, and the excess can be sold to the grid at a "green" tariff. Currently, it is the most popular type of solar power plant, as it combines the functionality of an autonomous and grid SPP. An autonomous system is less promising, because it eliminates the possibility of selling excess electricity produced in the future. The report [15] considered the development of decentralized solar power generation due to the construction of rooftop SPPs. Currently, the small solar generation sector has been growing in Ukraine, namely the installation of photovoltaic systems on the roofs of buildings and in households. This will provide an opportunity to ensure the reform of the electric power industry of Ukraine in the shortest possible time and to build and implement new power generation capacities, which will ensure the increase of stability and reliability of both the energy supply of consumers and the general energy system. The advantages of distributed generation based on rooftop SPPs are shown. The report [16] proposed the use of IGBT module as the power part of a hybrid inverter of a rooftop photovoltaic station, which can significantly reduce the costs of installing rooftop SPPs. The economic effect of its use is shown. An analysis of the prospect of changing support from a fixed "green" tariff to a market premium mechanism for SPP is presented in the report [17]. An assessment of the monthly income for the solar power plant was carried out for selling electricity at a "green" tariff, as well as for selling electricity independently on the "day-ahead" market and receiving compensation under the market premium mechanism. An example of the option of using the "market premium" mechanism to achieve a positive economic effect (payback point) after putting the SPP into operation is shown. The report [18] considered the payback period of grid SPP for own consumption for enterprises with using a loan from the European Bank for Reconstruction and Development (EBRD). In Ukraine, an ordinary 100 kW SPP, depending on the width and type of roof, its orientation and angle of inclination, is capable of generating from 90 to 120 thousand kWh per year. For most enterprises, the annual amount of savings can reach almost a million hryvnias, while the plant itself mostly costs up to 2 million hryvnias. The author cites the advantages of using the EBRD loan during the construction of the SPP, its attractiveness from the point of view of investment return. The assessment of the projected generation of electrical energy by a solar power plant, taking into account the degradation of photovoltaic cells, is presented in the report [19]. The authors simulated the generation of electrical energy by the SPP for the thirty-year period of operation, taking into account the degradation of the silicon cells of the photovoltaic module. The simulation results showed that as a result of the linear degradation, which is characteristic of photovoltaic cells, there is also a linear decrease in the annual production of electrical energy by the solar power plant.

**A number of reports at the conference focused on improving the energy efficiency of solar power plants.** In the report [20], experts presented an analysis of methods for calculating the technically achievable potential of converting solar energy into electrical energy. A comparison of 2 existing methods of assessing the technically achievable solar potential is presented and their improvement is proposed, with taking into account the technical features of the latest photovoltaic conversion technologies, expanding the division of archetypes of photovoltaic plants, plants of small and medium generation capacity, and the specifics of the territories that are acceptable for calculation. Considering the technical characteristics of the latest technologies of photoelectric conversion provides a significant potential increase in the comparison of these methods. The report [21] was devoted to the study of the problem of PWM- and MPPT-technologies of charge controllers within the limits of photovoltaic systems. A comparison of the main characteristics of PWM and MPPT charge controllers is given, their advantages and disadvantages are shown. Peculiarities of the SPP generation calculation algorithm, taking into account options for shading photovoltaic modules, are discussed in the report [22]. One of the requirements for the operation of SPP in the United Energy System of Ukraine is generation forecasting, which is a difficult task for damaged plants. Based on the analysis of different conditions of light hitting the surface of the photovoltaic module, block diagrams of algorithms for calculating coefficients for the first and second half of the day were developed, examples of algorithms inclusive of empirical formulas in the program for calculating the hourly generation of SPP were given. In the report [23], a new method of restoring missing data regarding the hourly schedule of generation by photovoltaic plants is proposed, which is based on the use of the clustering method (K-means) and allows to restore missing data based on information on photovoltaic plants that are assigned to the same group with that object, for which the data is being restored. The use of optimizers as a possible way of combating power losses during shading of a photovoltaic module is considered in reports [24, 25]. This primarily concerns private small solar power plants of 5-15 kW, installed on roofs or simply on the ground, for which, even with a small amount of shading, a significant drop in power can occur throughout the system. With the help of optimizers, the power reduction occurs only on the shaded panel, and the performance of the other photovoltaic modules in the row will not decrease. An important advantage of installing optimizers is the possibility of constant monitoring of their indicators and the state of the photovoltaic modules themselves. In the report [26], the problems of SPP protection from lightning are considered. A review of modern publications covering the problem of lightning protection of solar power plants was conducted. It is shown that with the increase in the use of solar energy for obtaining electrical or thermal energy, there are more problems of lightning damage to solar energy facilities. In addition, when studying this problem, it should be taken into account that the lightning protection of large ground-based solar power plants and rooftop solar power plants has its own differences and requires a separate approach. The report [27] was devoted to an overview of existing photovoltaic elements belonging to different generations and technological groups, an assessment of their advantages and disadvantages, current performance indicators and prospects for development, technologies for increasing their efficiency. It is noted that: technology based on silicon wafers is still dominant; the latest photovoltaic technologies, including perovskite, tandem and organic, have shown growth in recent years, while the issues of solving problems related to improving their efficiency, stability and scaling of production remain relevant; research and development of technologies to mitigate the impact of photovoltaic systems on the environment by reducing the use of toxic materials, energy intensity and toxicity of production processes, and recycling of end-of-life panels remain relevant. The temperature regime of photovoltaic panels was studied by the authors in the report [28]. This influence directly depends on the type and physical structure of the solar cells and significantly affects the efficiency and lifetime of the SPP. To study the influence of the temperature regime, a non-stationary mathematical model of temperature distribution in the layers of the solar panel under real conditions of its operation is proposed. The report [29] considered factors affecting the efficiency of photovoltaic cells and solar panels during operation. Today, there are already photovoltaic thermal (PVT) solar panels with cooling and additional thermal energy production. Such panels make it possible to obtain additional thermal energy, which can be used for heating and hot water purposes, as well as to generally improve not only the electrical efficiency of the system, but also to obtain a much higher overall efficiency of solar radiation energy conversion. In reports [30, 31] the results of mathematical modeling of solar panels with water and air cooling are presented. The study of changes in the thermodynamic parameters of the photovoltaic module during heat exchange was performed using mathematical modeling in the software environment "Comsolmultiphysics 6.1" with an equivalent composite material. The report [32, 33] was devoted to the operation of bifacial photovoltaic modules, which are rapidly gaining popularity. In the report [32], the authors paid special attention to the study of factors influencing the generation of energy through the rear surface. The studies show that where a solar power plant is installed on highly reflective surfaces (such as a white roof or soil with light-colored stones), the generation increase for dual-sided solar cells can be up to 30% just from the additional power generated by the rear surface. In the report [33], using the Sentaurus TCAD software, the specialists built geometric models of single- and dual-sided solar modules based on monocrystalline silicon, and numerical simulations showed the advantages of dual-sided solar cells compared to single-sided ones. Calculations and obtained results show that higher current and voltage can be obtained from double-sided solar modules.

Promising technologies for building's energy supply – envelope-integrated photovoltaic systems, which become widely used, are presented in the report [34] of the conference. The design and construction of innovative buildings today is decisively determined by the need to observe maximum energy efficiency. BIPV (Building-integratedphotovoltaics) technologies are solar power plants that are integrated into buildings and structures) are a promising addition to the improvement of the building's envelopes. The authors present the advantages, disadvantages and possibilities of introducing BIPV technologies integrated into the structure of engineering systems of the building.

The application of the practice of agrophotovoltaics, which combines agriculture and the production of photovoltaic energy, is shown in the report [35]. By installing solar panels over crops, farmers can harness solar energy while optimizing land use, reducing water consumption and the amount of direct sunlight reaching the plants during the hot part of the day. This will help create a more favorable environment for growth, which will increase the yield of agricultural crops.

The use of photovoltaic modules for energy supply of warehouses is proposed in the report [36]. The author investigated the effectiveness of using photovoltaic modules as a constant power source for warehouses under conditions where connection to stationary energy sources is not available. An analysis of the advantages of this approach compared to other energy sources was carried out.

Problems and ways to improve the efficiency of electronic waste disposal were presented in the report [37]. The solution to the e-waste problem is to move from landfilling and incineration to industrial recycling. Today, Ukraine has not yet created an extensive e-waste recycling infrastructure, so the issue of recycling solar modules remains open. The report points to the need for a legislative establishment of the procedure for waste collection, the provision of incentive benefits, in particular, a reduction in the cost of supplying new equipment, etc. The problems of recycling photovoltaic modules were also considered in [38]. The authors present an overview of the state of the art in the recycling of the main components of photovoltaic plants - photovoltaic modules in terms of the regulatory regulation of these works and the development of the necessary additional regulatory acts, taking into account the available technologies that are in use, those that have been developed or are in the process of development. The necessity and possibilities of reuse of photovoltaic modules, materials and connections obtained during disposal are indicated. The goals and tasks that must be completed in Ukraine towards the disposal of photovoltaic modules are shown.

The reports of the Uzbek experts were mostly concentrated on the research of solar cells with the aim of improving their durability and reliability, operational stability as well as efficiency to resist various kinds of external influences. An original method that allows generating uncontrolled impurity atoms located in the volume of a silicon crystal, which are activated during various thermal annealing, is proposed in the report [39]. The basis of the method is the formation of electroneutral clusters of nickel atoms in the crystal lattice of silicon, which is important in the manufacture of various electronic devices and especially in the development of efficient silicon-based solar cells. This method of generation makes it possible to increase the lifetime of minor charge carriers, and also ensures the stability of the electrical and recombinational parameters of the initial material, which is repeatedly subjected to heat treatment in the process of manufacturing photoelectronic devices. The report [40] presents the results of a study of thermal annealing of nCdS/pCdTe solar cells in air with the aim of practical use of a heterostructure subject to thermal radiation - heating in the field. The efficiency of the nCdS/pCdTe solar battery is largely determined by the perfection of the structure of the solid solution and its geometric dimensions, phase. The effect of thermal annealing on the thin transition layer has a positive effect on the properties and initial parameters of nCdS/pCdTe solar cells, improves their stability. The report [41] was devoted to the study of electron-hole homojunctions with a surface heterolayer window, which are of particular interest in photoconversion technology. As a result of the research, it was established that by the method of liquid phase epitaxy it is possible to obtain homo-p-n junctions of gallium arsenide from surface heterolayers $(GaAs)_{1-x}(ZnSe)_x$, $(Ge_2)_{1-x}(ZnSe)_x$ and photoelectric properties that are of interest to development of solar energy converters. The results of research on the doping of silicon solar cells with nickel atoms and changes in their parameters during additional temperature annealing were considered in the report [42]. It was experimentally established that doping solar cells with impurity nickel atoms followed by additional heat treatment allows to improve their main parameters. The report [43] proposed a method for determining the main parameters of real solar cells by solving one transcendental equation and processing the results obtained in the experiment according to the current-voltage characteristic using the "Least Squares Method". The advantage of this method is the use of a single current-voltage characteristic and control of the accuracy of the calculation of the parameters of the solar cells. The closeness of the calculation results to the experimental results indicates the effectiveness of the method. The evaluation of the efficiency of solar cells with a vertical p–n junction is presented in the report [44]. It is shown that the research and development of solar cells with "vertical" p–n junctions, parallel to the incident light flux, opens up new perspectives and has a number of advantages compared to conventional "horizontal" structures: 1) since there is no metallization on the front and rear surfaces of such cells, they can be transparent in the long-wavelength part of the spectrum beyond the main absorption band, which allows them to effectively use the light spectrum; 2) such solar cells can convert light both from the front and from the back, which makes them more versatile. Analytical expressions for the current density, maximum power and efficiency of these elements are given. In the report [45], on the basis of a microscopic study of plates obtained under different technological conditions, it is proposed to study the mechanism of the increase of individual grains and the growth of crystallites and the nature of heat transfer in powder and moulded wafers of polycrystalline silicon, as well as in structures made on its basis. A significant difference between the thermal conductivity of polycrystalline silicon and monocrystalline silicon was established. Thermal and optical effects on the p-n structures of polycrystalline silicon, which are present both in the technique and under different operating conditions of the devices, can lead to both positive and negative results, which is associated with their stimulating or deteriorating effect on generation-recombination and kinetic processes of non-equilibrium charge carriers. Therefore, it is relevant to carry out special research to optimize technological and operational processes of thermal and optical effects on polycrystalline silicon and structures based on it.

**Conclusions.** In Ukraine, conditions should be created to stimulate projects of distributed solar power generation - installation of small and medium-sized solar power plants in households and energy cooperatives.

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