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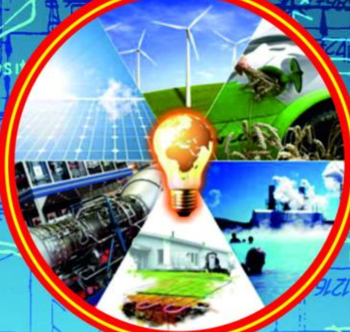

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ТЕХНІКА ЕНЕРГЕТИКА ТРАНСПОРТ АПК

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MODERN INNOVATIVE TECHNOLOGIES AND MATERIALS FOR ENHANCING THE EFFICIENCY OF SOLAR PANELS

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The use of alternative energy sources, such as solar, wind, hydropower, etc., can reduce dependence on traditional energy sources, which are unstable and limited. This can help solve the problem of energy shortages and reduce the risk of energy crises.

The article provides an overview of modern innovative technologies in the field of production, operation, and recycling of solar panel systems.

Photovoltaic technologies have a long history of development and refinement, as from their inception, they were relatively large, costly, and inefficient systems. However, over the years, scientists and engineers, recognizing the extraordinary importance of renewable systems, have worked on comprehensive improvement and modernization of these technologies. Today, modern panels are capable of achieving an efficiency ratio of around 20%. Panels have gradually become more accessible to people, their application in various sectors has increased, and now solar energy systems are used both for energy generation for sale and for the self-consumption of homeowners or factories.

The article primarily examines modern materials for the photovoltaic elements of panels, their advantages and disadvantages, and application peculiarities. Various innovative approaches and panel enclosure materials are considered to ensure the strength and lightness of solar systems.

Additionally, perovskite solar panels are discussed in detail, along with the prospects of their industrial-scale application. Given that like any technology, solar panels have a limited lifespan, approaches to panel recycling after their operational life are also considered.

Finally, the article addresses the application of innovative technologies in the field of renewable energy sources in Ukraine, as many systems will require replacement due to military actions in the south and east of the country.

Key words: *solar panels, SES, photovoltaic technologies, renewable energy, perovskite panels.*
Fig. 3. Ref. 20.

1. Introduction

The modern world is faced with a growing need for energy, with a growing awareness of the need to reduce the use of carbon fuels and reduce greenhouse gas emissions. Solar energy is considered one of the important sources of renewable energy, and modern solar panels are a key element for its production. However, despite progress in the design and manufacture of solar panels, there are several unsolved problems that limit their efficiency and widespread application.

The main aspects of the problem:

1. Efficiency - Despite technological progress, solar panels still have a low conversion efficiency of solar energy into electrical energy. This limits their production on a large scale and increases dependence on other energy sources.

2. Dependence on weather conditions - The use of solar panels is limited by the presence of solar radiation. Cloudy days and nighttime periods reduce the performance of the panels, making it difficult to use them as a primary energy source.

3. Cost - The cost of manufacturing and installing solar panels remains high, making them unaffordable for many regions and businesses.

4. Technical limitations - The large areas required for the installation of solar panels, as well as their limited possibilities of integration into architectural solutions, may limit their application in urban environments.

5. Materials - The choice of suitable materials for the manufacture of solar panels is of great importance. Materials must be efficient in absorbing solar radiation and expensive or rare materials that can increase the cost of the panels should be avoided.

6. Stability and durability - Solar panels must be resistant to extreme weather conditions, including rain, snow, wind, as well as UV radiation and temperature changes. Their characteristics should not deteriorate over a long period.

7. Integration into the environment - One of the important requirements is the ability to integrate solar panels into various architectural and design solutions. Modern panels should be easy to install as well as be able to be used in a variety of locations, including homes, commercial buildings, cars, and more.

8. Difficulty in storage - Solar energy production depends on the availability of the sun, so storing and storing energy for use at night or on a cloudy day is a significant challenge.

9. Environmental Aspects - The manufacturing processes of solar panels must be based on best environmental practices to avoid environmental degradation during development and use.

To solve these problems, a comprehensive approach with the use of modern materials and technologies is necessary.

2. Analysis of recent research and publications

Every year, solar energy utilization technologies become increasingly popular and more efficient. According to the National Oceanic and Atmospheric Administration of the United States, the Earth receives 173,000 terawatts of solar energy, which is 10,000 times more than what the planet's population uses [1].

The development of this industry currently tends toward rapid growth, as forecasts suggest a transition to 100% use of alternative energy sources by 2050. Of this, 69% is projected to come from solar energy [2]. As of 2018, the total capacity of such systems reached 480 gigawatts, ranking second among renewable energy sources after wind energy [3].

Modern modules have become significantly more efficient than previous developments. Nowadays, conventional panels produce 25% more energy than older ones. Moreover, the cost of innovative technologies, which were previously very expensive, is decreasing. Currently, the development of bifacial solar panels is actively progressing. The essence of these panels lies in the fact that the rear part of the bifacial panel also captures sunlight, thus being able to produce 10-15% more electricity than traditional single-sided panels. According to the National Renewable Energy Laboratory (NREL) data, single-axis solar trackers can increase panel productivity by up to 30%, while dual-axis solar trackers can increase it from 50% to 70% compared to fixed-size solar installations [4].

Additionally, the Japanese company Toshiba has made a significant contribution to the development of solar batteries by creating next-generation solar panels primarily designed for electric vehicles and proving to be much more efficient. This was reported on the official Toshiba website [5].

Innovative solar batteries have received an additional layer based on cuprous oxide ($Cu2O$), which has increased the energy conversion efficiency to 8.4%. When this layer is placed above the standard silicon wafer, the efficiency ratio (ER) increases to a record 27.4% [6].

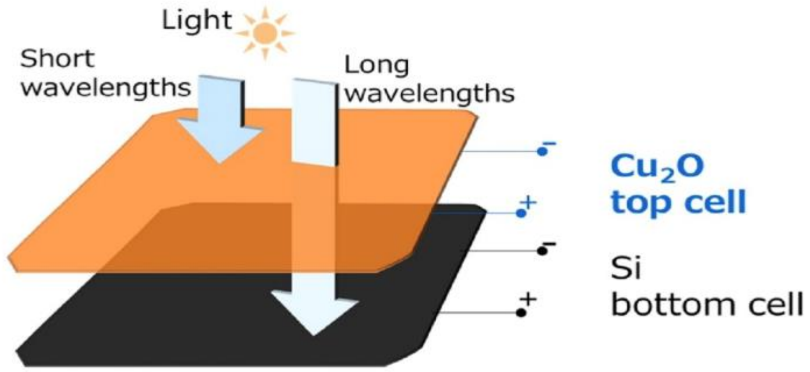

Fig. 1. Structure of Toshiba solar panels

Scientists from the University of Pennsylvania have developed a new technology that not only significantly increases the productivity of solar photomodules but also simplifies the manufacturing process. According to Dr. Shashank Priya, Vice President for Research and Professor of Materials Science, "With the results obtained, we will be able to create inexpensive and environmentally safe technologies based on solar elements with perovskite. In the future, we will be able to significantly reduce the cost of creating solar elements by replacing expensive chemical substances with readily available natural materials [7]".

The use of solar energy in agriculture is becoming increasingly simple and accessible thanks to the rapid development of technologies and the implementation of innovations in the field of solar energy.

In agriculture, alternative energy has become an attractive area for investment and a reliable tool for optimizing work processes and opening up new areas of activity.

Agrovoltaics represents an innovative approach in agriculture that allows for the effective combination of energy production through solar installations and farming activities on one territory.

Solar stations can be installed on cultivated fields, which allows for optimizing land use and increasing crop yields. Partial shading of fields promotes the improved growth of certain crops and provides dual cooling, as illustrated in Figure 2. Plants under the protection of panels can absorb more carbon dioxide for photosynthesis; leaves evaporate moisture, leading to the creation of a more comfortable microclimate. This accelerates plant growth and contributes to the cooling of the solar modules themselves, further reducing energy losses [8].

Fig. 2. Example of dual use of a solar panel with a sunflower field in agriculture on land plots

3. The aim of the study

The purpose of this study is to identify all innovative technologies and materials used in the construction of solar panels.

4. Results of the researches

Technological solutions for the production of solar cells and photovoltaic materials continue to evolve actively. Manufacturers and researchers are diligently working on finding new approaches aimed at enhancing the efficiency of solar panels, increasing energy output per unit area, improving performance under various light and temperature conditions, and enhancing resistance to environmental factors.

Over the past decade, the quality of photovoltaic components and technologies has steadily increased, and their operational characteristics have significantly improved.

This article is dedicated to analyzing the current state of photovoltaics, researching technologies and primary materials used in photovoltaics, as well as trends in their improvement and the utilization of advanced technologies. Studying technological solutions that lead to the dynamic growth of the photovoltaic industry and the expansion of the market is particularly important for Ukraine, considering the opportunities and challenges of this sector, which continues to expand and diversify.

Over the years of photovoltaic and solar energy development, various types of solar cells have been developed, which can be divided into three technological generations: silicon-based (first generation), thin-film (second generation), and organic (third generation). Types of solar cells of the second and third generations differ in efficiency, cost, service life, production methods, and material modifications. The main attention is paid to light-absorbing environments - from inorganic monocrystalline and multicrystalline semiconductors to organic, polymeric, and hybrid compounds. The actual conversion efficiency of light energy into electricity is only possible with all the necessary components of the solar cell in place.

According to the International Renewable Energy Agency (IRENA) [9], first-generation technologies continue to dominate the development of the photovoltaic industry with a market share of 95%. Tandem and perovskite technologies also offer innovative solutions, but to achieve large-scale production, it is important to address the issues of cost and reliability of photovoltaic elements. Changes in cell structure can lead to higher efficiency, especially in combination with other innovative elements such as bifacial cells, modules, or PERC technology with a passive (dielectric) layer on the rear side of the cell (Passivated Emitter Rear Cel - PERC), or even half-cut cells (Figure 3).

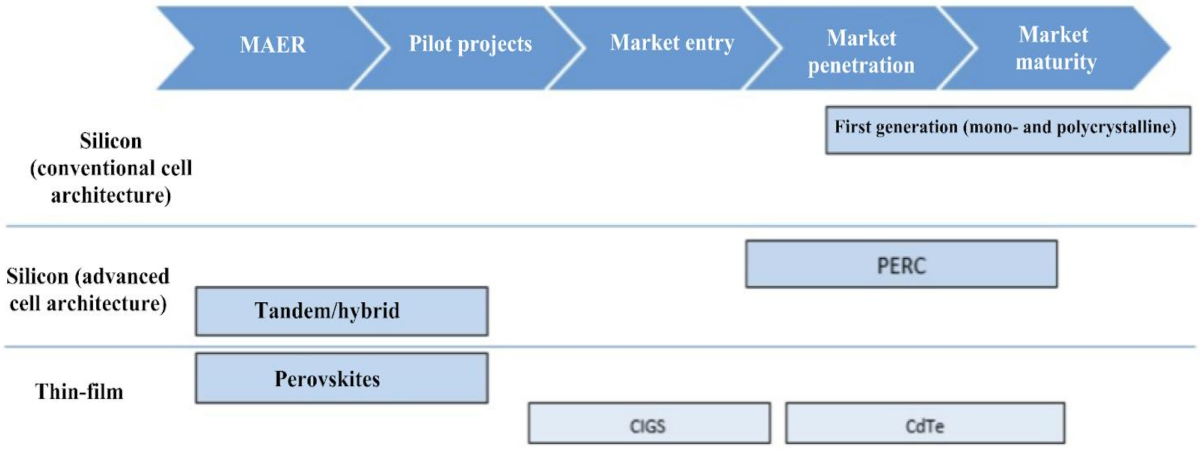

Fig. 3. The stages of development of solar photovoltaic (PV)

Silicon Technologies

In pursuit of continuously improving the characteristics of photovoltaic devices, equipment manufacturers for solar energy systems choose monocrystalline silicon, which has fewer defects compared to polycrystalline silicon, allowing for higher cell efficiency. The use of this material holds a predominant position in the solar energy market, estimated at around 80% [10].

In the production process of monocrystalline silicon panels, purified silicon is used. After purifying the monocrystal, it solidifies, and then it is sliced into very thin plates, up to 300 microns thick.

These plates are interconnected by a grid consisting of electrodes in a battery. Solar systems made from such elements resemble silicone tiles or tiles that are connected into one structure. Such batteries have a relatively high efficiency ratio of up to 20%, but the manufacturing process is technologically expensive and complex. On average, the area occupied by a 1 kW system based on monocrystalline panels is approximately 7 m^2.

Monocrystalline panels are used in various sectors. They can be applied in mini-cottage projects, private homes, tourist complexes, and are most commonly used in projects with installed capacities of up to 10 kW.

Traditionally, monocrystalline modules are inserted into an aluminum frame and covered with impact-resistant glass. The color of monocrystalline photovoltaic elements is dark blue or black [11].

Organic Solar Panels

Organic solar panels, also known as polymer or plastic panels, are a type of panel that utilizes organic electronics. Their peculiarity lies in the use of environmentally friendly organic polymers - carbon and plastic. Currently, the production of solar modules using organic materials is not a widespread phenomenon. The technology for manufacturing organic solar modules is still in the research and development stage. These modules can be made from compounds that dissolve in inks. Their advantages include lightness, thinness, flexibility, and transparency. Additionally, they have a high absorption coefficient that can be tuned at the molecular level. These modules are economically advantageous to produce on a large scale and have a smaller negative impact on the environment.

However, it is worth noting some drawbacks. These include low productivity, high cost in small production volumes, as well as limited strength and a high degree of degradation during operation [12].

Passivated Contacts

In the evolution of solar cell technology, after PERC technology, the next step will likely be passivated contact cells (Topcon - Passivated Contact cells, or TOPCon). The introduction of Topcon technology has the highest potential for efficiency (compared to all crystalline silicon c-Si cells) - up to 28.75% [13]. The German Research Institute for Solar Energy (ISFH) achieved an efficiency of 26.1%, and in June 2021, JinkoSolar announced a world-record efficiency of 25.25% at the commercial level.

Tandem/Hybrid Cells

Tandem solar cells are individual cells stacked in layers, each responsible for a specific wavelength of radiation, converting it into electrical energy.

New cell architectures have enabled achieving higher levels of efficiency. The main driving force behind such changes is the PERC technology, along with its combination with other innovations like half-cut cells, solar shingles, and multi-busbars. However, the most significant technological advancement is the development of bifacial cells and modules, driven by the desire to improve cell architecture and increase productivity.

Bifacial solar cells have been known in the market for several years, but recently, they are gaining more popularity due to the reduced manufacturing cost of monocrystalline silicon.

Bifacial cells consist of front and back transparent glass surfaces and can generate electricity not only from sunlight falling on the front panel but also from reflected light from the ground surface. This allows achieving productivity of up to 27%, surpassing traditional monocrystalline photovoltaic elements.

Despite the advantages of bifacial cells, there are still obstacles in their development path, such as the lack of an international testing standard, common labeling norms, or pricing.

One type of bifacial element is the "glass-glass" module. These modules are typically used in ground-mounted metal structures for large power plants. They are characterized by high moisture resistance and can operate in high-temperature conditions. Although this technology was developed several decades ago, its high cost and significant panel weight hinder its widespread adoption. According to The International Technology Roadmap for Photovoltaic (ITRPV[14]), it is expected that the share of such modules (glass-glass) will increase to 40% over the next 10 years.

Half-cells:

The technology of using half-cells involves cutting a fully processed cell in half using modern laser machines. This approach improves the productivity and durability (longevity) of the module and can provide an instant increase in power by 5-6 watts.

The integration of PERC technology and half-cells has increased the efficiency of photovoltaic elements to 18% and power to 300 watts.

Multi-busbars:

Multi-busbars are thin metal strips located on the front and back surfaces of the photovoltaic cell and serve to transmit the current generated by the module. In previous generations of solar panels, there were two multi-busbars, but over time their number increased to three, five, or even more in most modern photovoltaic cells. Additional multi-busbars improve the operational characteristics of photovoltaic modules compared to traditional models.

Shingles Cells:

Shingles cells are solar panels that resemble roofing tiles or colored glass and can be used as conventional roofing materials. They function as electricity generators while adding aesthetic design to buildings. It is predicted that the market share of shingles cells will increase by 10% by 2029.

BIPV (Building-integrated photovoltaics) is a construction technology that involves integrating photovoltaic elements into a building as roofing structures, canopies, awnings, canopies, and facades. In this case, solar modules become both structural elements of the building and a source of electricity. They protect the building from wind and moisture, perform thermoregulation and sound insulation functions. The installation of solar elements is planned at the design stage of the building, and removal is carried out by replacing them with equivalent building materials [15].

HJT Cells:

Heterojunction cells are photovoltaic elements that combine standard crystalline silicon with thin layers of amorphous silicon, forming "heterojunctions." Each of these heterojunctions is optimized for a specific spectrum of solar radiation wavelengths, which ensures an increase in efficiency ratio. Panels based on HJT have the potential to achieve a high efficiency ratio of up to 26.5%.

Companies such as Panasonic, Sharp, Aurora, LONGi, and Huasun are researching and developing photovoltaic modules based on heterojunction cells for commercial use.

The issue of panel disposal is also crucial. Within the European Institute of Innovation & Technology (EIT), funding is provided until 2025 for a project called ReProSolar in EU countries, managed by Veolia, a leading waste management company. This research project collaborates with partners from Germany, France, and Spain. Its aim is to create an efficient process for utilizing decommissioned solar modules using a new delamination technology, which allows separating solar panels from glass. This innovative physicochemical methodology will enable the recovery of all materials without the need to destroy photovoltaic modules. The project encompasses all stages from processing and purifying the raw materials to their use in various sectors, forming a closed-loop resource cycle.

The efficiency of the technology is planned to be tested on an industrial scale by the end of the year, with an annual processing capacity of 5,000 tons of decommissioned photovoltaic modules expected by 2023 according to the new system.

This new technology, developed in South Korea and tested on 72 panels, addresses the processing of both damaged and undamaged panels and consists of four stages:

1. Automated dismantling of the frame and junction box.
2. Glass separation.
3. Recovery of metal components.
4. Photovoltaic cell processing.

This optimized methodology reduces electricity consumption by a third and greenhouse gas emissions by 1.2 tons. The technology can restore high-quality glass with minimal iron content (less than 200 parts per million) and more than 65% of solar panel components. The extracted and processed silicon is used to create 6-inch monocrystalline ingots and wafers with an efficiency of 20.05% [16].

5. Conclusion

The global trend is on the verge of fundamental changes in the field of modern technology and the efficient utilization of solar panels.

In conclusion, summarizing the information provided in this work, we have examined and described the main contemporary materials for solar panel photovoltaic cells, their advantages, disadvantages, and application peculiarities. These include silicon technologies, organic solar panels, passivated contacts, tandem/hybrid cells, half-cells, multi-busbars, shingled cells, BIPV (Building-integrated photovoltaics), heterostructure cells, and other new materials.

The overview of panel enclosures has demonstrated that they provide strength and lightweight properties to solar systems, employing various approaches and materials such as aluminum, fiberglass, plastic, and even glass or carbon composites. These materials are chosen based on specific system requirements such as weight, weather resistance, service life, and so forth.

Solar panels are prone to change, particularly perovskite solar panels, which, due to their unique properties, have the potential to become an effective alternative to traditional technologies. They can be manufactured from inexpensive materials and have high conversion rates of light energy into electricity. However, to achieve widespread industrial-scale use, issues regarding stability, efficiency, and production processes need to be addressed.

The main idea is the shift from expensive to cheaper composite materials in the production of solar panels, where they can offer a lot of functionality and economic advantages. Their dual use can lower the cost of energy production and even provide benefits in the form of dual-action solar panels. For example, their use in agriculture fields (Figure 2) not only generates energy but also provides shade for the plants, enhancing their reproductive performance.

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СУЧАСНІ ІННОВАЦІЙНІ ТЕХНОЛОГІЇ І МАТЕРІАЛИ ДЛЯ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ РОБОТИ СОНЯЧНИХ ПАНЕЛЕЙ

Використання альтернативних джерел енергії, таких як сонячна, вітрова, гідроенергія тощо, дозволяє зменшити залежність від традиційних джерел енергії, які є нестійкими та обмеженими. Це може допомогти у вирішенні проблеми з нестачею енергії та зменшити ризики енергетичних криз

В статті проведено огляд сучасних інноваційних технологій у галузі виробництва, експлуатації і утилізації систем сонячних панелей.

Фотоелектричні технології мають довгу історію свого створення і вдосконалення, адже з початку свого існування, це були доволі великі, дороговартосні і низькоефективні системи. Та з кожним роком, науковці і інженери, розуміючи надзвичайну важливість відновлювальних систем, працювали над всестороннім вдосконаленням і модернізацією цих технологій. І з декількох відсотків ККД, сучасні панелі здатні виробляти в середньому 20%. Панелі з часом почали ставати все більш доступніші для людей, галузь їх застосування збільшувалась, і тепер СЕС використовуються у як і для генерації енергії на продаж, так і для власних потреб власників будинків чи заводів.

В статті, в першу чергу, розглянуті сучасні матеріали фотоелементів панелей, їх переваги і недоліки і особливості застосування. Розглянуто різні новітні підходи і матеріали корпуса панелей, для забезпечення міцності і легкості сонячних систем.

Також детально розглянуті перовськітні сонячні панелі, та перспективи їх застосування у промислових масштабах.

Через те, що як і будь-яка техніка, має обмеженний термін працездатності, розглянуто також і підходи утилізації панелей після їх відпрацювання.

І наприкінці, розглянуто питання застосування інноваційних технологій у галузі відновлювальних джерел в Україні, адже багато систем будуть потребувати заміну у результаті бойових дій на півдні і сході країни.

Ключові слова: *сонячні панелі, СЕС, фотоелектричні технології, відновлювана енергія, перовскітові панелі.*

Рис. 3. Літ. 20.

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