Improving Solar Panel Efficiency Using Integrated System Designs

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Abstract: The technical objective of this invention is to create an integrated system for the simultaneous measurement of key parameters affecting a solar panel's performance efficiency. The technical result consists in the development of a solar panel containing a fully integrated device within the encapsulant layers and backsheet, based on a flexible substrate. This device includes a spatially-aligned matrix of sensors (irradiance, temperature, wind, angle, humidity), a data processing unit for calculating performance metrics, and a low-power wireless transceiver for transmitting data to the panel's integrated circuit for monitoring and potential operational control. This technology has a great impact on energy saving. As is known, depending on the amount of light falling on the solar cell, its energy efficiency increases. Furthermore, if we focus on the issue of efficient energy use, solar power plants will have a great impact.

Keywords: solar energy, panels, solar cells, photoelectric effect, integrated systems, performance monitoring.

1. Introduction Without producing any raw materials for the generation of electricity from solar energy, we can preserve existing natural energy resources. One of the most widely used forms of alternative energy in today's practice is solar energy. Solar cells and photovoltaic cells are the main converters of energy into electricity. On a clear day, 1 m^2 of the Earth's surface receives 100 W of light energy. But this result cannot be obtained everywhere on Earth. Some parts of the world have 320-350 sunny days a year, but some places, far from the equator, have fewer. Therefore, solar cells are positioned perpendicular to the direction of the Sun to increase their efficiency [10].

To calculate the effective performance of a solar panel, the forces acting on the solar panel must be taken into account. The forces affecting a solar panel include air temperature, solar panel surface temperature, sunlight, and wind speed. It is necessary to determine the appropriate equipment and design the integrated circuit topology to calculate the aforementioned forces [9].

In the process of designing the electronic circuit topology, the main operations are performed by its controller, i.e., a microcontroller. When designing the integrated circuit, several checks must be performed to ensure that the aforementioned operations are executed quickly and smoothly [8].

2. Materials and Methods The invention relates to the field of solar energy, particularly to devices for monitoring and controlling parameters that affect the efficiency of solar panels. More specifically, the invention concerns solar panels equipped with an integrated system for the simultaneous measurement of a range of key environmental and panel parameters. This allows for performance monitoring, early detection of potential problems, and optimization of solar power plant operation [8].

Currently, there are many solutions for monitoring the performance of solar panels. These solutions can be divided into several groups: external monitoring systems connected to already installed solar panels, and partially integrated solutions that may include separate temperature or voltage sensors embedded in the panel.

U.S. Patent No. US 8,044,347 B2 (SunPower Corporation, 2011) titled "Solar panel with integrated temperature sensor" describes a solar panel with an integrated temperature sensor designed to monitor the temperature of solar cells. The temperature sensor is in thermal contact with one or more solar cells and is electrically connected to a monitoring system. The disadvantage of this solution is the limited range of measured parameters (temperature only) and the inability to simultaneously measure several key parameters affecting panel performance [1].

The known utility model CN 203734845 U (Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 2014) "Solar cell intelligent monitoring system," which describes an intelligent solar cell monitoring system including temperature, voltage, and current sensors, as well as a microcontroller for data processing and wireless information transmission. The system allows monitoring the electrical operating parameters of solar cells. However, this solution does not provide for the integration of sensors to measure external parameters such as irradiance, wind speed, tilt angle, and humidity, which significantly affect the performance of solar panels [2].

The known patent application WO 2016/134438 A1 (Trina Solar (Changzhou) Science and Technology Co., Ltd., 2016) "Solar module with monitoring function and monitoring system."

This patent application describes a solar module with a monitoring function, including temperature and voltage sensors, and a wireless communication module. The system allows tracking the main electrical parameters and module temperature. The disadvantage is the lack of comprehensive simultaneous measurement of external factors affecting solar panel operation and limited integration of the monitoring device into the structural panel [3].

The article "Solar Panel Monitoring Systems: Types, Components, and Benefits" (Greentech Renewables, 2023) provides an overview of various types of solar panel monitoring systems, including string inverters with monitoring functions, standalone system monitoring, and system-level monitoring modules. The article describes the benefits of monitoring, such as fault detection, performance optimization, and reduced maintenance costs. However, the article does not address the full integration of multi-parameter sensors directly into the solar panel structure [4].

Also, the known article "The Impact of Environmental Factors on Solar System Panel Efficiency" (Energy Sage, 2024) elaborates on the influence of various environmental factors such as temperature, irradiance, shading, tilt angle, and soiling on solar panel efficiency. The article highlights the importance of considering these factors for optimizing solar power plant operation. However, the article does not propose specific technical solutions for simultaneously measuring all these parameters using an integrated device [5].

The scientific article "Development of a Low-Cost Wireless Sensor Network for Solar System Panel Monitoring" (IEEE Sensors Journal, 2018) describes the development of a low-cost wireless sensor network for monitoring solar panels. The system includes separate temperature, voltage, and current sensors that transmit data wirelessly. The article focuses on the development of communication infrastructure rather than the full integration of a multi-parameter device into the structural panel [6].

As a prototype, the active U.S. Patent US 9,871,187 B2 (LG Electronics Inc., 2018) "Solar cell module and monitoring method thereof" was taken. This patent describes a solar module that includes temperature and humidity sensors integrated into the module. Information from the sensors is used to determine the module's condition and predict its performance. Although this patent provides for the integration of temperature and humidity sensors, it does not cover the simultaneous measurement of a full set of key parameters (irradiance, wind speed, tilt angle) and does not describe the full integration of the device using thin-film technology into the structural panel, including a data processing unit and a wireless transceiver [7].

Analysis of the current state of the art reveals that existing solutions for monitoring solar panel operation have the following disadvantages:

- **Limited set of measured parameters:** Most existing monitoring systems measure only electrical parameters (voltage, current) and temperature. External factors such as irradiance, wind speed, tilt angle, and humidity, which significantly affect solar panel performance, are often not monitored or are measured by separate, non-integrated devices [11].
- **Partial or absent integration:** Many monitoring systems are external devices that connect to already installed panels, which can complicate installation and increase system cost. Even in cases of partial integration, the monitoring device is typically not fully integrated into the structural panel using advanced technologies such as thin-film electronics.
- **Lack of full spatial localization of sensors:** In most existing solutions, sensors measuring different parameters are located in different places, which can reduce the

accuracy of data correlation and complicate a comprehensive analysis of the influence of various factors on panel performance [12].

- **Limited built-in data processing capabilities:** Many monitoring systems transmit raw data to an external server for analysis. The lack of advanced built-in data processing can limit the ability to make operational decisions and identify problems in real-time [9].
- **Insufficient integration with the panel's integrated circuit:** Existing solutions often do not provide deep integration of the monitoring device with the main integrated circuit of the solar panel, which limits the possibility of using the obtained data to control panel operation or optimize its parameters.

The technical objective of the present invention is to develop a solar panel equipped with an integrated device for the simultaneous measurement of a full set of key parameters affecting its operation, ensuring high measurement accuracy, reliability, and durability, as well as the possibility of built-in data processing and wireless information transmission for effective monitoring and control of solar panel performance [5].

The technical result of the present invention is the creation of a solar panel with a fully integrated multi-parameter monitoring device that provides:

- simultaneous measurement of irradiance, temperature, wind speed, tilt angle, and humidity with a high degree of spatial co-localization of sensors.
- full integration of the device into the structural panel using thin-film electronic technology on a flexible substrate, providing mechanical and climatic protection.
- built-in real-time calculation of at least two key solar panel performance indicators selected from the group consisting of: Performance Ratio (PR), Fill Factor (FF), and Efficiency (Eff).
- wireless transmission of measured parameters and calculated performance indicators to an external monitoring system.
- use of data obtained by the solar panel's integrated circuit for performance monitoring and potential operational control.

The present invention is a solar panel that includes a structure consisting of an encapsulant and a backsheet, as well as a solar panel integrated circuit with a compatible wireless receiver. A distinctive feature of the invention is the presence of an additional device that is fully integrated into the encapsulating material layer and the backsheet structure of the solar panel.

The said device includes a spatially-coordinated sensor array configured for simultaneous measurement of parameters affecting solar panel operation. These parameters include: irradiance (illumination), temperature, wind speed, tilt angle, and humidity. The sensor array is characterized by the use of a VT93N1 photoresistor as an irradiance sensor, an anemometer as a wind speed sensor, a MEMS accelerometer for tilt angle measurement, and a capacitive humidity sensor for humidity measurement, as well as any suitable temperature sensor located in direct thermal contact with a solar cell. The sensors are arranged to ensure spatially-coordinated measurements within a defined area of the solar panel [6].

The device also includes a data processing unit that is directly connected to the solar panel's integrated circuit. The data processing unit is configured to receive signals from the sensors, representing simultaneously measured parameters, and to perform real-time built-in calculation of at least two solar panel performance indicators selected from the group consisting of: Performance Ratio (PR), Fill Factor (FF), and Efficiency (Eff). The data processing unit is also responsible for outputting data, including simultaneously measured parameters and calculated performance indicators, to the solar panel's integrated circuit.

The said device is fully integrated into the encapsulant layer and the backsheet structure of the solar panel. It is manufactured using thin-film electronic technology on a flexible substrate, and together with the said encapsulating material layers and backsheet, it forms a single laminated structure. Such integration provides mechanical and climatic protection for the sensors and electrical connections, increasing the reliability and durability of the device.

The sensor array is typically placed on a flexible substrate that is embedded in the encapsulating material layer. To ensure spatial alignment, the sensors are placed in a circular area with a diameter of no more than 5 cm on the said substrate [12].

The data processing unit additionally contains a low-power wireless transceiver for wireless transmission of data representing simultaneously measured parameters and calculated performance indicators. This data is transmitted to the solar panel's integrated circuit, which contains a compatible wireless receiver. The solar panel's integrated circuit is configured to use the received data for monitoring the solar panel's performance.

Figure 1. Conceptual diagram of an integrated monitoring device in a solar panel.

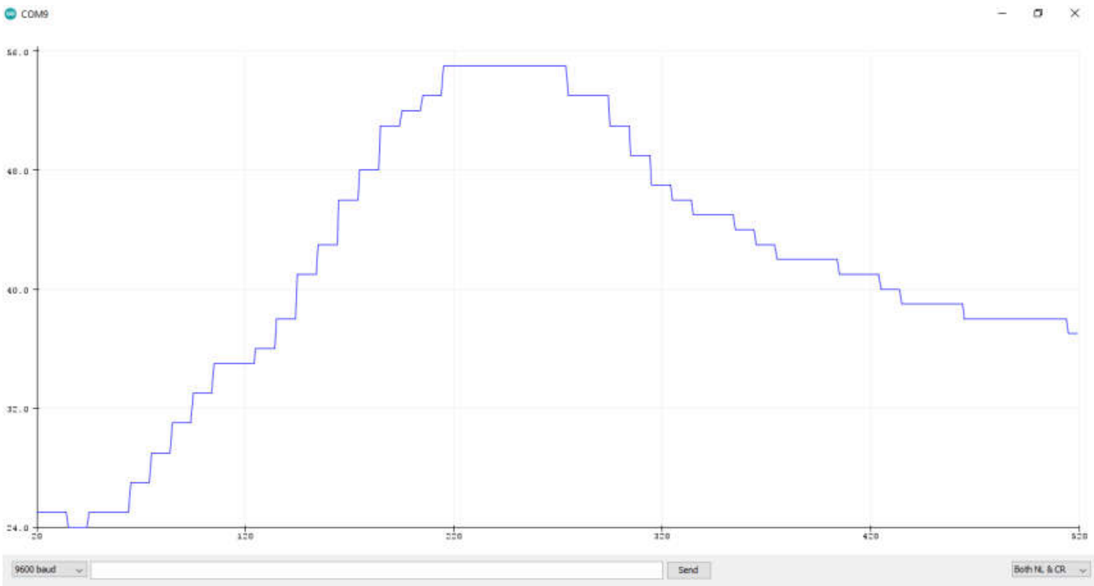

Figure 1.1 Temperature increase

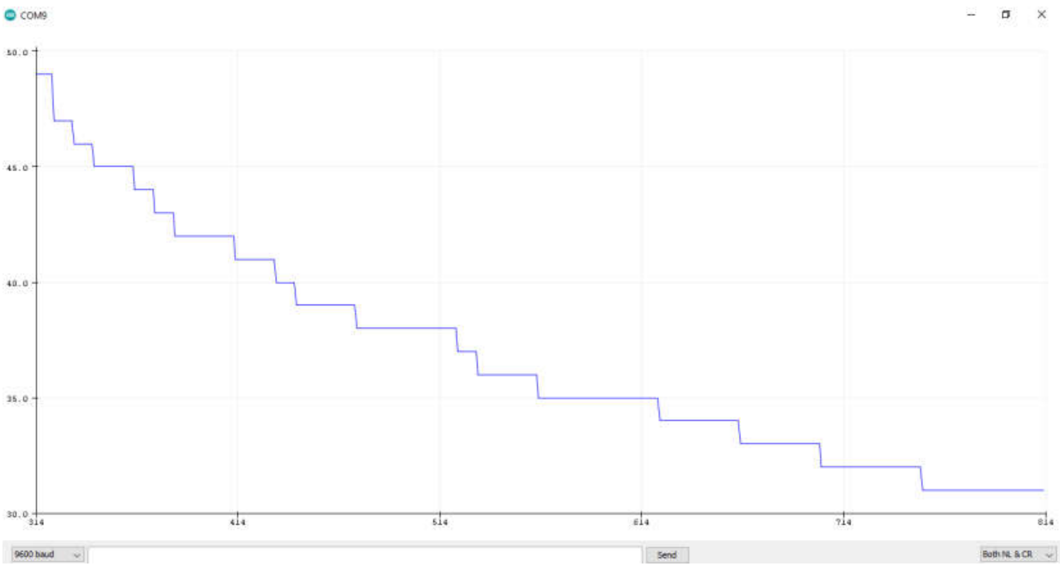

Figure 1.2 Temperature drop

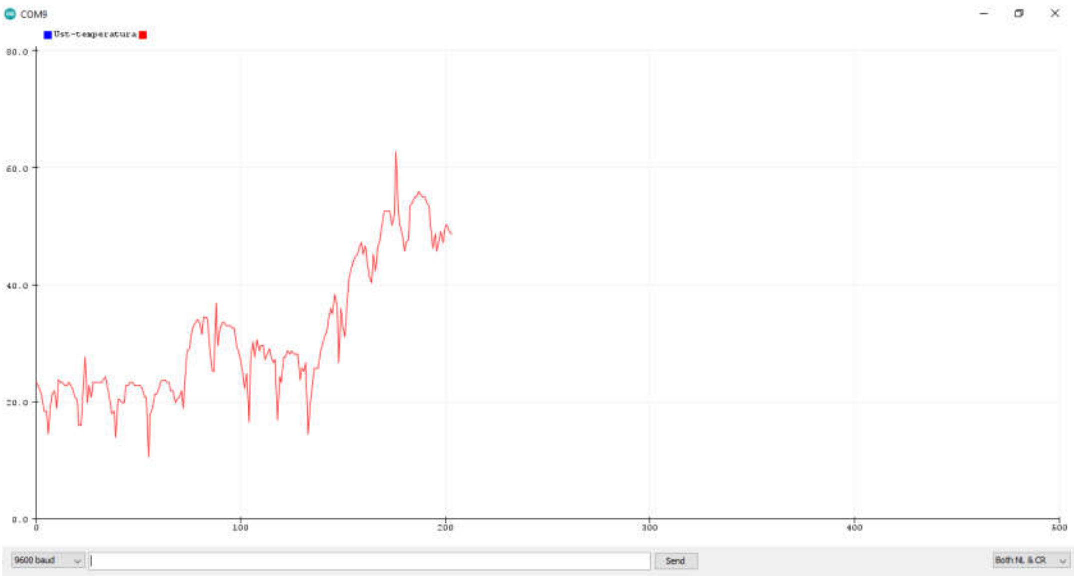

Figure 1.3 Solar panel temperature increase due to external environment

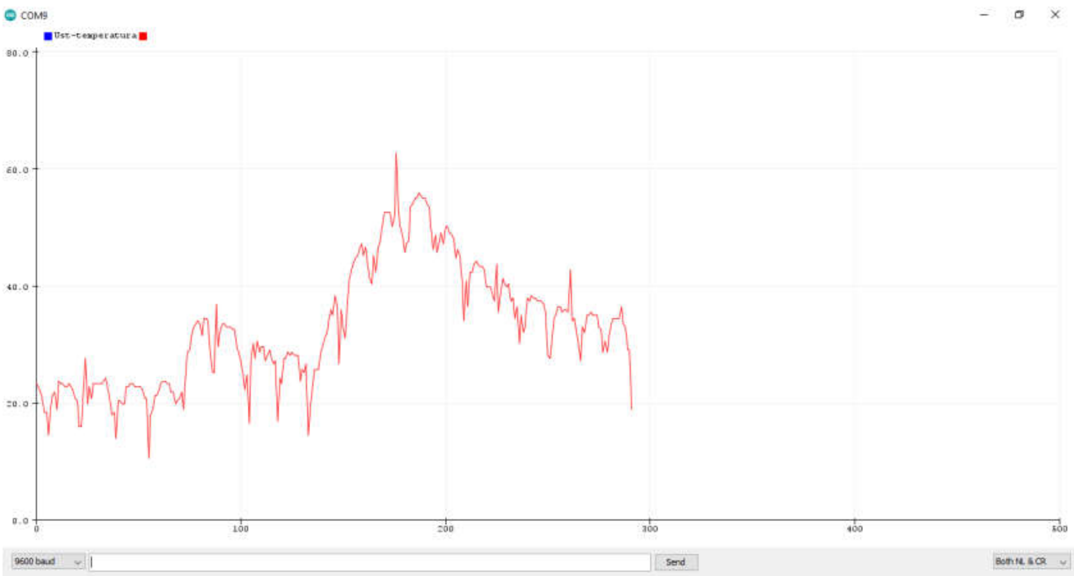

Figure 1.4 Solar panel temperature drop due to external environment

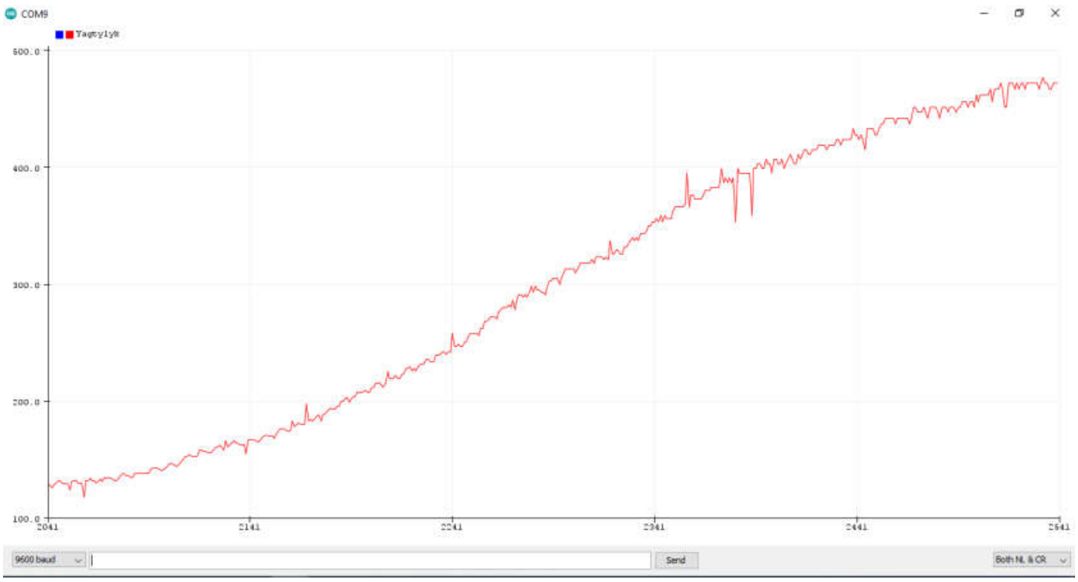

Figure 1.5 Light sensor readings in bright outdoor lighting

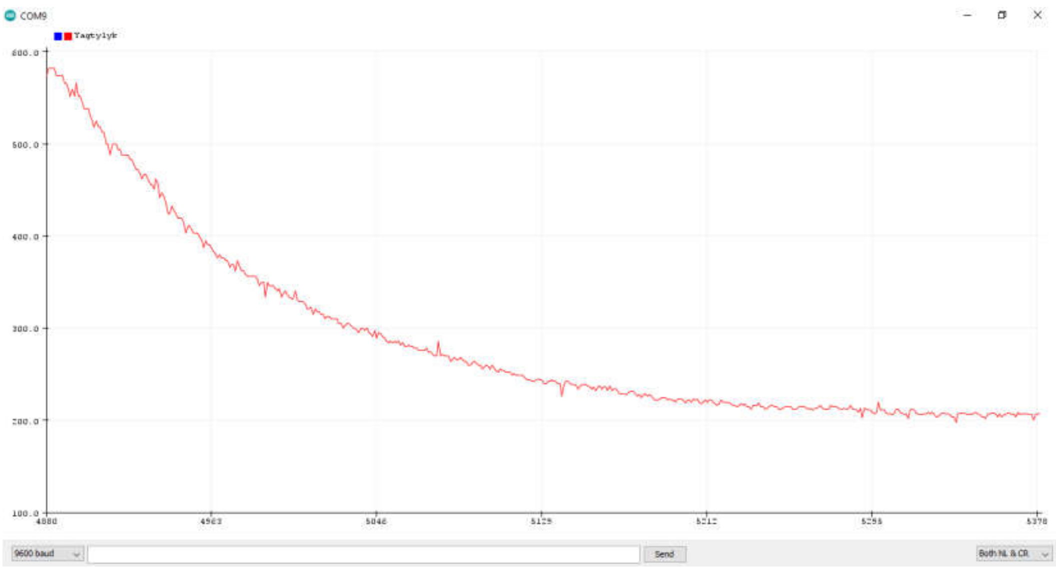

Figure 1.6 The effectiveness of light sensors decreases as the ambient light level decreases.

Table 1. Sensors and their functions in the integrated device

Sensor	Type/Model	Measured Parameter	Function
VT93N1	Photoresistor	Irradiance	Measurement of the intensity of incident solar light..
Анемометр VT93N1	Фоторезистор	Скорость ветра	Measurement of air flow velocity, important for assessing wind load and optimizing panel operation.
MEMS Accelerometer	Accelerometer	Tilt Angle	Measurement of the solar panel's tilt angle to optimize its orientation relative to the sun.

Capacitive Humidity Sensor	Capacitive Sensor	Humidity	Measurement of air humidity, important for preventing corrosion and optimizing panel operating conditions..
Thin-film Thermistor	Thermistor	Temperature	Measurement of the solar cell temperature to assess heat losses and the effect of temperature on performance.

Formulas:

$$\text{PF} = \frac{E_{actual}}{E_{expected}}$$

where E_{actual} — actual energy yield, $E_{expected}$ — expected energy yield..

$$\text{FF} = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

where V_{MPP} — voltage at maximum power point, I_{MPP} — current at maximum power point, V_{OC} — open-circuit voltage, I_{SC} — short-circuit.

$$\text{Eff} = \frac{P_{out}}{P_{in}} = \frac{V_{MPP} \cdot I_{MPP}}{I \cdot A_c}$$

where P_{out}— electrical output power, P_{in} — solar input power, I — solar radiation intensity, A_c — collector area.

Implementation of the invention: One of the possible embodiments of the invention is the integration of a device for simultaneous measurement of parameters during the production of a solar panel. At the first stage, a flexible substrate is made of polyimide film, on which the necessary electronic components, including conductors, contact pads and, if necessary, passive elements, are formed using thin-film electronic technology [11].

Then, sensors are installed on the flexible substrate: a VT93N1 photoresistor for measuring illumination, a miniature MEMS anemometer for measuring wind speed, a MEMS accelerometer for measuring the angle of inclination, a capacitive humidity sensor and a thin-film thermistor, which is positioned in such a way as to ensure direct thermal contact with one of the solar cells. The sensors are located in a circular area with a diameter of up to 5 cm to ensure spatial alignment of the measurements.

The microcontroller is also mounted on a flexible substrate, which functions as a data processing unit. The microcontroller is programmed to receive signals from sensors, process them, perform calculations of performance indicators (performance factor, fill factor and efficiency) in real time and control the operation of a wireless low-power transceiver (e.g. based on the Bluetooth standard) [9].

After all components are placed, the flexible substrate with sensors and the data processing unit is placed between layers of sealing material (e.g. ethylene vinyl acetate - EVA) and the backing of the solar panel. Then, a lamination process is carried out, as a result of which all layers of the panel, including the integrated device, are combined into a single monolithic structure. The lamination process ensures reliable sealing and protection of the electronic components from the environment.

4. Results and Discussion Electrical connections from the data processing unit to the integrated solar panel circuit can be made using thin wires routed within the laminated panel or using wireless communications via an integrated low power wireless transceiver and compatible receiver located on the integrated solar panel circuit [9].

The integrated solar panel circuit is programmed to receive data from the integrated device, process it, and use it to monitor the performance of the panel. The received data can be used to display current parameter values and performance metrics, identify anomalies in panel operation, predict potential performance degradation, and generate maintenance alerts.

The proposed invention has a number of significant advantages in the field of application:

• Comprehensive monitoring: Provides simultaneous measurement of a full set of key parameters that affect the operation of the solar panel, which allows for a more accurate and complete picture of its performance.

• High accuracy and reliability: Spatial alignment of sensors and full integration of the device into the panel structure ensure high measurement accuracy and reliable operation throughout the entire service life of the solar panel.• Miniaturization and durability: The use of thin-film electronic technology allows for the creation of a compact and lightweight device that is reliably protected from mechanical and climatic influences due to the laminated structure of the panel.

• Built-in data processing: The ability to perform built-in calculation of key performance indicators in real time allows for a quick assessment of the panel's condition and the identification of potential problems.

• Wireless data transmission: A built-in low-power wireless transceiver provides convenient and cost-effective data transmission to external monitoring systems.

• Integration with the integrated circuit of the panel: Deep integration of the device with the main integrated circuit of the solar panel opens up the possibility of using the obtained data not only for monitoring, but also for potential control of the panel's operation and optimization of its parameters.

• Simplification of installation and maintenance: Full integration of the device into the structural panel eliminates the need to install additional external sensors and monitoring systems, which simplifies the installation process and reduces the maintenance costs of solar power plants [10].

5. Conclusion The proposed invention is an innovative solar panel with a fully integrated device for simultaneous measurement of key parameters affecting its performance. By using thin-film electronic technology, spatial integration of sensors, embedded data processing and wireless information transmission, the invention provides comprehensive, accurate and reliable monitoring of solar panel performance, which allows to increase the efficiency of solar power plants, reduce maintenance costs and increase their service life.

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