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METHODOLOGY FOR ASSESSING THE QUALITY OF DYE-SENSITIZED SOLAR CELLS BASED ON TiO_2 USING COMPUTER TOMOGRAPHY

Abstract

The aim of this study was to develop a methodology for assessing the quality of dye-sensitized solar cells using computer tomography. This approach offers several advantages, including high precision and the ability to analyze the internal structure of the cells with micron-level resolution, enabling effective detection of internal defects and layer irregularities. A comparative analysis of various tomography models was conducted to evaluate their capability to detect and visualize internal damages in solar cells. The study identified defects that significantly impact the performance and lifespan of the cells. Based on the analysis, the causes of these defects were determined, and improved production methods were proposed to minimize their occurrence. The presented non-destructive testing methodology enhances diagnostic accuracy and optimizes solar cell manufacturing processes.

Keywords: dye-sensitized solar cells (DSSC), computer tomography, structural defects, quality control, damage diagnostics, photovoltaic properties, production optimization, high-precision scanning, reliability of components, resistance to external factors, innovative technologies, environmental safety.

Introduction

In the context of rapidly growing demand for renewable energy sources, dye-sensitized solar cells (DSSC) are emerging as a promising field. This study is

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

dedicated to the development of a methodology for assessing the quality of DSSCs using computer tomography (CT), which will improve quality control of manufactured cells and help detect defects at early stages.

Today, the majority of energy consumed worldwide comes from fossil fuels, such as thermal energy and nuclear power. However, these energy sources have significant drawbacks, including their limited availability, lack of environmental friendliness, and vulnerability to seismic activity. For this reason, modern requirements challenge humanity to turn to renewable and eco-friendly energy sources, such as solar and wind energy. Solar panels are among the most promising types of renewable energy sources. Solar cells are classified into two main groups: crystalline and thin-film solar cells. Dye-sensitized solar cells (DSSC), which belong to the class of thin-film solar cells, represent a new class of solar cells due to their simplicity and low energy production cost. Moreover, it has been shown that this type of solar cell, developed by Michael Grätzel, achieves a maximum efficiency of 14.3% and a lifespan exceeding 10 years.[1]

Since DSSCs with semiconductor properties are primarily made from organic and polymer materials, the cost of electricity generated by them is 3-5 times lower than that of conventional solar panels. Furthermore, studies have revealed that semiconductor-based DSSCs can operate in the spectrum of infrared and diffuse light.[2]

The working principle of dye-sensitized solar cells is based on a photoelectrochemical (redox) reaction occurring in the electrolyte and the movement of free charge carriers generated by the dye on the semiconductor (Figure 1).

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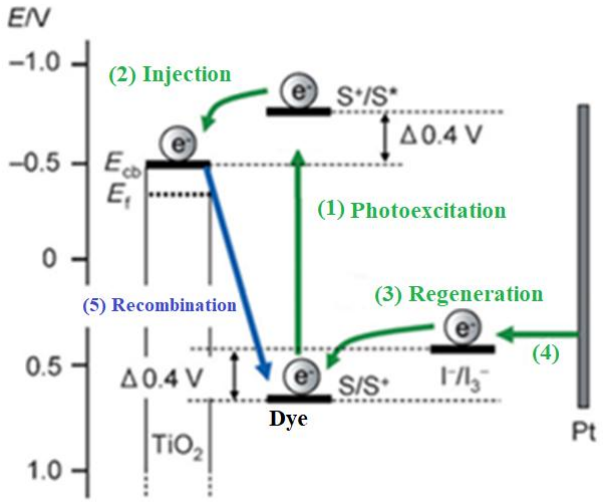


Figure 1 – Working principle of n-type semiconductor solar cells and their physical processes.

Stages of Operation for n-Type Semiconductor Solar Cells (TiO_2)

1. **Light Absorption and Photoexcitation**: upon absorbing sunlight, a high-sensitivity dye undergoes photoexcitation, where an electron transitions from the valence band of the dye molecule to its conduction band (1).

2. **Electron Injection into TiO_2**: the excited electrons are then injected into the conduction band of TiO_2 due to the potential difference between the conduction band of the dye and the photoanode (2).

3. **Reaching the External Circuit**: the potential difference during the transition to the conduction band of TiO_2 increases the electrons' kinetic energy, enabling them to reach the FTO window and transfer through it to the external circuit (3).

4. **Electron Regeneration at the Cathode**: returning electrons pass through the cathode and attach to iodine molecules in the electrolyte (4).

5. **Dye Regeneration**: the ionized iodine molecules donate electrons back to the dye molecules, restoring them to their original state (5).

This cycle repeats, converting solar energy into electrical energy.

One of the critical objectives in this process is to develop solar cells with cost-effective and straightforward manufacturing technology. This involves a

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Nashr etilgan sana: 30.01.2026

comprehensive study of the fundamental parameters of charge carriers, photovoltaic properties, and the influence of materials on the efficiency and photovoltaic characteristics of these types of solar cells. The ionic conductivity of polymer-based electrolytes is a key factor influencing the performance and stability of DSSCs.[3]

In modern solar cell production, particular attention is given to detecting and eliminating defects, as they significantly impact the efficiency and durability of devices. Defects can occur at various stages of production and include microcracks, layer inhomogeneities, and other structural anomalies. Research also focuses on improving the stability and efficiency of materials for solar cells. For instance, scientists have developed molecular additives known as "defect passivators," which significantly slow the degradation of perovskite semiconductor films. This advancement extends the lifespan of solar cells and reduces their cost.

Methodology

A novel method for evaluating the quality of solar cells, combining adhesion testing and computer tomography (CT), represents an integrated approach that provides a comprehensive analysis of the structure and layer strength in solar cells. Mathematical modeling provides deeper insights into charge transport processes in DSSCs, supporting the optimization of design parameters.[4]

1. **Adhesion Testing**: in the first stage, the methodology involves performing an adhesion test aimed at assessing the bond strength between the layers of the solar cell. This step helps identify areas with insufficient adhesion, which may lead to delamination and damage during operation. Adhesion testing detects weak zones at the layer boundaries, enabling early diagnosis of potential defects.

2. **Computer Tomography (CT)**: the next stage employs computer tomography (CT) to create a high-resolution three-dimensional image of the internal structure of the solar cell, down to the submicron level. Tomographic

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

analysis precisely identifies internal defects, such as pores, cracks, and layer inhomogeneities, that were not detectable during adhesion testing. CT confirms and refines the results of adhesion tests, providing visual data on how adhesion and material structure affect the quality and durability of the cells.

The combination of adhesion testing and tomographic analysis offers deeper insights into the internal structure of solar cells and their potential weaknesses. This innovative quality control method delivers precise data to improve production processes, enabling the early detection of defects and thereby enhancing the reliability and longevity of solar cells.

Practical Cone-Beam Algorithm

The **convolution-backprojection formula** is derived for the direct reconstruction of a three-dimensional density function from a set of two-dimensional projections. Although this formula is approximate, it offers several practical advantages, including errors that are relatively small in many applications and a computationally efficient form. The formula reduces to the standard fan-beam formula in the plane perpendicular to the axis of rotation and containing the point source. The algorithm is applied to a mathematical phantom as an example of its operation.

Direct three-dimensional (3D) reconstruction from projection data has been the focus of many studies. As used here, direct 3D reconstruction involves utilizing two-dimensional (2D) projection data to reconstruct on a three-dimensional grid of points, which may or may not be organized as parallel slices. In medical applications, direct 3D reconstruction remains at the forefront of research; to our knowledge, no commercial tomograph currently implements direct 3D reconstruction.

The industrial application of tomography as a method of non-destructive evaluation (NDE) is still quite limited. Using X-ray image intensifiers as tomographic input data is a natural extension of electronic radiography and is

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

conducted in laboratory systems with minimal mechanical complexity. The system comprises a microfocus X-ray source, a single-axis rotary stage, and an X-ray image intensifier with the associated electronics. Consequently, a fast and reliable procedure for direct reconstruction is highly advantageous.[5]

Essentially, the **Feldkamp Algorithm (FDK)** consists of three steps:

1. Filtering in the projection space,
2. Backprojection,
3. Weighting in the volume-space domain.

These steps are reflected in the following three equations (Figure 2).

$$f(r)=\frac{1}{4\pi^2}\int_0^{2\pi}\frac{d^2}{(d+rx_\varphi)^2}\hat{P}_\varphi(r)\,d\varphi \qquad (1)$$

where

$$\hat{P}_\varphi(r)=\hat{P}_\varphi\big(Y(r),Z(r)\big),\ Y(r)=\frac{ry_\varphi}{d+rx_\varphi}D,\ Z(r)=\frac{rz_\varphi}{d+rx_\varphi}D \qquad (2)$$

and

$$\hat{P}_\varphi(Y,Z)=\frac{D}{\sqrt{D^2+Y^2+Z^2}}P_\varphi(Y,Z)**g(Y) \qquad (3)$$

In these equations, a voxel is represented by the vector r = (x, y, z) in the volumetric reconstruction space defined by (Xv, Yv, Zv), where Yv is the axis of rotation. Elements on the projection plane (detector), oriented at an angle φ, are represented as Pφ(Y, Z), where Y and Z indicate the spatial position of an element in detector coordinates. The vector Xφ is orthogonal to the detector plane and connects the center of the detector to the source S. Two orthogonal vectors, Yφ and Zφ, complete the three-dimensional coordinate system of the detector space, which is related to (Xv, Yv, Zv) through a transformation matrix consisting of gantry rotation and potential gantry distortion. Finally, the distances from the source to the center of rotation O and the detector center are defined as d and D, respectively.

- Equation (3) represents the filtering operation in the projection space.

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

- Equation (2) describes the backprojection operation, which maps a voxel to its corresponding position on the projection plane and assigns it an interpolated value.
- Equation (1) integrates the contributions of backprojection for a given voxel across all projections, appropriately weighted in the volumetric space.

These three equations form a natural decomposition of the FDK algorithm, creating a pipeline consisting of filtering, backprojection, and weighting. This structured approach facilitates efficient and precise volumetric reconstruction.

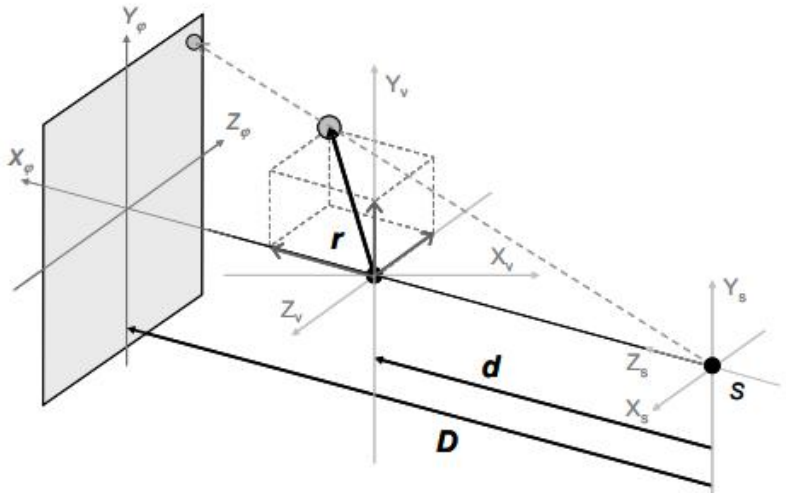


Figure 2 – Feldkamp Filtered Backprojection Algorithm

Key Results from the Experiment

- Coating Thickness: the analysis revealed that the thickness of the TiO_2 layers and the photosensitive dye coating ranges between 45-70 microns. Significant deviations were observed in certain areas, indicating uneven layer application. This non-uniformity can negatively impact the efficiency of the solar cells, as uneven coatings reduce light absorption and electron injection (Figure 3). Advances in DSSC manufacturing technology have contributed to significant improvements in efficiency and cost-effectiveness. [6]

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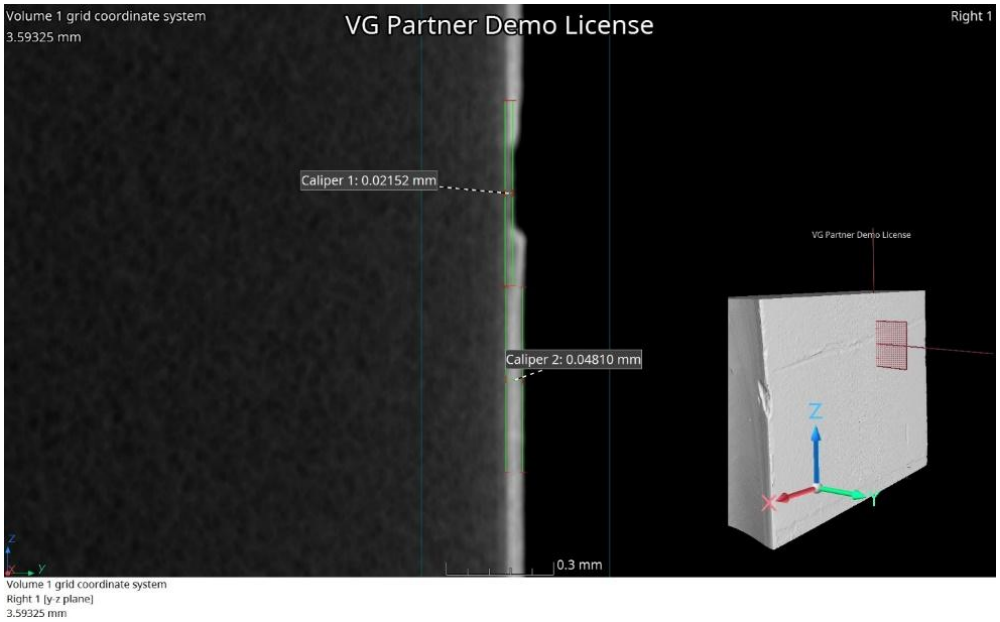


Figure 3 – Tomogram of the Solar Cell showing variations in coating thickness

Structural Defects

Various defects were identified in the DSSC coatings, including pores, cracks, and delaminations. Pores with diameters up to 110 microns and cracks with depths up to 30 microns were observed, which adversely affect conductivity and the overall efficiency of the cells (Figure 4). These defects are often caused by uneven dye application or insufficient adhesion between layers. Quasi-solid-state gel electrolytes have been shown to enhance both the ionic conductivity and the photovoltaic performance of DSSCs. [7]

The scanning results proved to be highly effective, not only in detecting defects but also in calculating layer thickness and evaluating coating uniformity. Additionally, the analysis allowed us to investigate the causes of thickness deviations, identify factors contributing to out-of-range values, and better understand the parameters affecting the quality of the coatings.

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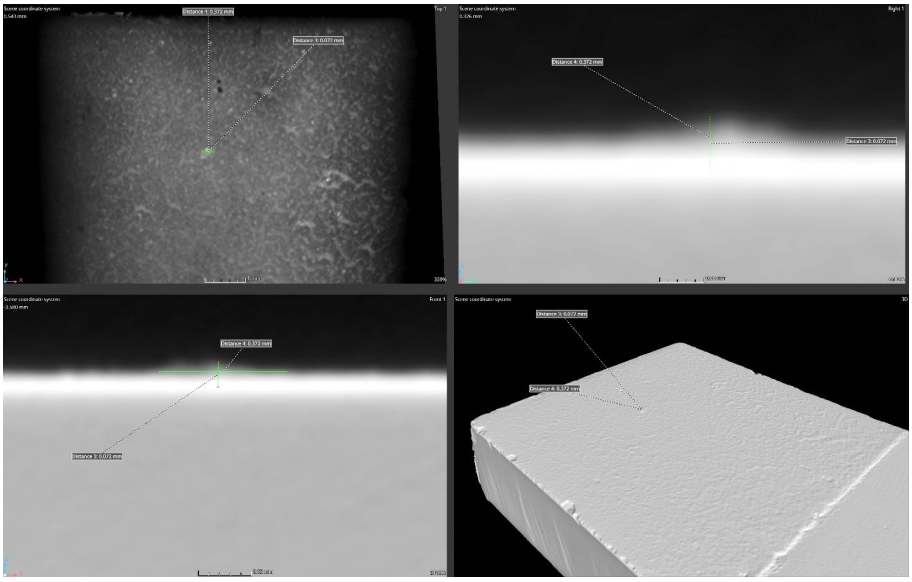


Figure 4 – Tomogram of DSSC Showing Structural Defects (Pores and Cracks)

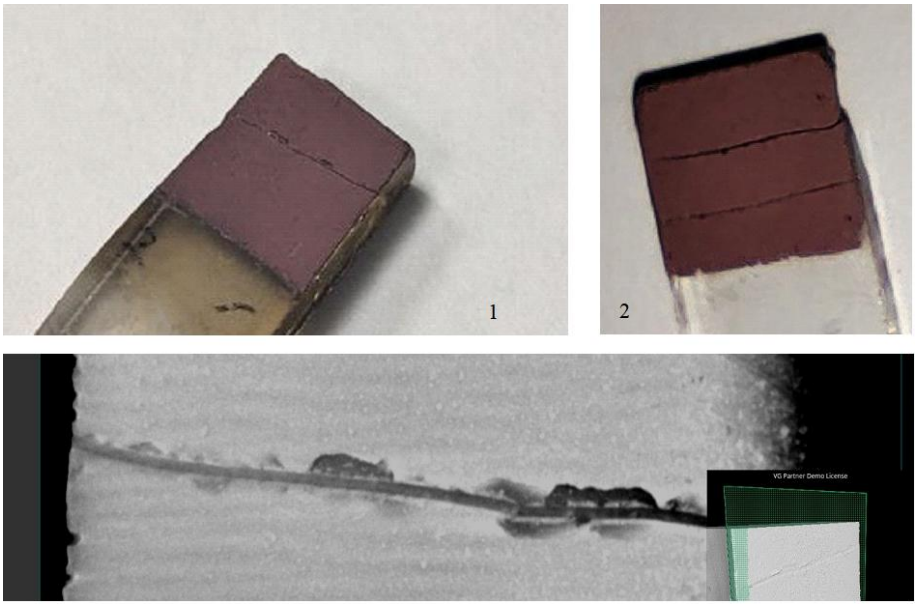


Figure 5 – Measurement of Adhesion Strength Using the Cross-Cut Method According to GOST 15140-78

Contact Quality Between Layers

Tomographic analysis revealed adhesion issues between layers, leading to the formation of microcracks and pores. These defects degrade electrical conductivity and may result in the long-term degradation of the solar cells (Figures 5-6).

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

According to GOST 15140-78, adhesion testing involves making cross-cuts on several areas of the sample, applying adhesive tape to the cuts, and then peeling it off after a few seconds. The percentage of edge detachment is then evaluated. Polymer-containing electronic elements play a critical role in improving adhesion and reducing delamination in DSSCs.[9]

In our tests, Sample 1 (shown on the slide) exhibited poor results, with the detached area exceeding 35% of the cut area. On the right side, Image 2 illustrates an example of a good result, demonstrating minimal detachment and high adhesion quality.

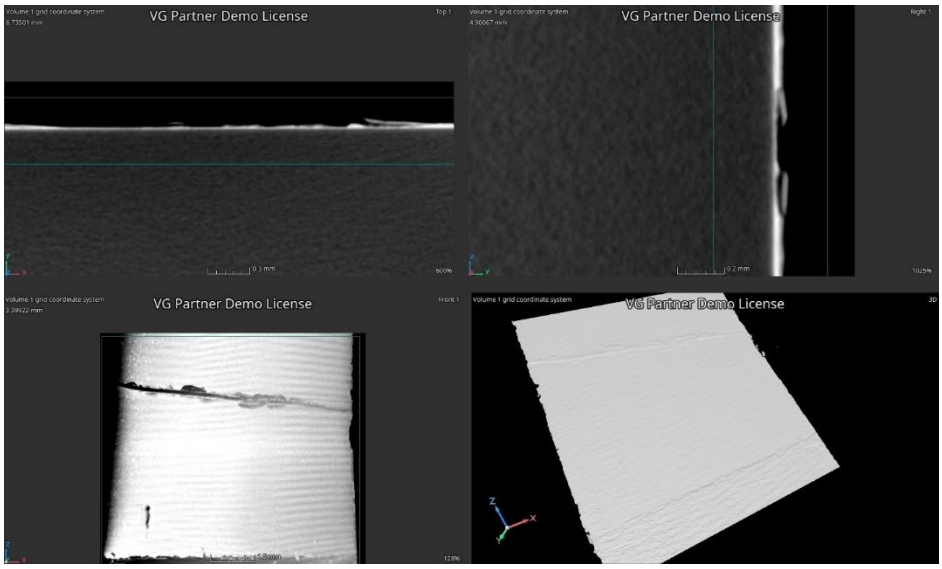


Figure 6 – Analysis of Layer Contact Quality Showing Microcracks and Defects

Structural Characteristics of DSSC

The study of the structural characteristics of dye-sensitized solar cells (DSSC) revealed that the uniformity of the cell structure plays a critically important role in ensuring their stable and efficient operation. The analysis demonstrated that inconsistencies in layer coatings could lead to localized changes in electrical properties, which, in turn, negatively impact the overall performance of the solar cells.

The presence of such inconsistencies creates regions with increased resistance or conductivity defects, reducing the efficiency of converting sunlight

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

into electrical energy. This issue is particularly critical for DSSC, where each layer and its adhesion properties directly affect the device's stability and longevity. Eliminating these structural defects and improving the uniformity of layer coatings are essential steps toward enhancing the efficiency and stability of solar cells. Studies on the environmental and operational resilience of DSSCs highlight the importance of early defect detection and layer uniformity for improving their longevity. [8]

Conclusions

Based on the research conducted using industrial tomography, valuable insights and practically significant results were obtained, contributing to the improvement of dye-sensitized solar cells (DSSC) quality:

1. **Role of Layer Uniformity**: Industrial tomography established that the uniformity of the structure and even application of TiO_2 and photosensitive dye layers are critically important for the stable and efficient operation of DSSCs. Any deviations in thickness or density of these layers lead to localized changes in electrical properties, thereby reducing the overall performance of the solar cells.

2. **Detection of Microstructural Defects**: Tomographic analysis identified typical internal defects such as pores, cracks, and delaminations, which may arise during the layer application and formation processes. These defects not only decrease energy conversion efficiency but also accelerate wear and degradation. The application of tomography at early production stages enabled the evaluation of defect prevalence and characteristics, providing opportunities for their elimination during manufacturing.

3. **Optimization of Application and Thickness Control Processes**: Analysis using industrial tomography demonstrated that high-quality application of TiO_2 and dye layers requires optimization of application methods and control of thickness and density. Regular scanning of elements during the layer application and curing stages allows for monitoring of coating parameters and timely

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

adjustments to the application process. This ensures enhanced quality, longevity, and stability of finished solar cells.

4. **Potential of Industrial Tomography as a Control Standard**: The data obtained through industrial tomography demonstrated the method's high informativeness and accuracy in defect diagnostics. Regular tomographic analysis on DSSC production lines not only minimizes waste and identifies defects at early stages but also enables dynamic monitoring of structure. This improves control over production processes and minimizes potential structural deviations in products.

5. **Enhancing DSSC Durability and Efficiency**: Identifying and eliminating structural defects using industrial tomography contributes to extended service life and resistance to external influences. This is particularly important for operation in diverse climatic conditions, where stability and durability are critical. The tomographic method identified factors contributing to degradation, which, in turn, allows for improved designs and increased reliability of the cells.

Final Remarks

The use of industrial tomography as a standard method for DSSC quality control not only enhances product quality and operational stability but also facilitates the development of optimized production technologies. This positively impacts the efficiency and competitiveness of the final product.

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