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DETERMINING THE EFFICIENCY OF RESTORED PHOTOVOLTAIC MODULES UNDER NATURAL LIGHTING CONDITIONS

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The object of this study is thin-film photovoltaic modules without physical damage, manufactured by CIGS technology, affected by potential-induced degradation, after restoration. The possibility of improving the efficiency of the array of restored photovoltaic modules of the Q.SMART UF L 105 type has been established experimentally, under natural lighting conditions, up to 50 % and higher with respect to the new reference photovoltaic panel. An expression for evaluating the efficiency of restored photovoltaic panels has been derived. It is proposed to use a relative indicator – the efficiency index, which is calculated based on the specific generation data of photovoltaic modules. During the experiment, photovoltaic panels were connected to the OpenSCADA dispatch control and data collection system. Experimental studies were carried out in the autumn-winter period under three weather scenarios: clear day, variable cloudiness, continuous cloudiness. The specific monthly generation of photovoltaic modules was defined as the amount of energy produced during the month per unit of power, which is 100 W. During the experiment, minute and hourly fluctuations in the generation of photovoltaic modules were recorded. Based on the results of calculating the efficiency index, it was concluded that the generation of electrical energy by exhausted photovoltaic modules after restoration under real operating conditions allows for the possibility of their secondary application.

The results of the research could be used as a basis for evaluating the efficiency of restored photovoltaic modules while the resulting statistical data on their performance could be used to devise rules and standards for the secondary application of exhausted photovoltaic panels

Keywords: photovoltaic module, potential-induced degradation, photovoltaic generation, SCADA system, restoration efficiency

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1. Introduction

Under modern conditions, most countries of the world are moving towards decarbonization of their energy systems. The European Union has taken a course on the green transition, the goal of which is to achieve climate neutrality by 2050 with the replacement of fossil fuels with renewable energy sources by 2035 [1]. In view of this, in various branches of industry, agriculture, transport, as well as in the private sector, there is a rather rapid increase in the capacities of installed photovoltaic systems (IPSs) [2, 3]. At the end of 2018, the total installed capacity of IPSs was 515 GW; at the end of 2022, it reached a value of 1050 GW [4], continuing to grow until now.

In most developed countries, large-scale photovoltaic installations appeared around the beginning of the 2000s. Given that photovoltaic modules (PVMs) are designed for a service life of 20 to 30 years, a significant part of them is at the end of its operational life cycle. It is expected that after 2030 a considerable volume of photovoltaic waste will appear [5]. The International Renewable Energy Agency (IRENA) [6] predicts that by 2030 there will be from 1.7 to 8 million tons, and by 2050 – from 60 to 78 million tons of photovoltaic waste.

Quite a large amount of waste from solar cells is a consequence of the delay between the moment of installation and the final stage of the PVM life cycle [7], so often FMs do not meet the stated service life. As an example, we could note the Solarpark Ammerland solar power plant, built in the fall of 2011 by GP JOULE in Germany. About 196,000 thin-film modules Q-Cells CIGS, type Q.SMART, with an installed capacity of 21 MW were placed on an area of 57 hectares [8]. However, in 2017, the operation of the solar park stopped, all FMs were replaced by the owners with 80,000 new silicon panels because the thin film modules did not have the stated warranty period of 25 years of operation. Thus, the actual volume of photovoltaic waste may turn out to be higher than predicted, and the waste may appear earlier than expected.

All over the world, exhausted PVMs are traditionally either destroyed or landfilled, resulting in the loss of valuable metals and environmental degradation due to leakage of toxic materials. It is possible to reduce the negative impact on the environment by recycling photovoltaic waste or further exploitation of PVMs. Complete recycling of PVMs is a problematic task. In Ukraine, there are no PVM processing enterprises, as well as special requirements for their disposal [9]. At the same time, extending the service life of PVMs has not only significant environmental advantages but also makes it possible to obtain a certain economic effect. Thus, secondary use IPSs could be used as backup power sources at small business enterprises, reducing the cost of purchasing new equipment. Extending PVM operation could prove useful for the private sector as well. Therefore, under these conditions, the development of technologies for the recovery of exhausted PVMs with the extension of their service life appears to be promising. And assessing the effectiveness of PVMs in secondary use is a relevant area of scientific research.

2. Literature review and problem statement

In [10], a comprehensive review of the degradation factors that are associated with the aging of PVMs and that significantly affect the performance and service life of IPSs is given. In particular, factors such as surface contamination with soil particles, dust, snow, building materials, as well as discoloration, cracks, and delamination were considered. High temperatures, ultraviolet radiation, high air humidity, extreme weather conditions (hail, heavy snowfall, or wind) that could lead to physical damage to the panels are also included in [11] as factors that impair PVM operation. But questions related to how these factors affect the development of potentially induced degradation (PID) remained unresolved because of the complexity of studying the mechanism of this phenomenon.

The physical basis of the mechanism of PID occurrence is considered in [12]. During PID, there is a gradual loss of PVM performance because of the high potential difference between the cell (semiconductor) and other grounded parts of the module, e.g., frame, glass. This leads to current leakage and ion migration, which weakens the photoelectric effect and causes a gradual loss of PVM power. However, in work [12], the main emphasis is on the physical features of the degradation process of PVM based on crystalline silicon. The PID mechanism for thin film modules was not considered.

Studies of the PID effect show varying levels of degradation impact on photovoltaic technologies such as crystalline silicon and copper indium gallium selenide (CIGS). Thus, in [13], it was concluded that photovoltaic systems based on CIGS have a higher resistance to PID compared to crystalline silicon under identical test conditions. Possible strategies for mitigating degradation are also presented in [13]. However, a thorough analysis of PID prevention issues is lacking. This problem is also complicated by the gradual increase in the rated power of PVM (more than 600 W).

An option to mitigate or prevent PID is to use new materials and design solutions. An important role in protecting sensitive solar cells from degradation and damage belongs to the film material of the back sheet of the solar panel. Work [14] reports the study of the relationship between PID and a change in the degree of crystallinity of the back layer of the solar module during degradation tests. The research results in [14] are aimed at mitigating the consequences of degradation. At the same time, issues related to the prevention of PID have been neglected by researchers.

Research results reported in [15] showed that the use of materials with higher resistance to moisture penetration, such as fluorine-doped tin oxide (SnO_2) (FTO), is an effective means of preventing PID. This material is used as the front electrode material in PVM. The risk of PID could be reduced, as shown in [16], by glass with a metallic coating applied by sputtering, the thickness of which could be controlled. However, it should be noted that the methods for preventing degradation, presented in [15, 16], were used during the manufacture of PVMs.

In [17], several strategies for PID mitigation that could be used during the operation of a IPS are defined. Specifically, strategies such as sealing PVM edges, using ventilation to reduce temperature, avoiding the use of certain chemicals, and using proper grounding techniques during PVM installation. At the same time, it is important for solar IPS owners to maintain and monitor PVMs to reduce the negative effects of PID and extend the life of PVMs. In work [17], these issues were not considered.

A monitoring system for detecting surface or structural damage to solar panels during their installation and operation using drones is proposed in [18]. In this case, PVMs are checked for defects and measures are taken to improve electricity production, for example, through a panel cleaning mechanism. Artificial intelligence methods are proposed for image processing, in particular, pattern recognition. However, the system proposed in [18] should be used only at large industrial solar IPSs.

Maximum power point tracking (MPPT) algorithms are also used to detect PVM faults [19]; wavelet transform for analyzing the frequency spectrum of microgrid photovoltaic system data and detecting anomalies that may indicate a malfunction [20]. However, in [19], there are no practical recommendations for using the proposed MPPT tracking algorithm under conditions of partial PVM shading. In [20], a method of protection against short circuits in a microgrid is proposed, which is suitable for detecting short circuits in limited cases. Insufficient attention to the study of technical monitoring issues is due to the fact that PVMs are usually sold as energy sources that do not require additional maintenance.

There is also a lack of scientific research on end-of-life PVM management, including recycling, reclamation, repair, recovery, and reuse of end-of-life PVMs, which is reviewed in [21]. It is concluded that research and development for the recovery of end-of-life PVMs remains scarce, and best practices and commercial services for reliability testing and re-certification, as well as for the trade of secondary PVMs, are not standardized.

An analysis of methods for restoring degraded PVMs is given in [12]; the authors suggested using a reduction of the applied voltage; reverse voltage; active or passive methods of thermal management; decrease in current density; PVM storage in a dark place. As noted in [22], most research on PVM recovery is related to standard modules based on crystalline silicon because they dominate the IPS market. In [22] it was shown that thermal recovery, reverse voltage, and their combinations are able to restore the efficiency of PVMs based on crystalline silicon, and could also be applied to other photovoltaic technologies, in particular, CIGS. However, a serious problem is that most of the proposed methods and technical solutions for PVM recovery do not provide the desired efficiency or increase the cost of recovered PVMs.

In [23], the scenarios of PVM recycling at the end of their life cycle are considered, in particular: reuse of the module, extraction of components, and extraction of material. The work concludes that the reuse of PVM is distinguished by the least number of processing stages and could bring the highest income. The main problem is to find sales markets for the reuse of exhausted PVMs after their recovery.

Thus, our review of the literature [10–23] demonstrated that current research mostly tackles the influence of various factors on the performance of PVMs under which they could enter the waste stream. Peculiarities of the mechanism of degradation and issues related to the use of new materials and structural solutions to mitigate the consequences of degradation are also considered. At the same time, there is a certain lack of research and publications on technical monitoring and recovery of exhausted PVMs for the purpose of their further use under cyclical economy conditions. Without proper maintenance, PVMs could experience reduced efficiency, increased downtime, and equipment failure. In turn, the restoration of decommissioned PVMs is complicated by the lack of a procedure for checking (certification) of secondary PVMs and, as a result, the difficulty of implementing them for reuse. There is also a lack of actual (experimental) data on the effectiveness of the secondary application of various types of PVMs after restoration. All this allows us to state that the issues of assessing the functionality and efficiency of PVMs under real operating conditions after their restoration require additional investigation and generalization.

3. The aim and objectives of the study

The purpose of our study is to determine experimentally under actual natural lighting conditions the effectiveness of PVMs prone to potentially induced degradation, after their restoration. The results of the research will make it possible to evaluate the functionality of recovered PVMs with respect to new solar panels and justify the expediency of their secondary use. This will ensure the extension of the service life and, as a result, an increase in the environmental sustainability of PVMs through the reduction of photovoltaic waste and its negative impact on the environment. In addition, statistical data on the performance of recovered PVMs could be used to devise rules and standards for the reuse of PVMs.

To achieve the goal, the following tasks were set:

– to obtain an expression for calculating the efficiency of restored photovoltaic panels;

– to conduct experimental studies to determine the functionality of restored PVMs under natural lighting conditions.

4. The study materials and methods

Exhausted thin-film PVMs without physical damage, produced by CIGS technology, affected by PID degradation were chosen as the object of our research. The subject of the study is a comparative analysis of the performance of degraded PVMs after their restoration with respect to new monocrystalline panels under different natural lighting conditions. The main hypothesis of the study assumes that the generation of electrical energy by exhausted PVMs after recovery under real operating conditions could be sufficient for their reuse.

During the experiment, photovoltaic panels were connected to the OpenSCADA supervisory control and data acquisition system, which is an open implementation of SCADA (Supervisory Control And Data Acquisition) and HMI (Human-Machine Interface) systems. OpenSCADA is built on the principles of modularity, cross-platform, and scalability [24].

For experimental research, 24 exhausted photoelectric thin film modules (CIGS) of the Q.SMART UF L 105 type, produced in 2011, were purchased. According to the data given in [25], in 2011 similar panels were produced in the world with a total capacity of more than 3000 MW and a weight of more than 500 thousand tons. In 2011, First Solar, Inc. (USA) became the largest producer of thin-film PVMs in the world in terms of capacity (1,981 MW) [25].

Thin-film modules of the Q.SMART type, because of the damage from PID degradation, produced at the initial stage from 2 to 10 % of the rated power P_{max}=105 W for standard test conditions (STC) [11]. Standardized conditions assume a solar radiation intensity of 1000 W/m^2 at a module temperature of 25 °C in the absence of wind. In this case, the photovoltaic panel must be oriented southwards.

As mentioned above, PID-prone PVM recovery methods provide an opportunity to restore the functionality of failed modules. Using the method described in [26], by tracking the change in the volt-ampere characteristic of PVM on a specially built bench, it was possible to increase the performance of some panels. Studies on the restoration of PVM productivity were conducted in 2022 over 3 months. The maximum PVM power after recovery was 30 % (33.5 W) of the STC-declared rated power P_{max} (105 W) and was obtained for a sun-facing PV panel on a sunny, windless day (October 16, 2022).

PVM efficiency η_{ef} is determined from the following expression [11]:

$$\eta_{ef} = P_{max} / P_{rad} = P_{max} / (E \cdot S), \quad (1)$$

where P_{rad} is the power of incident radiation; E – intensity of solar radiation according to STC (1000 W/m^2); S is the PVM area.

The efficiency η_{ef} of the Q.SMART UF L 105 module under standardized conditions is 11.2 % [27], and the efficiency of the restored module was 3.57 %, respectively. Comparison of the technical characteristics of restored PVMs with parameters of PVMs according to STC is not correct. Standardized conditions are ideal conditions that do not reflect the real pattern of PVM electrical energy generation. The performance of exhausted PVMs after restoration should be evaluated with new solar panels of a similar configuration under real operating conditions.

It should be noted that at the time of the experiment, the new PVM Q.SMART UF L 105 were not available for order. Therefore, for observation under real natural lighting conditions, together with an array of restored Q.SMART UF L 105 panels, an available new monocrystalline panel Risen Energy RSM110-8-545 was installed, which served as a reference. Specifications, according to STC, of the restored Q.SMART UF L 105 [27] and reference Risen Energy RSM110-8-545 [28] panels are compared in Table 1.

Thus, taking into account the features and technical characteristics of the restored panels Q.SMART UF L 105, selected for our experiment, it is proposed to determine the efficiency of the array of restored panels in comparison with the reference monocrystalline panel Risen Energy RSM110-8-545.

Table 1

Specifications of restored Q.SMART UF L 105 and reference Risen Energy RSM110-8-545 photovoltaic panels

Parameter	RSM110-8-545M	Q.SMART UF L 105
Rated power $P_{\max}$, W	545	105
Idle voltage U_{oc}, V	38.02	93.1
Short-circuit current l_{sc}, A	18.23	1.63
Voltage at the point of maximum power U_{mpp}, V	31.66	71.5
Current at the point of maximum power l_{mpp}, A	17.22	1.47
Module efficiency, %	20.9	11.2
Solar cells	Monocrystalline	Thin-film (CIGS)
Module dimensions, mm	2384×1096×35	1190×789×7.3
Weight, kg	29	16.5

5. Results of analyzing the generation of electrical energy by photovoltaic modules prone to degradation after restoration

5. 1. Expression for calculating the efficiency of restored photovoltaic panels

Evaluation of the efficiency of restored PVMs was carried out using a relative indicator – the *IE* efficiency index. The calculation of the *IE* indicator was carried out through the value of the specific generation of the array of restored Q.SMART UF L 105 modules and the reference photovoltaic panel Risen Energy RSM110-8-545.

The specific generation of PVM was defined as the amount of energy produced during a certain period of time per unit of base power, which is chosen for convenience as 100 W. Recalculation of PVM power was carried out in relation to 100 W of the installed rated power $P_{\max}$ according to STC (Table 1). The power conversion factor $k=P_{\max}/100$ was, respectively: $k=545/100$ W$=5.45$ – for PVM of type Risen Energy RSM110-8-545; $k=105n/100=1.05n=25.2$ ($n=24$ – the number of solar panels in the array) – for restored PVMs of the Q.SMART UF L 105 type.

Specific indicators of hourly p_{PV} and monthly w_{PV} (for a period of time *T*) of electric energy generation, reduced to 100 W of the installed rated power of PVM, were determined as follows:

$$p_{PV} = P_{PVi} / k,$$
$$w_{PV} = p_{PV} \cdot T = P_{PVi} \cdot T / k, \quad (2)$$

where P_{PVi} is the PVM generation power at the i-th time point.

With the help of the *IE* efficiency index, the energy of the array of restored panels generated during the month of observation w_{PV}^{D} is compared with the specific indicator w_{PV}^{E} for the generation of the reference PVM. The value of the *IE* is calculated from the following formula:

$$I \;\; = \frac{w_{PV}^{D}}{w_{PV}^{E}} \cdot 100\,\%. \quad (3)$$

If the condition $IE \geq 50$ % is met, the efficiency of restored photovoltaic panels could be considered sufficient to ensure the possibility of their reuse.

5. 2. Experimental studies on the functionality of restored photovoltaic modules under natural lighting conditions

To determine the real data on the generated PVM energy of the Q-Cells Q.SMART UF L-105 type, an array of 24 parallel-connected restored panels with a total rated power of 2520 W was assembled. The Q-Cells Q.SMART UF L-105 PV array and the new Risen Energy RSM110-8-545 panel were installed at the same angle of 68° and azimuth of 206° (southwest).

The experiment was conducted in the Kyiv oblast, the average annual insolation rate for which, according to NASA observations, is 3.1 kWh/m^2/day. PVM generation was measured from October 2023 to February 2024. This is a period of low solar activity when the average value of the insolation index does not exceed 1.35 kWh/m^2/day.

Research into the generation of solar panels was carried out in the winter period, which is the worst in terms of solar insolation. For the region of the city of Kyiv, the indicators of solar insolation in winter, respectively, are [29] as follows: December – 0.86, January – 1.07, February – 1.87 kWh/m^2/day. Days with different cloudiness coefficient values (Table 2) were chosen, which corresponded to the following three weather scenarios:

– scenario 1 – a clear day (January 30, 2024), the cloudiness factor changes from 0 to 2;

– scenario 2 – variable cloudiness (January 31, 2024), the cloudiness factor changes from 4 to 7;

– scenario 3 – solid cloudiness (December 6, 2023, January 11, 2024, February 1, 2024), the cloudiness factor changes from 7 to 8.

On the days of observations given in Table 2, wind speed and air temperature were approximately the same: wind speed varied from 2 to 4 m/s, air temperature ranged from −2 to +4 °C. There was no precipitation during the day. Under different weather scenarios (30.01.2024, 31.01.2024, and 01.02.2024), the restored PVMs Q-Cells Q. SMART UF L-105 were installed both at an angle and horizontally. PVM generation schedules with hourly and minute averaging were registered. Table 2 gives values of specific peak power for each type of PVM based on an hourly average.

As mentioned above, during the experiment PVMs were connected to the OpenSCADA dispatch control and data collection system [24].

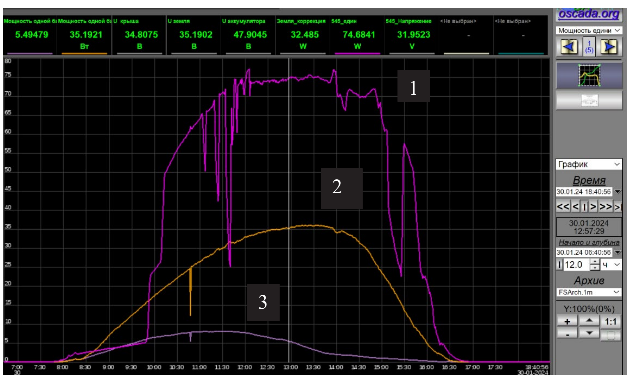
Table 2

Specific peak powers of the array of restored Q.SMART UF L 105 and reference Risen Energy RSM110-8-545 photovoltaic panels under different weather conditions

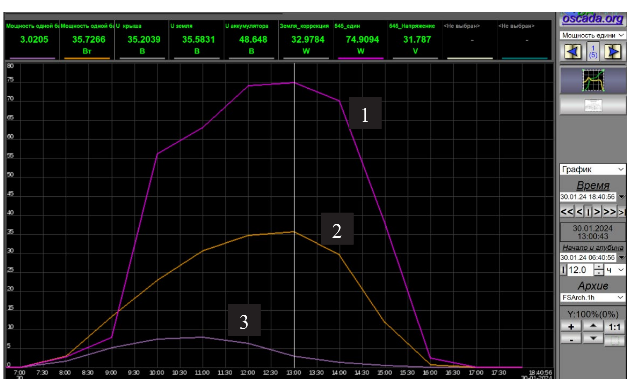
No.	Date	Cloudiness in points during the daytime	Specific hourly peak power of PVM, W		
			Risen Energy RSM110-8-545	Q-Cells Q.SMART UF L-105	
				Installed at an angle	Installed horizontally
1	06.12.2023	7–8	7.5	3.55	–
2	11.01.2024	8	3.5	1.48	–
3	30.01.2024	0–2	74.98	35.73	7.5
4	31.01.2024	4–7	72.5	33.7	7.6
5	01.02.2024	7–8	5.6	2.45	3.2

PVM generation was measured with minute and hourly averaging under the following weather scenarios.

Weather scenario 1. Fig. 1 shows plots for the specific generation of PVM per light day for the conditions of a clear winter day (January 30, 2024). On this day, the maximum generation of PVM was observed. The specific hourly peak power was 74.98 W – for Risen Energy RSM110-8-545; 35.73 W and 7.5 W – for an array of restored Q-Cells Q.SMART UF L-105 panels installed at an angle and horizontally, respectively.



a

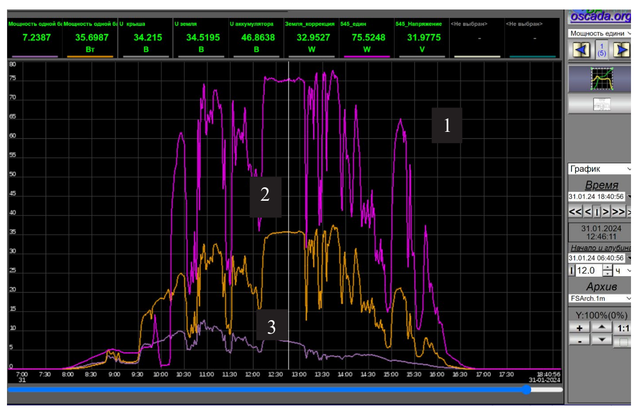


b

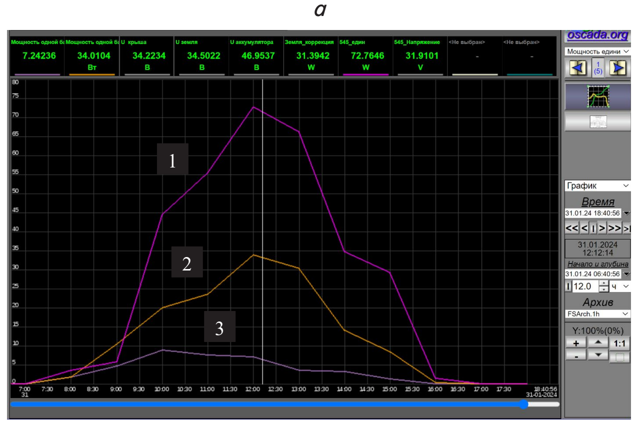
Fig. 1. Specific generation p_{PV} over a light day on January 30, 2024: *a* — minute averaging; *b* — hourly averaging; 1 — new Risen Energy RSM110-8-545 monocrystalline panel; 2 — restored Q-Cells Q.SMART UF L-105 panels, located at an angle; 3 — restored panels Q-Cells Q.SMART UF L-105, located horizontally

During the day on January 30, 2024, there were some small clouds, the cloudiness coefficient varied from 0 to 2 points. When the cloud density changes, fluctuations in the generation of Risen Energy RSM110-8-545 (Fig. 1, *a*) are noticeable, which are not visible on the generation plot for Q-Cells Q.SMART UF L-105. This is due to the fact that the array of Q-Cells Q.SMART UF L-105 consists of many panels and occupies a large area compared to the area of the new PVMs, so the effect of cloud shading is averaged out.

Weather scenario 2. Fig. 2 shows plots of the specific generation by PVMs over a light day for variable cloudiness conditions (January 31, 2024), when the cloudiness factor varied from 4 to 7 points.



a

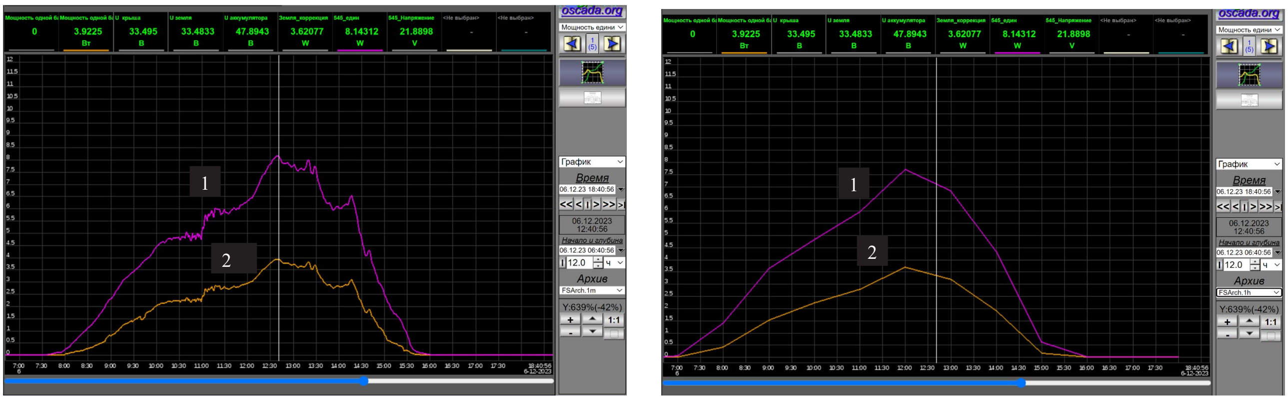


b

Fig. 2. Specific generation p_{PV} over a light day on January 31, 2024: *a* — minute averaging; *b* — hourly averaging; 1 — new Risen Energy RSM110-8-545 monocrystalline panel; 2 — restored Q-Cells Q.SMART UF L-105 panels, located at an angle; 3 — restored panels Q-Cells Q.SMART UF L-105, located horizontally

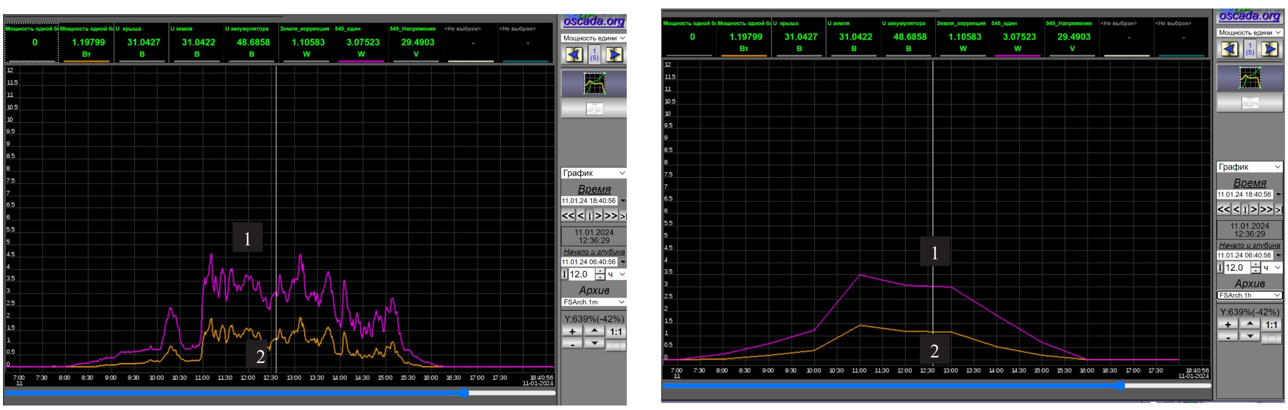
On January 31, 2024, reasonably high generation was also observed. The specific hourly peak power was 72.5 W – for Risen Energy RSM110-8-545; 33.7 W and 7.6 W – for an array of restored Q-Cells Q.SMART UF L-105 panels installed at an angle and horizontally, respectively. Compared to the previous plots (Fig. 1, *a*), the impact of clouds on both arrays of panels (Fig. 2, *a*) could be observed with minute averaging.

Weather scenario 3. Fig. 3–5 show plots for the specific generation by PVMs p_{PV} over a light day for the conditions of continuous cloudiness (06.12.2023, 11.01.2024, 01.02.24), when the cloudiness coefficient was the highest, varying from 7 to 8 points.



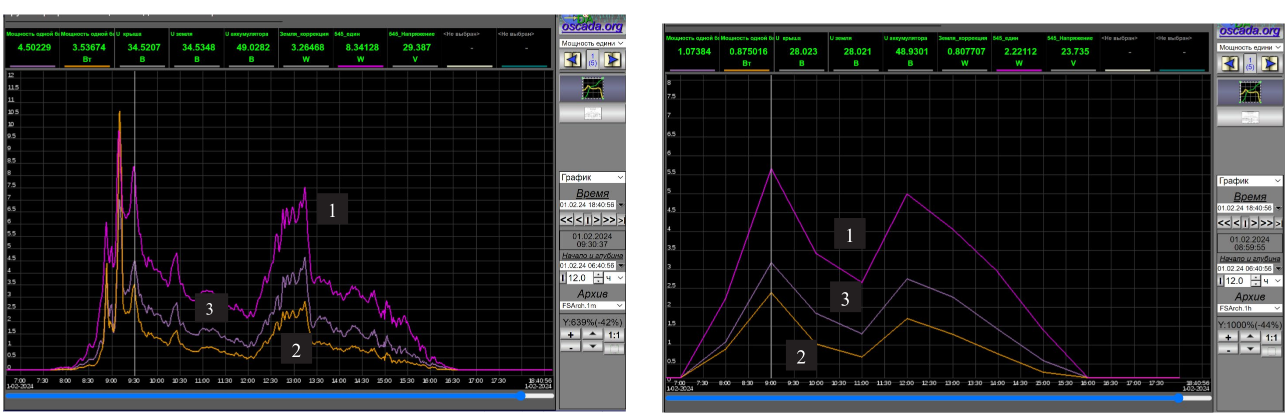
a *b*

Fig. 3. Specific generation p_{PV} over a light day of 06.12.2023: *a* — minute-by-minute averaging; *b* — hourly averaging; 1 — new Risen Energy RSM110-8-545 monocrystalline panel; 2 — restored Q-Cells Q.SMART UF L-105 panels, located at an angle



a *b*

Fig. 4. Specific generation p_{PV} over a light day of January 11, 2024: *a* — minute-by-minute averaging; *b* — hourly averaging; 1 — new Risen Energy RSM110-8-545 monocrystalline panel; 2 — restored Q-Cells Q.SMART UF L-105 panels, located at an angle



a *b*

Fig. 5. Specific generation p_{PV} over a light day of February 1, 2024: *a* — minute averaging; *b* — hourly averaging; 1 — new Risen Energy RSM110-8-545 monocrystalline panel; 2 — restored Q-Cells Q.SMART UF L-105 panels, located at an angle; 3 — restored panels Q-Cells Q.SMART UF L-105, located horizontally

As could be seen from Fig. 3, generation on a gloomy winter day on December 6, 2023, was low enough without sharp jumps. Specific hourly peak power was 7.5 W – for Risen Energy RSM110-8-545; 3.55 W – for an array of Q-Cells Q.SMART UF L-105 panels installed at an angle.

Fig. 4 shows PVM generation on a cloudy winter day on January 11, 2024, when it was completely cloudy with different cloud densities. Low generation was observed, but noticeable changes in generation with changes in cloud density. The specific hourly peak power was 3.5 W – for Risen Energy RSM110-8-545; 1.48 W – for an array of Q-Cells Q.SMART UF L-105 panels installed at an angle.

Fig. 5 also shows a plot with low PVM generation on a cloudy winter day on February 1, 2024; there are noticeable changes in generation with changes in cloud density. However, in Fig. 5, one can see that a horizontally located array of restored PVMs generates more energy under diffused lighting than panels installed at an angle. Specific hourly peak power was 2.45 W and 3.2 W for an array of Q-Cells Q.SMART UF L-105 restored panels installed at an angle and horizontally, respectively. The horizontal arrangement of the panels is inferior in direct sunlight, but provides an advantage in diffused lighting, which is often seen in the winter months or on cloudy days. This could be useful for stand-alone IPSs when energy is needed under all lighting conditions.

The general statistics on the generation by renewable photovoltaic panels Q-Cells Q.SMART UF L-105 and the new panel, as well as the *IE* efficiency index of recovered PVMs, are given in Table 3 for two characteristic months of the fall (October 2023) and winter (January 2024) seasons. Table 3 also gives specific monthly generation of electrical energy, reduced to 100 W of the installed rated power of PVM.

Table 3

Indicators of electric energy generation by the reference monocrystalline panel Risen Energy RSM110-8-545 and the array of restored panels Q-Cells Q.SMART UF L-105

Indicator	Month	
	October	January
Risen Energy RSM110-8-545		
Monthly electricity generation, kWh	31.476	13.852
Specific monthly generation w_{PV}^{E}, kWh	5.775	2.542
Q-Cells Q. SMART UF L-105		
Monthly electricity generation, kWh	72.535	32.55
Specific monthly generation w_{PV}^{D}, kWh	2.878	1.292
Efficiency Index *IE*, %	50	51

Thus, our experimental studies have shown that exhausted PVMs manufactured by CIGS technology and without physical damage could provide *IE* efficiency at the level of 50 % and higher compared to new PVMs.

6. Discussion of results based on the research on electricity generation by photovoltaic modules under natural lighting conditions

In our work, the main efforts were focused on conducting experimental studies to evaluate the generation of electrical energy by restored thin-film PVMs of the Q.SMART UF L 105 type under natural lighting conditions. It should be noted that in most works, in particular in [22], the issue of PVM recovery based on crystalline silicon is considered due to their dominance in the IPS market.

This work is a continuation of the research started in [26]. The results of the process of restoration of thin-film PVMs, highlighted in [26], showed that the highest generation power of the photovoltaic system could be obtained under conditions close to ideal according to STC. Under real operating conditions, the generation indicators of recovered PVMs should be compared with the generation indicators of the reference photovoltaic panel, which could be selected according to two options:

– option 1 – a new photovoltaic panel of the same type (Q.SMART UF L 105), as it is done, for example, in [11], or a new panel with similar technical parameters is taken as a reference;

– option 2 – a new photovoltaic panel with arbitrary parameters, which is available, is accepted as a standard.

The practical implementation of the first option turned out to be problematic because the newly available monocrystalline panel of the Risen Energy RSM110-8-545 type [28] with the parameters listed in Table 1 was chosen as the reference.

In the work, an expression was derived for determining the efficiency of restored PVMs. The proposed quantitative indicator is the *IE* efficiency index, which is calculated using the indicators for specific PVM generation according to expressions (2), (3). It is recommended to consider the condition $IE \geq 50$ % reasonable to ensure the possibility of reusing the recovered PVMs, for example, for small manufacturing enterprises or for domestic purposes ay private households.

During the experimental research, an array of 24 parallel-connected restored PVMs of the Q.SMART UF L 105 type with a total power of 2520 W was assembled. Different modes of operation of restored and reference photovoltaic panels were studied depending on weather conditions. In particular, in the winter period on a clear day (fluctuations of the cloudiness coefficient from 0 to 2), a high enough generation was observed, as shown in Table 2 and Fig. 1. Noticeable are minute-by-minute fluctuations in the generation by Risen Energy RSM110-8-545 (Fig. 1, *a*), which are not visible on the generation plot for restored Q-Cells Q.SMART UF L-105 panels. Under conditions of variable cloudiness, as shown in Table 2, a reasonably high generation is also observed, but clouds affect both arrays of panels (Fig. 2, *a*) during minute averaging. Finally, under conditions of continuous cloud cover, as could be seen from Table 2 and Fig. 3–5, PVM generation significantly decreases. However, as could be seen from Fig. 5, a horizontally located array of recovered PVMs under diffused lighting generates more energy than panels installed at an angle, which must be taken into account in the autonomous power supply to local consumers.

The results of our calculation of the *IE* efficiency index that are given in Table 3 satisfy the condition $IE \geq 50$ %. Therefore, the generation of electrical energy by exhausted PVMs after recovery under real operating conditions is sufficient for their reuse. In addition, recovered PVMs will continue to contribute to the decarbonization of the energy sector instead of filling landfills.

Our results are similar to the findings reported in [30], in which the authors confirm in practice that the PVM power loss under the influence of PID could be up to 40 % in an open area. In [22], degradation exceeding 50 % is defined as significant.

Certain limitations of this study are:

– the choice of a monocrystalline panel of the Risen Energy RSM110-8-545 type as a benchmark because of the difficulty of ordering a new PVM with parameters similar to the renewable PVM of the Q.SMART UF L 105 type;

– the insufficient validity of the $IE \geq 50$ % condition due to the lack of a secondary PVM certification procedure; this condition was determined based on the practical experience of using IPS.

The main drawback of our study is that it does not take into account the influence of different photovoltaic technologies (crystalline silicon or CIGS) on the results of comparative analysis of PVM generation.

Further prospects for this research involve determining experimentally the efficiency of renewable PVM generation, taking into account the influence of ambient temperature in the spring-summer period.

7. Conclusions

1. To evaluate the efficiency of restored photovoltaic panels, a relative indicator – the *IE* efficiency index – has been proposed. An expression for calculating the *IE* indicator using specific PVM generation data has been derived. A conversion factor of the generated PVM power with respect to 100 W of the installed rated power of photovoltaic panels has been determined, which is 5.45 for the Risen Energy RSM110-8-545 type PVM; 25.2 for an array of restored panels of the Q.SMART UF L 105 type, respectively.

2. Experimental studies were conducted to determine the functionality of restored PVMs under real lighting conditions in the autumn-winter period under three weather scenarios: clear day, variable cloudiness, continuous cloudiness. It has been established that the *IE* efficiency index of photovoltaic panels of the Q.SMART UF L 105 type restored without physical damage, manufactured according to CIGS technology, satisfies the condition $IE \geq 50$ %. Ensuring the efficiency of exhausted PVMs at the level of 50 % and higher with respect to the reference solar panel is the basis for making a decision to extend the service life of exhausted PVMs.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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