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ANALYSIS OF SOILING MEASUREMENT SYSTEMS AND CLEANING METHODS OF SOLAR PHOTOVOLTAIC MODULES

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Enhancing the efficiency of photovoltaic solar energy converters is of paramount importance. This study presents a comprehensive analysis of soiling measurement systems and cleaning methods for photovoltaic modules aimed at improving their efficiency. The research highlights the significant impact of dust and dirt accumulation on the surface of PV modules, which can reduce efficiency by more than 35%. Various soiling measurement systems are discussed, including optical systems and systems using paired photovoltaic modules, along with their respective advantages and disadvantages. The analysis also covers different cleaning methods, such as natural cleaning, manual cleaning, automated cleaning, and self-cleaning coatings. Each method's benefits and drawbacks are examined in terms of efficiency, cost, and applicability. The integration of digital technologies and automation, including artificial intelligence and IoT systems, is identified as a promising direction for future development in the field of solar panel soiling measurement and cleaning systems. This study provides valuable insights and comparative analyses for researchers, solar energy professionals, and solar plant owners to enhance the efficiency, longevity, and economic returns of photovoltaic installations. The implementation of efficient cleaning methods and advanced soiling measurement systems can lead to significant increases in the efficiency and durability of solar modules, as well as environmental benefits by reducing dependence on fossil fuels.

***Keywords*:** photovoltaic module, cleaning method, efficiency improvement, soiling measurement system, digital technologies, automation.

Introduction. Photovoltaic (PV) converters are used to convert solar energy into electrical energy. Quantitative characteristic of transformed energy is efficiency. The efficiency value depends on a number of external influences, among which the degree of contamination of the glass surface plays an important role. The accumulation of dust particles and dirt on the surface of photoelectric modules has a very negative effect on their efficiency, because in the presence of dust, sunlight does not penetrate to the semiconductor converters [1,2]. In order to solve the mentioned problem, the development and researches of solar PV modules surface cleaning methods, sensors for recording the presence of dust and systems for measuring the level of pollution are currently being carried out all over the world. The paper presents the importance of surface cleaning of solar PV modules, types of pollution measurement systems, cleaning methods and their analysis.

The importance of surface cleaning of solar PV modules. The accumulation of dust and dirt on the surface of solar PV modules depends on many parameters: the inclination of the PV module installation, the type of glass coating, the roughness of the surface, the external environmental conditions (wind speed, humidity, temperature, air pollution), as well as the geographical location. Biological, electrostatic, and chemical properties of dust, as well as the shape, size, and weight affect dust deposition on the surface of PV modules [3]. Fig. 1 shows the causes of pollution of solar PV modules [4].

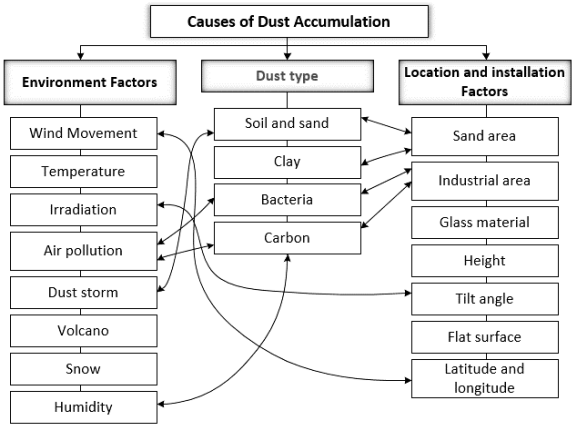

Fig. 1. Causes of dust accumulation on the surface of solar photovoltaic modules

Studies show that the Middle East and North Africa are the areas with the highest dust accumulation in the world [4]. Fig. 2 shows the levels of pollution intensity by regions [5].

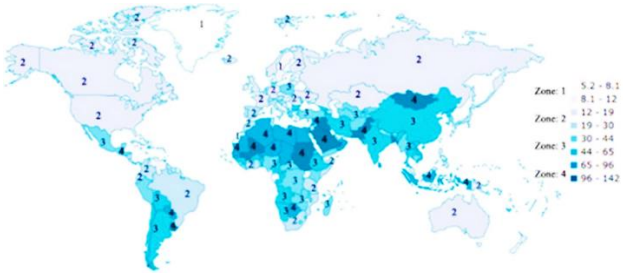

Fig. 2. Dust intensity worldwide

The presence of dust and dirt can reduce the efficiency of solar photovoltaic modules by more than 35% [6]. That is why the process of cleaning the surface of solar PV modules is very important. Cleaning methods of solar PV modules are important for increasing their efficiency and maintaining their durability. The importance of cleaning methods is summarized as follows:

• ***Efficiency increase.*** The implementation of regular cleaning process is an incentive for the maximum efficiency of the modules, potentially increasing their efficiency by 5-35%, depending on the severity of the soiling and environmental conditions [6].

• ***Longevity maintenance.*** Solar PV modules are installed with the expectation of operating for several decades. The presence of dirt and dust on their surface leads to a reduction in the working time. The use of appropriate cleaning methods is an incentive to extend the service life of the modules by up to 10-15 years, as it prevents the degradation and overheating caused by soiling [7].

• ***Economic advantages.*** Regular surface cleaning of solar PV modules can lead to increased financial returns for solar PV plant owners. Studies have shown that clean modules can increase annual energy yield by up to 10%, translating to a significant boost in revenue, particularly for large-scale installations [8].

• ***Impact on the environment.*** Working at the maximum efficiency of clean solar PV modules makes it possible to reduce the need to obtain additional energy from fossil fuels, which in turn contributes to the reduction of greenhouse gas emissions. It is estimated that every megawatt-hour (*MWh*) of electricity generated from clean solar modules can reduce CO_2 emissions by approximately 0.5 to 0.6 metric tons, significantly aiding in the fight against climate change [7,8].

Types of soiling measurement systems for solar PV modules and their comparative analysis. Incorporating the measurement of surface contamination of PV modules as part of the monitoring system is important for the quantitative characterization of efficiency reductions due to dust and dirt. There are two main types of PV module soiling monitoring systems.

1. *Soiling measurement optical systems.* Measurements are carried out on the basis of optical sensors included in the system. The following soiling systems and dust sensors working with this method are known in the world: "DustIQ" soiling monitoring system (Kipp & Zonen company, USA), "MarsTM" soiling measurement sensor (Atonometrics company, USA), "RK210-03" soiling monitoring system (Rika company, China). The main advantages and disadvantages of this type of system and sensors are:

Advantages:

• Real-time monitoring: Optical soiling systems can provide real-time monitoring of pollution levels.

• Convenience for use in large solar PV plants. They can be installed in large solar plants and measure the pollution of modules in several areas at the same time.

• Cost-effectiveness: Compared to other methods, it is cost-effective to use in large solar PV plants.

Disadvantages:

• Accuracy of measurement: A large error in the measurement of pollution

depending on the factors of the external environment. 4-20% error of the soiling ratio, depending on the system used for the measurement [9].

• Initial calibration: For the accurate operation of the sensors in the system, it is necessary to perform a preliminary calibration. During operation, it is necessary to carry out checks and regular calibration in order to maintain the accuracy of the measurement.

2. *Systems of two PV modules.* These systems include two solar PV modules, one of which is cleaned manually or by an automated system before measurement. After cleaning, measurements of the electrical characteristics of the two solar PV modules are carried out. The results of the measurements are compared and the effect of the presence of dust and dirt on the efficiency of the PV module is determined. The following systems working with this method are known: "RDE300i" (Atonometrics company, USA), "DustVue" pollution sensor (Campbell Scientific company, USA), "SEVEN" sensors (USA), "FLIP-SMU" ("Frugal Labs Tech Solutions", India), "ARES" ("Fracsun", USA).

Advantages:

• High accuracy: They provide high accuracy, up to 7% error in contamination ratio [9].

• Advanced data analysis: Measurements of electrical characteristics of PV modules and analysis of these data are performed.

Disadvantages:

• Application in large solar PV plants. Concentrating and measuring at one location does not provide an overview of the pollution of the entire solar PV plant.

• Time consumption: Measurements can be time-consuming, especially for large solar PV plants.

• Risk of module damage. There is a potential risk of damage to the modules during the measurement process, especially if there is physical contact.

Methods of cleaning solar PV modules. The process of cleaning the surface of solar PV modules is performed by different methods. Fig. 3 shows the block diagram of groups of cleaning methods [10].

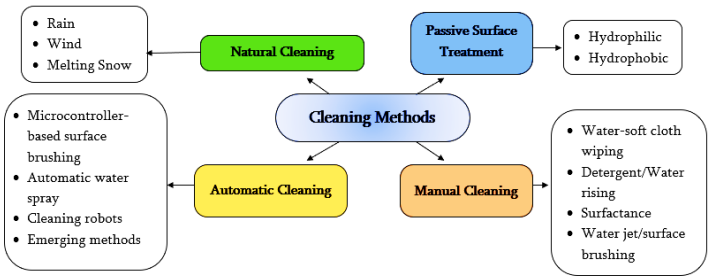

Fig. 3. The solar photovoltaic module surface cleaning methods

The surface cleaning methods of solar PV modules widely used in the world, differing from each other in their advantages and disadvantages, have been considered:

1. ***Natural cleaning.*** The simplest cleaning option is natural cleaning. In this version, the surfaces of the solar PV modules are cleaned by rain, wind and melting snow.

2. ***Manual cleaning***. Manual cleaning involves physical cleaning of the surface of the PV modules using tools such as squeegees, brushes, water and cleaning chemicals (Fig. 4).

Fig. 4. Manual surface cleaning of solar PV modules

The following world-famous organizations are engaged in the production of manual cleaning tools: "UNGER" (Germany), "Tucker" (USA), "LEHMANN" (Germany), "WCW" (Australia) and "SolarGlanzz" (Netherlands).

3. ***Automated cleaning.*** Automated cleaning systems use technologies such as cleaning robots, drones, and automated water systems that perform the cleaning process without human intervention (Fig. 5). These types of cleaners remove dust from the surface of PV modules using a brush, air, water and detergents [11].

Fig. 5. Automated surface cleaning of solar PV modules: cleaning robots, drones and automated water systems

Cleaning robots and drones are widely used mainly in large solar PV plants. Along with the development of technologies, new software and hardware packages of robot systems are being developed, which are based on IOT systems and elements of artificial intelligence [12]. Cleaning robots and drones equipped with the latest technologies also enable monitoring and maintenance services for solar PV modules.

The following companies producing similar robots are known in the world: "hiCLEANER" (Germany), "SolarCleano" (Luxembourg), "CleanSolar Solution" (Great Britain), "Ecoppia" (Israel), "SCM" (Spain) and "Serbot AG". (Switzerland). Drones are widely used in the monitoring and cleaning processes of PV modules. Drone cleaning of solar PV modules has been shown to increase the efficiency by up to 35% and reduce maintenance costs by up to 60% [13].

4. ***Self-cleaning coatings.*** Self-cleaning coatings of PV modules are used to reduce the adhesion of dirt and dust to the surface of the modules. The use of self-cleaning coatings should be based on the specific requirements and conditions of the installation of solar PV modules. A cost-benefit analysis should be performed to determine whether the benefits outweigh the initial investment and maintenance costs.

The table below shows the advantages and disadvantages of the above solar PV module surface cleaning methods [14].

Table

Advantages and disadvantages of surface cleaning methods of solar photovoltaic modules

Cleaning Methods	**Advantages**	**Disadvantages**
1	**2**	**3**
1. Natural cleaning	• Reduction in purchase and labor costs of cleaning systems. • Effective cleaning of large particles of dust and dirt. • The presence of wind and rain reduces the temperature of the solar PV module, which in turn ensures an increase in efficiency.	• Unable to control. • Light precipitation increases dust deposition on the PV module surface. • Dust removal depends on wind direction and speed. • Wind carries dust particles. Light wind can increase the level of contamination on the surface of the PV module.
2. Manual cleaning	• Reliable type of cleaning with human supervision. • It is done periodically according to the required time. • Fully restores the efficiency of PV modules. • If necessary, the cleaning supervisor can take corrective actions during the cleaning process. • Cleaning work can remove all kinds of dust and dirt particles.	• High costs for labor and cleaning tools. • High costs of labor training. • Relatively large consumption of water, which limits the work of this cleaning method in regions with little water. • Risk of falling from high places when cleaning the PV module by hand. • It is impractical in large solar plants and regions with high dust threshold.

Table (continued)

1	2	3
3. Automated cleaning	• Lack of manpower. • Reducing the possibility of damaging the surface of the solar PV module. • Widely found in water-rich and water-scarce regions (dry cleaning robots and automatic systems). • Low energy consumption. • Speed of cleaning.	• High operating and maintenance costs. • Limited applicability in small stations. • Frequent checking of the system is required. • Power is required to operate.
4. Self-cleaning coating	• Maintain the efficiency of the solar PV module by reducing the accumulation of dirt and dust on the surface of the module. • Reducing the frequency of cleaning operations. • They extend the service life of the solar PV module.	• High cost, which can be an obstacle for some owners of PV systems. • Performance may vary depending on environmental conditions. • They decay and wear out over time.

Natural cleaning does not require additional costs, but the effectiveness of this method depends on unpredictable weather conditions. Manual cleaning is reliable but has high labor costs, which in turn limits the application of this method to large solar PV plants. Automated cleaning systems that include automatic recording of dust presence and measurement of contamination levels are a promising way to minimize manual intervention, although there are challenges such as high operating costs and limited applicability in small solar PV plants. Self-cleaning coatings provide a long-term solution to cleaning problems, but initial costs can be a deterrent to choosing this method. Each method has certain advantages and disadvantages, and the choice of cleaning method depends on factors such as the geographical location of the solar PV plant, its size, and the initial cost of cleaning.

Conclusion

1. The types of existing solar photovoltaic module soiling measurement systems and cleaning methods, along with their comparative analysis, are presented.

2. Cleaning the surface of solar photovoltaic modules ensures increased efficiency of the modules, maintenance of longevity of operation, increased income of solar plant owners and positive impact on the environment.

3. The integration of digital technologies and automation in solar photovoltaic module soiling measurement and cleaning systems is a promising development. The analysis carried out in the article highlights the importance of incorporating elements of artificial intelligence, IoT systems, and automation in the further development of

these systems.

4. Valuable insights and comparative analyses are provided, which can be used by researchers, solar energy professionals, and solar plant owners to enhance the efficiency and longevity of photovoltaic installations.

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ԱՐԵՎԱՅԻՆ ՖՈՏՈՎՈԼՏԱՅԻՆ ՄՈԴՈՒԼՆԵՐԻ ԱՂՏՈՏՎԱԾՈՒԹՅԱՆ ՉԱՓՄԱՆ ՀԱՄԱԿԱՐԳԵՐԻ ԵՎ ՄԱՔՐՄԱՆ ՄԵԹՈԴՆԵՐԻ ՎԵՐԼՈՒԾՈՒԹՅՈՒՆ

Ն.Կ. Բադալյան

Արևային էներգիայի ֆոտովոլտային փոխարկիչների արդյունավետության բարձրացումը առաջնային նշանակություն ունի: Այս ուսումնասիրությունը ներկայացնում է ֆոտովոլտային մոդուլների աղտոտվածության չափման համակարգերի և մաքրման մեթոդների համապարփակ վերլուծություն՝ ուղղված դրանց արդյունավետության բարձրացմանը: Հետազոտությունն ընդգծում է փոշու և կեղտի կուտակման զգալի ազդեցությունը ֆոտովոլտային մոդուլների մակերեսի վրա, ինչը կարող է նվազեցնել արդյունավետությունը ավելի քան 35%-ով: Քննարկվել են աղտոտվածության չափման տարբեր համակարգեր, ներառյալ օպտիկական համակարգերը և այն համակարգերը, որոնցում օգտագործվում են զուգակցված ֆոտովոլտային մոդուլներ, ինչպես նաև՝ դրանց առավելություններն ու թերությունները: Վերլուծությունը ներառում է նաև մաքրման տարբեր մեթոդներ, ինչպիսիք են բնական մաքրումը, ձեռքով մաքրումը, ավտոմատ մաքրումը և ինքնամաքրվող ծածկույթները: Յուրաքանչյուր մեթոդի առավելություններն ու թերություններն ուսումնասիրվում են արդյունավետության, արժեքի և կիրառելիության տեսանկյունից: Թվային տեխնոլոգիաների և ավտոմատացման, ներառյալ արհեստական ինտելեկտի և IoT համակարգերի ինտեգրումը համարվում է զարգացման հեռանկարային ուղղություն արևային մոդուլների աղտոտվածության չափման և մաքրման համակարգերի ոլորտում: Այս ուսումնասիրությունը արժեքավոր պատկերացումներ և համեմատական վերլուծության հնարավորություն է տալիս հետազոտողներին, արևային էներգիայի մասնագետներին և արևային կայանների սեփականատերերին ՝ բարձրացնելու համար ֆոտովոլտային կայանքների արդյունավետությունը, երկարակեցությունը և տնտեսական եկամուտը: Մաքրման արդյունավետ մեթոդների և աղտոտվածության չափման առաջադեմ համակարգերի ներդրումը կարող է հանգեցնել արևային մոդուլների արդյունավետության և երկարակեցության զգալի ավելացման, ինչպես նաև բնապահպանական արդյունքների՝ նվազեցնելով հանածո վառելիքից կախվածությունը:

Առանցքային բառեր. ֆոտովոլտային մոդուլ, մաքրման մեթոդ, արդյունավետության բարձրացում, աղտոտվածության չափման համակարգ, թվային տեխնոլոգիաներ, ավտոմատացում:

АНАЛИЗ СИСТЕМ ИЗМЕРЕНИЯ ЗАГРЯЗНЕНИЙ И МЕТОДОВ ОЧИСТКИ СОЛНЕЧНЫХ ФОТОВОЛЬТАИЧЕСКИХ МОДУЛЕЙ

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Повышение эффективности фотовольтаических преобразователей солнечной энергии имеет первостепенное значение. В данном исследовании представлен комплексный анализ систем измерения загрязнения и методов очистки фотовольтаических модулей, направленный на повышение их эффективности. Исследование подчеркивает значительное влияние накопления пыли и грязи на поверхности фотоэлектрических модулей, что может снизить эффективность более чем на 35%. Обсуждаются различные системы измерения загрязнения, включая оптические системы и системы, использующие парные фотовольтаические модули, а также их соответствующие преимущества и недостатки. Анализ также охватывает различные методы очистки, такие как естественная очистка, ручная очистка, автоматическая очистка и самоочищающиеся покрытия. Преимущества и недостатки каждого метода рассматриваются с точки зрения эффективности, стоимости и применимости. Интеграция цифровых технологий и автоматизации, включая системы искусственного интеллекта и IoT, определена как перспективное направление будущего развития в области систем измерения загрязнений и очистки солнечных панелей. Работа предоставляет ценную информацию и сравнительный анализ для исследователей, специалистов по солнечной энергетике и владельцев солнечных электростанций, чтобы повысить эффективность, долговечность и экономическую отдачу фотовольтаических установок. Внедрение эффективных методов очистки и передовых систем измерения загрязнения может привести к значительному повышению эффективности и долговечности солнечных модулей, а также к экологическим преимуществам за счет снижения зависимости от ископаемого топлива.

Ключевые слова: фотовольтаический модуль, метод очистки, повышение эффективности, система измерения загрязненности, цифровые технологии, автоматизация.