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An Improved Electrostatic Cleaning System for Dust Removal from Photovoltaic Panels

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Abstract

A cleaning device has been improved to clean solar panels using the concept of ionic wind to effectively remove accumulated sand dust. The actuator comprises two parallel electrodes (wire and plate) fixed in a rectangular plastic frame. The cleaning mechanism operates by applying a high DC voltage to a wire electrode, while the plate electrode is grounded. In operation, the cleaning device is guided by a vehicle that traverses the entire surface of the solar panel and cleans the plate of sand dust by generating an ionic wind through an opening located at the base of the actuator. Tests have demonstrated the remarkable efficiency of this cleaning system with the "wire-plate" configuration proposed here, achieving a dust removal rate of almost 100% with a wind velocity of around 2.5 m/s, while consuming a minimum of energy. This improved solution could significantly increase the performance and efficiency of solar installations, particularly in regions characterized by high levels of dust and sand, such as desert environments.

Keywords: Ionic wind, Corona discharge, PV panel, Electrostatic cleaning.

1. Introduction

Renewable energies are playing an increasingly important role in our quest for a sustainable energy future. Among these clean energy sources, solar power stands out for its immense potential and positive impact on the environment [1-2]. Photovoltaic solar panels, which convert sunlight into electricity, have become an essential component of our energy infrastructure, offering a promising alternative to traditional energy sources [3].

However, a major challenge facing photovoltaic panels is the accumulation of dust and sand on their surfaces. This accumulation can considerably reduce the efficiency and performance of panels, limiting their ability to generate electricity optimally [4-13]. It is, therefore, crucial to find techniques to mitigate the degree of dust on solar photovoltaic systems [14-15] and then to find effective solutions to keep solar panels clean and ensure their maximum performance.

Various cleaning methods are used to keep photovoltaic panels clean and efficient. Manual cleaning involves using brushes or rags to clean the panel surface, while water-based cleaning uses water spray to remove dirt [16-17]. Automated cleaning uses specially designed devices to clean panels autonomously, while ultrasonic vibration cleaning uses sound waves to dislodge dust. The implementation of these processes is complex and involves moving parts that consume a significant amount of energy [18-24]. The electrostatic cleaning system for photovoltaic panels has been presented as a promising approach that could eliminate the need to use water and prevent damage caused by friction, as it does not require mechanical components in direct contact with the panel.

Among electrostatic dust collection systems, electrodynamic screens (EDS) are the most popular [25-30]. The EDS system uses electric curtain panels to expel dust from the panel surface. EDS application methods involve fabricating transparent interdigitated indium tin oxide microelectrode arrays that are embedded in a dielectric film, or installing insulated copper mesh electrodes on the surface of photovoltaic panels. Another electrostatic cleaning system has been developed, in which dust particles are repelled from the electrodes by charge induction assisted by adsorbed moisture [31]. This system makes it possible to define the electrical potential threshold required to remove particles during dust removal over a wide range of relative humidity.

Various dust-cleaning techniques have been developed to meet this challenge. However, each method has its own specific drawbacks. Manual methods require frequent human intervention and can be costly and time-consuming, particularly for large solar farms. Techniques using water and chemicals can have a negative environmental impact, in addition to consuming precious resources such as water [32]. Automated methods, while potentially effective, can be costly to implement and require a complex infrastructure. Electrostatic methods such as EDS systems show promise but have drawbacks, Moisture ingress into the dielectric film can cause short circuits and failures [33]. In addition, the microfabrication costs of interdigitated electrodes and shading on the panel surface are limitations. The second system, which is based on the electrostatic charge of induction acquired by the particles, has a major drawback in that it requires the use of two high-voltage power supplies with

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opposite polarities, making this complex and costly approach difficult to implement because of the back-and-forth motion required to charge and lift the particles.

The movement of air induced by the electro-hydrodynamic (EHD) principle, known as ionic wind, is a fascinating phenomenon in plasma science. Corona discharge, resulting from the application of a high voltage between pointed electrodes or small-diameter wires and less curved surfaces, causes ions to collide with neutral molecules and move towards a receiving electrode, creating an air movement known as ionic wind [34]. Different electrode configurations, such as needle-cylinder, needle-plate, wire-plate, etc., have been studied by researchers to optimize the velocity of the ionic wind. Among these configurations, the needle-cylinder arrangement and the wire-plate arrangement are widely used due to their ability to generate higher wind velocity with a variation in energy consumption.

In this study, we focus on a new approach to cleaning photovoltaic solar panels filled with sand dust, based on the concept of ionic wind. To optimize wind speed and cleaning efficiency, we used a new wire/plate configuration, with the actuator comprising a wire electrode connected to a high-voltage DC and a grounded steel plate electrode. The cleaning device contains the actuator that generates the ionic wind, guided by a four-wheeled vehicle, two stepper motor-driven wheels for each wheel, and two smaller wheels at the rear of the vehicle to facilitate its movement.

The fundamental properties have been studied and demonstrated for two different wire/rectangle and needle/rectangle configurations [35, 36]. It has been shown that the application of high DC voltage creates an ionic wind to effectively remove sand dust from photovoltaic panels. However, cleaning performance is poor for large quantities of dust. Measures are proposed here to improve the cleaning efficiency of solar panels, especially for large quantities of dust sand, using the new wire/plate configuration, by improving the wind speed to clean larger quantities. This approach has great potential for improving the efficiency and durability of photovoltaic panels, especially in desert environments.

2. System configuration

Figure 1 shows the configuration of the proposed electrostatic cleaning system. The operation of this system is identical to that previously reported (Wire/Plate) [36], as illustrated in Figure 2, but the actuator has a new wire-plate configuration. A high direct voltage is applied to a wire with a diameter of 0.1 mm and a steel plate is grounded. The plate has a length of 400 mm and a variable width "L". The high voltage wire is located above the plate at a distance "d" and it's powered by a high voltage direct current source (Xpower, 40 kV, 15 mA). (Fig. 1).

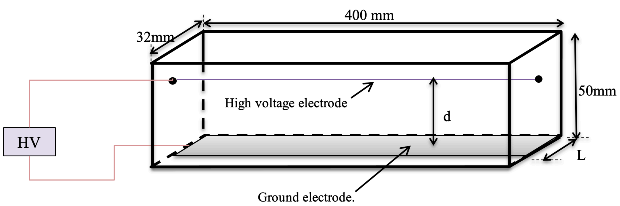

Fig. 1. Electrostatic cleaning system configuration.

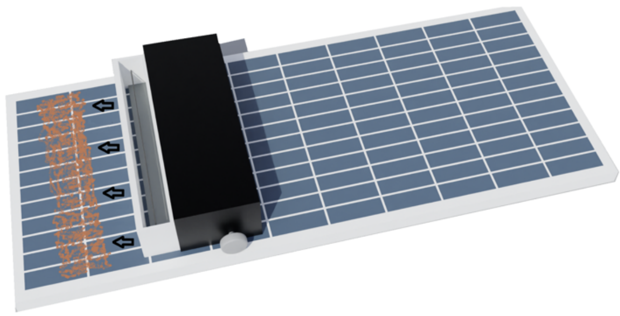

Fig. 2. Ionic wind actuator mounted on PV panel.

The ionic wind resulting from the corona discharge generated by the application of high voltage to an electrostatic actuator passes through the plate and exits through a small variable opening located at the bottom of the actuator along the length of the steel plate. This opening is located directly above the solar panel, where particles near the actuator are ejected by the ionic wind, and sand deposited on the panel is cleaned. The parallelepiped-shaped electrostatic actuator is made of PVC to ensure electrical insulation and fixation of the electrodes. The top opening of the actuator is designed for air intake, and the very small opening at the bottom of the device, at the end of the plate, allows the ionic wind to escape. The width of the electrode plate and the inter-electrode gap between the wire and the plate have been studied in this work, and the tests carried out show the effects of these configurations on wind speed and cleaning efficiency. The actuator is driven by a vehicle containing two stepper motors controlled by an Arduino board and two additional wheels to facilitate the mobility of the device. a quantity of 5g of sand dust was manually deposited through a sieve on a limited area in a rectangular frame of 30x16cm2 on the solar panel.

2.1. Characteristics of power consumption as a function of voltage

The corona discharge was studied by measuring the power consumed as a function of the voltage applied in the negative polarity. A microammeter was used to measure the current generated, and the voltage values were recorded on the display of the high-voltage power supply. The voltage was gradually increased until the breakdown value was reached. This analysis was carried out for different values of inter-electrode gap (d = 20, 30, and 40mm) and plate width (L = 20 and 30mm).

2.2. Wind velocity characteristics as a function of voltage

To measure ionic wind speed, a Benetech GM8903 hot-wire anemometer with a data logger was placed under the actuator, at the opening through which the electric wind escapes. Wind speed was measured for three different electrode spacing configurations (d = 20, 30, and 40 mm) and two different plate width configurations (L = 20 and 30 mm).

2.3. Cleaning characteristics

To carry out the cleaning experiments, three speeds adapted to the movement of the cleaning device were determined (0.273, 0.52, and 0.815 cm/s). The cleaning efficiency was calculated based on the voltage variation with a comparison between two different plate width configurations (L=20 mm and L=30 mm) and for different movement speeds of the cleaning device using the configuration which gives the best wind speed values.

For each test, a considerable amount of estimated sand with an MT mass of 5 g was evenly distributed over a demarcated area of the solar panel measuring 30 x 16 cm2, then the remaining amount of sand in the MR panel was measured and the mass of the sand removed ME from the panel was calculated. The formulas below show the mass Me removed and the cleaning efficiency η:

$$M_E = M_T - M_R \quad (1)$$

$$\eta = \frac{M_E}{M_T} \times 100 \quad (2)$$

3. Results and discussion

3.1. Power consumed characteristic

Figure 3 shows that when the electrode gap increases from 20 to 40 mm, the onset voltage, the breakdown voltage, and the maximum electrical power of the device near the breakdown voltage increase. Finds that the inter-electrode distance influences the electric field intensity between the electrodes which in turn has an effect on the onset voltage, breakdown voltage, and power consumption of the actuator. It is also seen that when the voltage remains constant, the power consumption decreases with increasing spacing because the electrodes' gap charge density decreases.

3.1.1. Effect of the gap between the electrodes on the power consumed

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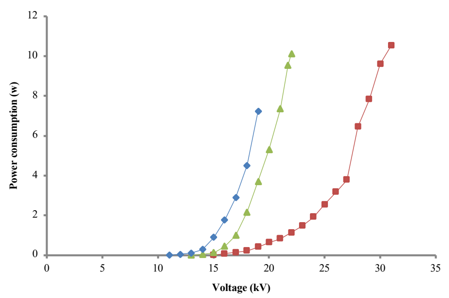


Fig. 3. Power consumption at different electrode gaps wire-plate (d=20, 30 and 40mm)

3.1.2. Effect of plate width on the power consumed

Figure 4 shows the influence of the width of the "plate" of the collecting electrode on the electrical power. This variation in width influences the intensity of the electric field, which in turn has an effect on the power consumed by the actuator. The energy corresponding to the greatest width L = 3 cm is higher than L = 2 cm, This increase in energy is due to the increase in current flowing through the plate, which results in an increase in charge density in space since the ion collection area increases with plate size.

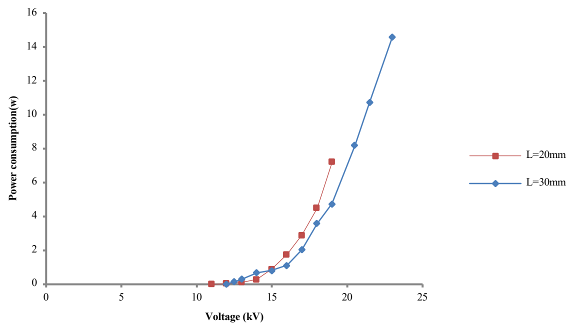


Fig. 4. Power consumption at different plate widths (L=20mm and 30mm).

3.2. Output velocity characteristic

The relationship between ionic wind velocity and generator voltage is summarized in this section, an increase in wind velocity is observed as the voltage increases, due to the enhancement of the electric field. However, this voltage increase cannot be increased infinitely, as it would result in spark discharge when the voltage reaches the breakdown threshold, determined by the structural parameters of the actuator and atmospheric conditions.

3.2.1. Effect of the gap between the electrodes on the velocity of the ionic wind:

Figure 5 shows the tests of the variation in the velocity of the ionic wind for different wire-plate gaps (d=20, 30, and 40 mm) with a plate width of l=20 mm. We note that the velocity of the wind increases when the electric field amplifies with increasing voltage, The optimal gap between the electrodes is the small distance of 20mm which gives a significantly higher ionic wind velocity than d=30mm and d=40mm. If the voltage is kept constant, the wind velocity decreases as the gap between the wire and the plate increases, reflecting the decrease in the charge density of the space, which affects the ionic wind velocity. However, the gap between electrodes affects the electric field strength, which in turn impacts the wind speed of the actuator.

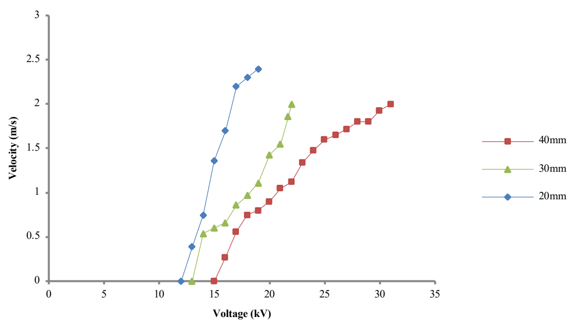


Fig. 5. Variation of wind velocity at different electrode gaps (d=20, 30 and 40mm)

3.2.2. Effect of plate width on ionc wind velocity

This part presents the variation of the electric wind velocity as a function of the voltage for different plate widths. Figure 6 clearly shows the increase in ion wind speed as the plate width increases for a maximum voltage of 22.5 kV which presents the maximum value applied without reaching the breakdown voltage, the wind velocity reaches the value higher by 2.45 m/s when the width of the plate is 30mm. This means that as the plate width increases, the inertia force of the loads becomes higher than small plate widths. This increase in force is due to the greater distance the electrical charges travel, which increases the likelihood of impact on air molecules near the plate. Finally, the best configuration that produces the best wind is that of a width of 30mm.

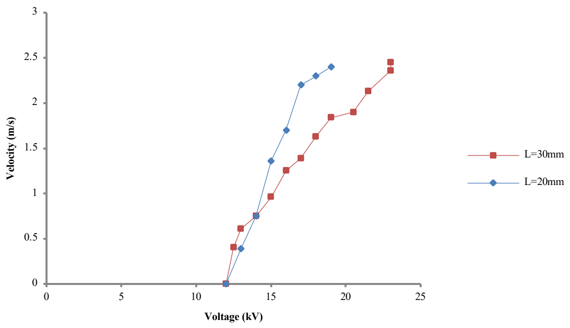


Fig. 6. Variation of wind velocity for different plate widths (L=20mm and 30mm).

3.3. Cleaning efficiency

This section presents the variation of the cleaning efficiency of the solar panel for different voltage levels and two constant movement speeds of the device: 0.273 cm/s and 0.815 cm/s.

Figure 7 shows the cleaning efficiency as a function of the applied voltage obtained by two actuation of the same wire/plate configuration but with different plate widths l=20 mm and l=30 mm. The best cleaning efficiency values were obtained for voltages close to the breakdown voltage. The cleaning efficiency was close to 100% when the plate width was 30 mm, which is maximum, consistent with previous results observed in terms of energy consumed and wind speed. If we take the example of the plate width L = 30 mm, we see that when the maximum voltage is close to the breakdown voltage, the efficiency equal to 98% is higher than that of the plate width d =20mm which is equal to 68%.

From Figure 8, It can also be seen that varying the speed of the cleaning device influences the cleaning efficiency, almost all the best cleaning efficiency results are obtained at the slowest moving speeds. It can be seen that when the operating voltage is near the breakdown voltage which is 24kv, a reduction in movement speed from 0.815 to 0.273 cm/s causes an increase in efficiency from 98 to 99.8% and the same thing if taking another operating voltage of 16 kV we see an increase in efficiency from 21 to 42.8%, The cleaning efficiency decreases as the speed increases due to the decrease in wind energy and of the inertia of the sand particles. Therefore, more dust is moved at a lower speed, which is why the best cleaning results are achieved at the slowest speed which is 0.273 cm/s.

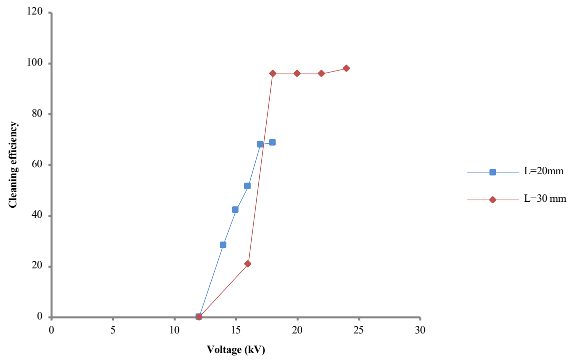


Fig. 7. Variation of cleaning efficiency as a function of voltage for different plate widths (L=20 mm and 30 mm).

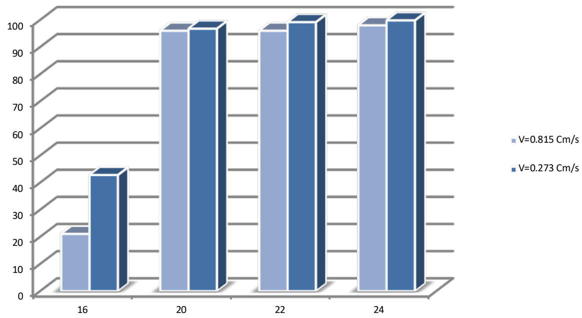
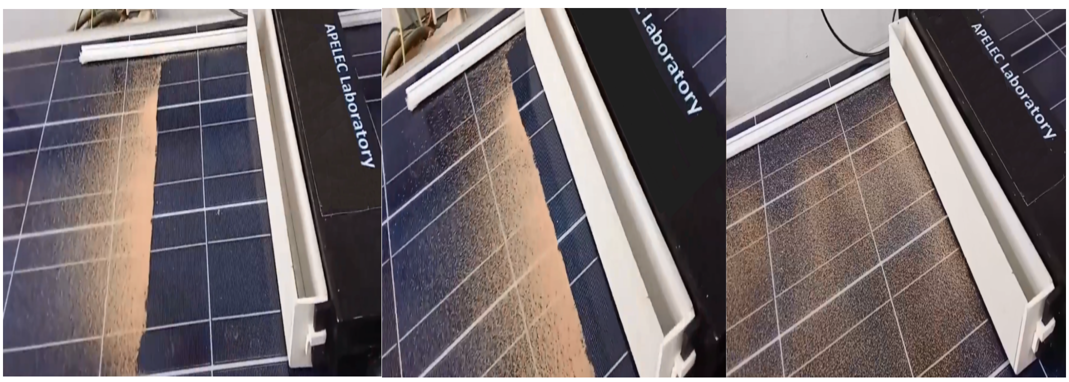


Fig. 8. Device cleaning efficiency for two displacement speeds as a function of voltage for L=30mm

The images in Fig. 9, taken at two points in time, before and after cleaning the solar panel, show that after this operation, the cleaning process appears to be distributed evenly over the entire panel surface. Compared with conventional methods, the ionic wind cleaning method based on corona discharge offers the advantage of low power consumption, requiring only around 14 watts at most to clean a solar panel.



(a) (b) (c)

Fig. 9. Photovoltaic panel cleaning, (a) cleaning device before cleaning, (b) cleaning device after cleaning.

The cleaning process studied in this manuscript, which harnesses the ionic wind generated by the corona discharge, offers several advantages over other methods for cleaning PV panels. It stands out for its low energy consumption, typically around 15 W for cleaning a 1-meter panel. Moreover, this method allows cleaning without physical contact with the solar panel. This cleaning process provides another significant advantage, particularly in the absence of the need for water, a particularly advantageous feature in arid environments where water resources are limited. Additionally, thanks to the Electro Hydrodynamic (EHD) technology created by the corona discharge phenomenon to induce airflow, our cleaning device has superior potential to surpass the limitations associated with mechanical fans. It offers various advantages, including the absence of moving parts, silent functionality, diverse design options, good performance, easy maintenance, and the ability to generate a significant volume of airflow.

However, certain potential limitations of the electrostatic cleaning system with ionic wind must also be taken into consideration. It is imperative to conduct tests in real conditions, especially in high-humidity regions, to ensure the effectiveness of the cleaning process. It is important to note that this study was based on a laboratory prototype, i.e., the cleaning of a single photovoltaic panel, emphasizing the need for further research to assess the device's reliability when deployed in large solar power plants over an extended period. Optimization of the device's geometric configuration can improve its performance by generating wind speeds exceeding 2.5 m/s.

It is also essential to conduct a techno-economic analysis to compare this method with other commonly used cleaning systems. A significant challenge associated with this technique lies in the need for high-voltage power to generate the corona discharge which must be powerful enough to generate the necessary wind while being lightweight and compact for easy transportation and attachment to the actuator.

Furthermore, regular cleaning of the corona electrodes is essential to ensure the efficiency of the corona discharge and electric wind. Sand dust particles typically accumulate on the actuator plate connected to the ground, making this maintenance step crucial for maintaining optimal performance. Additionally, selecting suitable materials in the construction of our device is crucial to ensure resistance to corrosion due to ozone. For example, electrodes can be made from stainless steel, while plastic frames can be made from a polymer like PVC. However, the impact of this corrosion seems negligible under operational conditions.

Photovoltaic panels, usually installed in open spaces, facilitate the rapid dispersion of any produced ozone, which decomposes due to reactions with other chemical species in the air. The constant movement of air limits the residence time of ozone, thereby preventing its accumulation. Moreover, the cleaning device operates for short periods, maintaining a relatively low average ozone concentration. To address concerns about potential damage to the PV module from the corona discharge actuator, the electric charges generated by the corona discharge do not come into contact with the PV module but are directed to the ground via the grounding electrode. Additionally, this electrode acts as an electrostatic shield, preventing any impact of the electric field on the PV panel. To ensure a comprehensive comparison with other methods, we have included the electrostatic cleaning method based on the ionic wind in the referenced comparison table [5].

Table 1. Cleaning Methods Comparison

Method	**Manual**	**Automatic**			**Coating method**		**Electrostatic method**
	Washing & brushing	**Water Spray Machine**	**Static Robotic Cleaning**	**Portable Robotic Cleaning**	**Superhydrophilic coating**	**Superhydrophobic coating**	**Ionic Wind Cleaning**
Operational Cost	High	Medium	Low	Low	Low	Low	Medium
CO2 Emissions	Medium	Medium	Low	Nil	Low	Low	Nil
Labor costs	High	Low	Nil	Nil	Low	Low	Low
Water wastage	High	High	Medium	Low	Low	Low	Nil
Air pollution	Medium	Medium	Medium	Medium	Low	Low	Low
Fuel consumption	High	High	Low	Low	Low	Low	Nil
Human safety	Low	High	High	High	High	High	High
Major Advantage	Reliable	Sustainable and require almost no human intervention			Easier method to remove dust, especially for titled PV’s		- Clean without making any physical contact with the panel surface - Low power consumption - Does Not involve the use of water
Major Disadvantage	Slow and labor intensive	High costs of maintenance			Reduced electrical efficiency due to reduced solar irradiance absorption		The high voltage power supply required for crown discharge must be compact and lightweight to be attached to the actuator and transported easily

4. Conclusion

A cleaning device designed to remove accumulated sand dust from solar panels using ionic wind has been developed. This new configuration has not only been conceptualized but has also yielded exceptionally effective results. High performance is achieved by applying a high-voltage direct current with negative polarity to a device consisting of a wire electrode connected to a high-voltage direct current source and a grounded plate electrode.

Measurements carried out using this method have resulted in an improved wire-plate configuration with an inter-electrode gap of 20mm, producing ionic wind velocity of up to 2.45 m/s. Consequently, this enhancement has driven the cleaning efficiency to approach nearly 100%, all accomplished in a single pass of the cleaning device on the photovoltaic panel.

The adoption of this electrostatic method provides an ingenious solution to the specific challenges faced in desert regions, where water is often a scarce and precious resource. In contrast, electrostatic technology eliminates the need for water, which is a significant environmental advantage in these arid areas. Furthermore, the use of mechanical components for traditional cleaning carries the risk of creating cracks or damaging the solar panels, potentially leading to a decrease in their long-term efficiency. The combination of environmental sustainability and operational efficiency makes this technology an ideal solution for the future of solar power plants. To improve this device, it is recommended to explore other configurations capable of achieving 100% cleaning efficiency in a single operation of the cleaning device. Furthermore, to achieve successful integration of the suggested cleaning equipment within large solar power plants, it will be essential to integrate a robotic system capable of automatically performing a complete sweep of all solar panels. This robotic system is of crucial importance in optimizing the cleaning process and ensuring comprehensive and efficient coverage of the solar panel fields.

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