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ADVANCEMENTS IN SOLAR PANEL MAINTENANCE: A REVIEW OF IOT-INTEGRATED AUTOMATIC DUST CLEANING SYSTEMS

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Abstract. *This study aims to develop an IoT-integrated automatic dust cleaning device tailored for solar panels to enhance their performance and longevity. The cleaning process combines dry and wet cleaning techniques to effectively clean solar panels in a single line. First, dry cleaning methods such as brushes are used to remove loose debris like dust, leaves, and bird droppings. Then, wet cleaning is applied using a vinegar with mild detergent solution to remove stubborn stains and dirt buildup. This combination ensures thorough cleaning while minimizing water usage and environmental impact. The developed IoT-integrated automatic dust cleaning device effectively mitigates the negative impact of dust accumulation on solar panel performance. When compared to the characteristics of the clean module, the short circuit current (ISC) and output power of the photovoltaic solar modules with dust accumulation on their surface are reduced. For a day, a week, and a month of panel exposure to dust, the average deprivation rates of the solar modules' efficiency exposed to dust are 7.32%, 10.78%, and 14.52%, respectively. Experimental results demonstrate significant improvements in energy output and operational efficiency of in average of 12.37%, following the implementation of this cleaning system. This system shows good solution to analyze the solar panel performance and to optimize it. This study presents a novel approach by integrating IoT technology into automatic dust cleaning devices for solar panels, enabling proactive maintenance and remote monitoring capabilities. It offers both dry and wet cleaning methods consequently for having optimized output. The innovative design contributing to the sustainability of solar energy systems with low cost for the users and provides remote accessing of data from anywhere in the world through cloud server. It is cost effective solution for the solar farm maintenance and helps in reducing the frequent manual interventions.*

Keywords: IoT, automatic cleaning, dust removal, solar panels, renewable energy

ROZWÓJ W KONSERWACJI PANELI SŁONECZNYCH: PRZEGLĄD SYSTEMÓW AUTOMATYCZNEGO CZYSZCZENIA Z KURZU OPARTYCH NA INTERNECIE RZECZY

Streszczenie. *Celem tego badania jest opracowanie zintegrowanego z IoT urządzenia do automatycznego czyszczenia kurzu dostosowanego do paneli słonecznych w celu zwiększenia ich wydajności i trwałości. Proces czyszczenia łączy techniki czyszczenia na sucho i na mokro, aby skutecznie czyścić panele słoneczne w jednym kroku. Najpierw stosuje się metody czyszczenia na sucho, takie jak szczotki, aby usunąć luźne zanieczyszczenia, jak kurz, liście i ptasie odchody. Następnie stosuje się czyszczenie na mokro przy użyciu octu z łagodnym roztworem detergentu, aby usunąć uporczywe plamy i nagromadzony brud. Ta kombinacja zapewnia dokładne czyszczenie przy jednoczesnym zminimalizowaniu zużycia wody i wpływu na środowisko. Opracowane zintegrowane z IoT automatyczne urządzenie do czyszczenia kurzu skutecznie łagodzi negatywny wpływ gromadzenia się kurzu na wydajność paneli słonecznych. W porównaniu z charakterystyką czystego modułu, prąd zwarciowy (ISC) i moc wyjściowa modułów fotowoltaicznych z nagromadzonym na ich powierzchni kurzem są zmniejszone. W przypadku dnia, tygodnia i miesiąca narażenia panelu na kurz średnie wskaźniki utraty wydajności modułów słonecznych narażonych na kurz wynoszą odpowiednio 7,32%, 10,78% i 14,52%. Wyniki eksperymentów wykazują znaczną poprawę wydajności energetycznej i sprawności operacyjnej wynoszącą średnio 12,37% po wdrożeniu tego systemu czyszczącego. System ten stanowi dobre rozwiązanie do analizy wydajności paneli słonecznych i jej optymalizacji. W niniejszym badaniu przedstawiono nowatorskie podejście poprzez integrację technologii IoT z urządzeniami do automatycznego czyszczenia paneli słonecznych, umożliwiając proaktywną konserwację i możliwości zdalnego monitorowania. Oferuje on zarówno metody czyszczenia na sucho, jak i na mokro, co pozwala na zoptymalizowanie wydajności. Innowacyjna konstrukcja przyczynia się do zrównoważonego rozwoju systemów energii słonecznej przy niskich kosztach dla użytkowników i zapewnia zdalny dostęp do danych z dowolnego miejsca na świecie za pośrednictwem serwera w chmurze. Jest to opłacalne rozwiązanie do konserwacji farmy słonecznej i pomaga w ograniczeniu częstych ręcznych interwencji.*

Słowa kluczowe: IoT, automatyczne czyszczenie, usuwanie kurzu, panele słoneczne, energia odnawialna

Introduction

Solar energy has emerged as a pivotal solution in the quest for sustainable energy sources, offering abundant potential to meet the escalating global energy demand while mitigating environmental concerns. The significant growth of solar energy capacity over the last nine years, increasing by 30 times to reach 82.63 GW by April 2024, underscores India's commitment to renewable energy development. With India's solar energy potential estimated at 748 GWp by the National Institute of Solar Energy (NISE), there remains ample opportunity to further harness this abundant and sustainable energy source to meet the nation's growing electricity demand and achieve energy security.

In India, the proliferation of solar farms has been a cornerstone of the nation's renewable energy ambitions. With vast expanses of land and abundant sunlight, India's potential for solar energy generation is immense. However, the successful erection and operation of solar farms are not without challenges, particularly in arid and dusty regions. One of the most significant hurdles faced by solar farm operators is the accumulation of dust on photovoltaic (PV) panels. Dust accumulation can significantly reduce the efficiency of solar panels, diminishing energy output and hampering the economic viability of solar farms. In regions like Rajasthan and Gujarat, where solar irradiance is high but dust deposition is rampant, addressing this challenge is crucial for the sustained performance of solar installations.

Efficient dust cleaning mechanisms are essential to mitigate the impact of dust accumulation on solar panels. Traditional cleaning methods, such as manual or mechanical cleaning, are labor-intensive, time-consuming, and often impractical for large-scale solar farms. Moreover, excessive water usage in cleaning processes can exacerbate water scarcity issues, particularly in water-stressed regions. Thus, there is a pressing need for innovative dust cleaning solutions tailored to the unique requirements of solar installations in India. Emerging technologies, including automated robotic cleaners and waterless cleaning systems, offer promising alternatives that not only enhance cleaning efficacy but also minimize water consumption and operational costs. Addressing dust cleaning challenges is paramount to unlocking the full potential of solar energy in India, advancing the country's transition towards a sustainable and resilient energy future.

In the open literature, extensive research has been conducted on the design and implementation of solar panel cleaning systems, ranging from manual methods to semi-automated and fully automated solutions. Traditional approaches often involve periodic manual cleaning, which is labor-intensive, time-consuming, and not always feasible in remote or expansive solar installations. Semi-automated systems, such as robotic cleaners, have been proposed to alleviate some of these challenges but are often limited in their effectiveness and scalability.

A noticeable gap in the existing research pertains to the integration of Internet of Things (IoT) technology into solar panel maintenance systems. While IoT has revolutionized various industries by enabling real-time monitoring, data analytics, and remote control, its application in solar panel maintenance remains relatively underexplored. By leveraging IoT, it becomes possible to develop intelligent, autonomous dust cleaning systems that can dynamically adapt to environmental conditions, optimize cleaning schedules, and minimize energy losses due to dust accumulation. The researches carried in dust mitigation with IoT are as follows,

The study by Waqas et al. (2020) delves into soiling losses in PV modules and proposes a cost-effective cleaning system. It offers insights on mitigating efficiency reduction due to dirt accumulation, crucial for maximizing solar energy generation [14]. Manju, Bari, and Pavan (2018) present an automatic solar panel cleaning system in their study. Their work addresses the need for efficient maintenance solutions to enhance solar panel performance. The system offers automation for regular cleaning, potentially improving energy output and reducing manual labor [10].

Abdolahzadeh, Mofrad, and Tayebi (2023) conduct numerical simulations of dust deposition on the rooftops of photovoltaic parking lots supporting electric vehicle charging. The research provides insights into the impact of dust accumulation on solar panels in such environments. This study contributes valuable knowledge for optimizing maintenance strategies and maximizing energy generation efficiency in integrated PV parking systems [1]. Amirov and Zatsarinnaya (2021) present an automated system for cleaning solar panels utilizing a linear actuator. Their study offers a novel approach to enhancing solar panel maintenance efficiency. By integrating a linear actuator, the system aims to optimize cleaning procedures, potentially increasing energy output and reducing manual intervention [3].

Guarav et al. (2022) propose a solar panel cleaner designed for desert environments, utilizing a combination of a vibrator and air blower. Their study addresses the specific challenges of cleaning solar panels in desert locations. The innovative design aims to efficiently remove dust and debris, ensuring optimal performance of solar panels in harsh environmental conditions [6]. Hasan and Dincer (2020) introduce a novel performance assessment methodology tailored for offshore applications of bifacial photovoltaic solar panels. The study offers insights into optimizing the efficiency and effectiveness of these panels in offshore environments. The research contributes valuable insights into maximizing energy generation potential from bifacial PV systems in marine settings [8].

Dhanalakshmi et al. (2021) presents a solar panel cleaning robot incorporating wireless communication technology. The research focuses on enhancing cleaning efficiency through remote control and monitoring. The study offers a technological solution for maintaining solar panels, potentially improving energy output and reducing manual labor [5]. Vaghani et al. (2019) introduces an automated solar panel cleaning system leveraging IoT technology. The research emphasizes the integration of IoT for remote monitoring and control. The system aims to enhance cleaning efficiency, potentially increasing solar panel performance and longevity [12].

Khadka et al. (2020) present a smart solar photovoltaic panel cleaning system. The system offers intelligent cleaning capabilities, likely utilizing automated features for efficient maintenance. This research contributes to optimizing solar panel performance through advanced cleaning technology [9]. Vinith et al. (2023) introduce an IoT-based smart and automated solar panel cleaning system. The innovative approach integrates IoT technology to enable remote monitoring and control of cleaning operations. This system offers potential advancements in efficiency and maintenance of solar panel installations [13].

Zatsarinnaya, Amirov, and Elaev (2020) present a solar panel cleaning system utilizing the Arduino microcontroller. Their innovative approach integrates Arduino technology for efficient cleaning operations [15]. This research contributes to enhancing solar panel maintenance and performance through automated systems [15]. Al-Badra, Abd-Elhady, and Kandil (2020) propose a novel technique for cleaning PV panels integrating antistatic coating and a mechanical vibrator. The method aims to enhance cleaning efficiency and reduce dust accumulation. This research offers a promising approach to maintaining optimal performance of solar panels by mitigating the impact of dirt and debris [2].

Moharram, Abd-Elhady, Kandil, and El-Sherif (2013) investigate the impact of cleaning PV panels with water and surfactants on performance. The study examines cleaning methods' efficacy in maintaining panel efficiency. The research provides insights into optimizing cleaning strategies to enhance photovoltaic system performance [11]. Khalid et al. (2023) conduct an extensive survey on dust accumulation and aggregation on PV panels, exploring impacts, mathematical models, cleaning mechanisms, and sustainable solutions. The research offers comprehensive insights into addressing challenges associated with dust accumulation on solar panels. This study contributes valuable knowledge towards optimizing cleaning strategies and promoting sustainable maintenance practices for photovoltaic systems [7].

Biswas, Bhuyan, and Hassan (2023) propose an IoT-based automated solar panel cleaning and monitoring technique. The study presents an innovative approach to streamline cleaning operations while facilitating remote monitoring. This research contributes to enhancing the efficiency and longevity of solar panel systems through advanced automation and monitoring technology [4].

These studies collectively explore various innovative techniques and technologies for optimizing the maintenance and performance of solar panels. From IoT-based automated systems to novel cleaning methods utilizing mechanical vibrators and antistatic coatings, researchers aim to enhance efficiency and reduce manual labor. Insights into cleaning strategies, performance assessment methodologies, and the impacts of dust accumulation contribute to advancing the sustainability and effectiveness of photovoltaic systems. Through the above review, it is clear that IoT-integrated automatic dust cleaning systems paves the way for the development of more efficient and cost effective sustainable solar energy solutions. It also offers remote monitoring and control capabilities, enhancing efficiency and reducing manual intervention. They enable real-time data collection and analysis, leading to optimized performance, predictive maintenance, and resource conservation.

While the review covers various cleaning techniques and technologies, it doesn't explicitly mention the simultaneous use of dry and wet-cleaning methods. However, it's possible that combining these methods could potentially offer optimized performance in solar energy efficiency. Wet cleaning can effectively remove stubborn dirt and grime, while dry cleaning methods like mechanical vibration can help prevent water streaks and residue. Implementing a hybrid approach may offer benefits such as thorough cleaning and reduced water usage, but specific studies or implementations focusing on this combination may not be explicitly discussed in the review. This paper focuses on the above challenge with integration of IoT.

1. Materials and methods for proposed system

The automatic cleaning system depicted in Fig. 1 incorporates crucial components such as the Solar Panel, Light Dependent Resistor (LDR), Voltage Sensor, Wi-Fi Module, Arduino, LCD Display, Relays, Water Pump, and Wiper Motor. The Voltage Sensor plays a pivotal role by continually monitoring the solar panel's output voltage, transmitting this data to the Arduino board for analysis. When the Voltage Sensor detects a decline in voltage due to dust accumulation, the Arduino activates the Wiper Motor to efficiently remove the accumulated dust particles from the panel's surface. This proactive approach ensures the solar panel's optimal performance by maintaining its cleanliness.

Moreover, the system's efficiency is further enhanced by employing dry cleaning methods, followed by water or chemical solutions. Dry cleaning mechanisms are effective in loosening and dislodging dust particles, while subsequent water or chemical solutions provide thorough cleaning, ensuring maximum light absorption by the solar panel. Vinegar is effective for breaking down dirt and grime, while the detergent helps to lift away any stubborn residues. Mixing it with water makes it safe for use on solar panels without causing damage. Traditional methods follow only with dry cleaning method but in this work by integrating these cleaning techniques, the system not only maintains peak performance but also extends the operational lifespan of the solar panels.

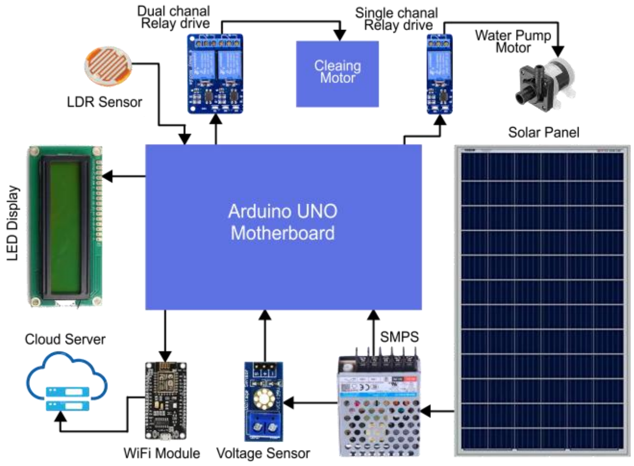


Fig. 1. Proposed PV dust mitigation system

Additionally, the inclusion of a Wi-Fi Module facilitates real-time data transmission and remote monitoring, enabling operators to monitor the system's performance and cleanliness status from a centralized location. The LCD Display provides intuitive visual feedback, presenting critical information such as cleaning schedules, system diagnostics, and operational status. Relays serve as the interface between the Arduino board and external devices, enabling precise control over the Water Pump and Wiper Motor's operation. This modular design allows for scalability and adaptability, accommodating varying solar panel configurations and environmental conditions.

2. Results and discussion

Hardware setup

In the laboratory environment, a prototype model has been developed to validate the practical applicability of the proposed system and the details of the dust migration system is given in Table 1. The prototype employs a Solar panel of Polycrystalline, 500/m^2 solar radiation with 30° inclination, with an output voltage of 18 V, serving as the basis for testing and evaluation. Figure 2 illustrates the experimental setup, showcasing the arrangement for assessing the system's performance. This dust mitigation system, designed for practical testing, incorporates a dust-cleaning handle controlled by the Arduino UNO microcontroller, a wiper motor for operating the handle, a cloud storage system connected with IoT. During the experimental phase, the prototype undergoes testing under two distinct conditions to evaluate its performance across varying scenarios. Throughout these tests, voltage measurements are continuously monitored to assess the system's response to dust accumulation and subsequent cleaning actions. By systematically observing voltage variations before and after the cleaning process, the effectiveness of the proposed system in mitigating the impact of dust on solar panel performance can be quantified.

Utilizing a dry-cleaning method, the system aims to effectively remove accumulated dust from the solar panel surface. Utilizing a wet cleaning process, a tube connected to a cleaning brush uniformly disperses the cleaning solution from top to bottom, ensuring comprehensive panel cleaning. This method facilitates efficient distribution of the cleaning agent, aiding in the removal of dirt and debris, thus enhancing the overall performance and longevity of solar panels.

In this setup, photodiodes and LDR (Light Dependent Resistors) are strategically positioned at the top of the solar platform to optimize sunlight detection. When these sensors detect maximum light intensity, the resistance of the photodiode significantly decreases, signaling a "0" signal to the microcontroller. This indication prompts the wipe motor to remain in an "OFF" state, ensuring that the cleaning mechanism is not activated when sunlight exposure is at its peak.

By integrating these sensors, the system efficiently regulates cleaning actions based on real-time sunlight conditions, maximizing solar panel efficiency while minimizing unnecessary cleaning operations.

Table 1. Details of the solar panel dust mitigation system

Item required	Specifications
Wiper motor	Voltage: 12 V/24 V Power: 180 W HighSpeed: 35 A, 5 rpm High Current: 3.0 A Make: Liancheng Auto Parts
Water pump	Operating Voltage DC 3V to 12 V Flow Rate : 80 ~ 120 L/H Maximum Lift : 40 ~ 110 mm Continuous Working Life: 500 hours Make: E-TRONIC
LCD	Alphanumeric: 16x4
Relays	Voltage/Current: 5 V/5 A
Electronic scale	Tata 1 mg
Digital anemometer	Wind Temperature Range: -10 – 45°C (14 – 113 F) Storage Temperature: -40 – 60°C Wind Speed Range: 0 – 30 m/s Air Velocity: Range: 0 – 30 m/s Make : ADEPT
Hygrometer	Digital thermo hygrometer (Model No. HV-1) HOVERLABS Temperature range: -10 – 50ºC (14 –122 F) Humidity range: 10% – 99% RH Resolution: temperature: 0.1 (0.1), humidity: 1% RH
Temperature sensor	MSPT-10, Voltage: 12 to 24 VDC MSPT-100: 4 to 20 mA Sensor Type: Pt100 (100 Ω @ 0°C), thin film Class A

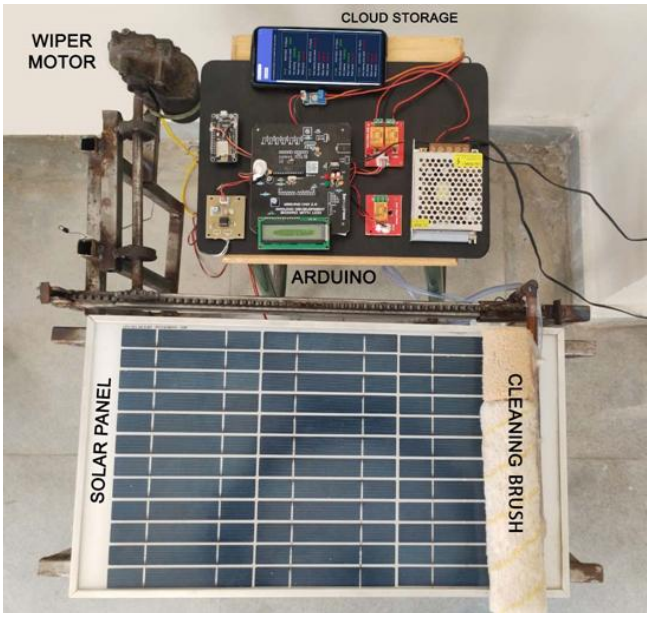


Fig. 2. IoT-Based experimental setup for solar panel cleaning system

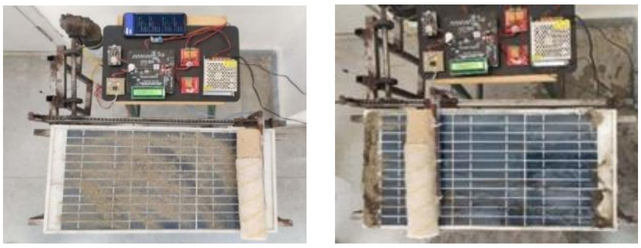
Observed results

In scenarios where the photodiode detects minimal light, the system activates the motor, prompting the platform to rotate and locate areas with optimal light exposure. Figure 3 illustrates numerous test scenarios conducted to assess the effectiveness of the IoT-based PV cleaning system, encompassing various conditions as depicted in Figure 3. Voltage measurements are taken before and after cleaning in each scenario, covering light sand with dry and wet conditions (Case 1 and 2), as well as heavy sand with dry and wet conditions (Case 3 and 4). The observed data reveals notable voltage increases: from 9.4 V to 11.9 V, 7.5 V to 10.4 V, 6.1 V to 11.2 V, and 5.6 V to 10.4 V, respectively, following the completion of panel cleaning operations in each test case.

(a) Normal condition – obtained output voltage 14.9 V

Output voltage 9.4 V Output voltage 11.9 V

(b) Case 1. Light sand with dry condition



Output voltage 7.5 V Output voltage 10.4 V

(c) Case 2. Light sand with wet condition

Output voltage 6.1 V Output voltage 11.2 V

(d) Case 3. Heavy sand with dry condition

Output voltage 5.6 V Output voltage 10.4 V

(e) Case 4. Heavy sand with wet condition

Fig. 3. Various test conditions of dust mitigation system

Following the dry-cleaning process, the wet cleaning phase commences uniformly across all scenarios. Activating the water pump initiates the spraying of the cleaning solution through the brush's perforations, ensuring a thorough cleaning of the panel surface. This wet cleaning procedure consistently yields superior panel output compared to dry cleaning alone, underscoring its efficacy in maintaining panel efficiency. In Case 1, the voltage is improved from 11.9 V to 14.4 V, in Case 2, the voltage is improved to 13.9 V, similarly in Case 3 and Case 4 as 13.45 V and 12.89 V respectively. These cases are observed for testing the performance a certain period. But, the tidy storm occasions that happened amid the measurements' period, the Current-Voltage (I-V) characteristics for PV systems can be observed as a day, for a week and for monthly operation within the over exposed sand/soil influenced environment Table 2–4 gives the details of daily, weekly and monthly measurement data taken from the solar panel. For each period inspected, the soiled PV module, which has been revealed straightforwardly to weather conditions for the complete period, and another similar set is made at the research lab to constant radiation rise to up to 500 W/m^2 and consistent temperature up to 27°C, utilizing the light source from SciSun-AM1.5G solar simulator.

Table 2. Daily measurements of a PV panel

Parameter	PV module without dust	PV module with dust
Measured mean dust density (mg/m^3)		0.612
Open circuit voltage – Voc(V)	18.52	18.21
Short circuit current – Isc(A)	2.34	2.20
VMPPT (V)	14.12	14.34
I MPPT (A)	2.12	1.54
Efficiency (η) %	11.22	10.51

Table 3. Weekly measurements of a PV panel

Parameter	PV module without dust	PV module with dust
Measured mean dust density (mg/m^3)		0.054
Open circuit voltage – Voc(V)	18.41	18.35
Short circuit current – Isc(A)	2.30	2.05
VMPPT (V)	14.12	14.48
I MPPT (A)	2.10	1.36
Efficiency (η) %	11.22	10.42

Table 4. Monthly measurements of a PV panel

Parameter	PV module without dust	PV module with dust
Measured mean dust density (mg/m^3)		0.021
Open circuit voltage – Voc(V)	18.50	18.10
Short circuit current – Isc(A)	2.30	1.78
VMPPT (V)	14.0	14.52
I MPPT (A)	1.92	1.23
Efficiency (η) %	11.14	9.61

The data shows a significant drop in current. This is likely caused by dust blocking sunlight. Fewer photons reach the panel, directly reducing the photocurrent generation. The data also shows a worsening effect from dust storms (Table 2-4). Here, V_{MPPT} and I_{MPPT} is the maximum power point Voltage and Current of solar panel respectively. Solar panels exposed for a day has a 5.9% current decrease, while those left outside for a month experience a much larger 15.5% drop. These results are further explained in the Figure. 4-6, with dust and without dust environments and it shows the improvement in cleaned PV panel compared with dusty panel. By using the proposed method of cleaning, the panel are cleaned and measurements are made and depicted. This method of cleaning system optimizes the solar power generation improved compared to other traditional system as it only has dry or wet cleaning system. The data related to the cleaning process are maintained in IoT cloud server and it is explained in the next section.

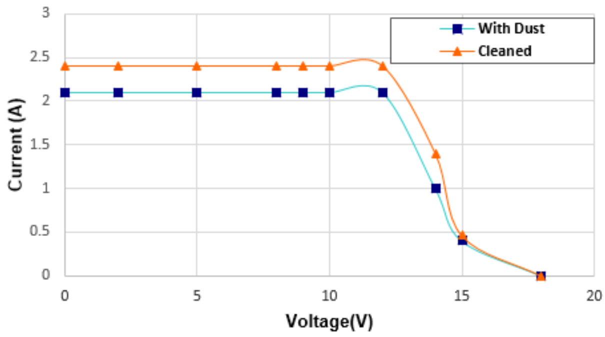


Fig. 4. I-V characteristics of PV panel with dust for daily measurements

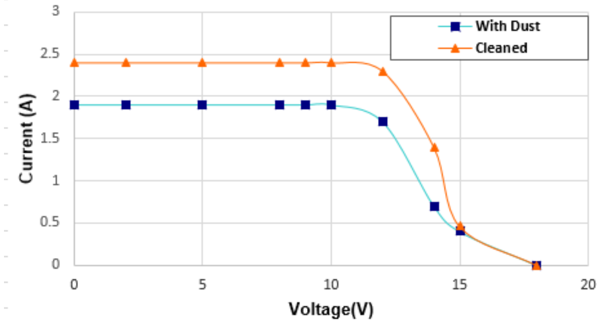


Fig. 5. I-V characteristics of PV panel with dust for weekly measurements

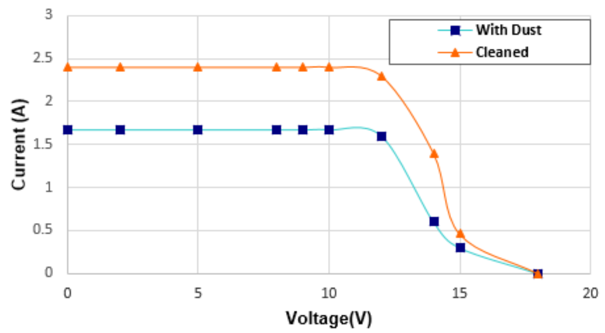


Fig. 6. I-V characteristics of PV panel with dust for monthly measurements

Table 5. Comparison of cleaning methods and components usage in dust mitigation methods

Parameter	Proposed cleaning system	Existing method of cleaning system
Sensors	LDR	LDR/WSN
Microcontroller	Arduino UNO	Arduino UNO
Display	LCD	LCD
Usage of IoT	Yes	Yes
Method of cleaning	Dry(Brush) and Wet (Vinegar + Water+ Detergent)	Either Water or Air flow
Requirement of cleaning (Frequency / month)	2 Times	4 Times
Maintenance frequency (Recommended)	After 2 Week of cleaning	Weekly
Cost (Based on the components usage)	Rs.3725 (Indian Rupees)	BDT3555(Bangladesh Currency)

Table 6. Analysis of the proposed IoT based cost effective cleaning system

Parameters examined	Solar Panel with dust	Solar Panel with the proposed IoT based cleaning system	Deviation
	Efficiency (η) %		
Daily exposure to dust	10.51	22.45	11.94%
Week exposure to dust	10.42	23.88	13.46%
Month exposure to dust	9.61	21.33	11.72%
Average enhancement of efficiency (η)			12.37%

Table 5 confirms that the proposed cleaning method yields optimized output from solar panels compared to existing methods. It shows the cos- effective and maintenance less operation of solar farms. By integrating both dry and wet cleaning, utilizing brushes with a vinegar solution, it ensures thorough cleaning. This approach presents an added advantage over traditional methods, which often rely solely on dry or wet cleaning processes. By combining these techniques, the proposed method achieves superior panel cleanliness, potentially leading to enhanced energy generation and prolonged panel lifespan. Table 6 depicts the efficiency comparison of the experimental test conditions with and without the proposed dust cleaning system. The average efficiency improvement observed is 12.37% for the three test conditions of a day, a week and a month dust exposure of panel.

Cloud storage of observed data

In this work, an IoT cloud storage system serves as a vital communication tool, providing customers with real-time updates on the cleaning process of solar panels. The user interface developed for this purpose, offering live data monitoring of the solar panel's condition. The page presents comprehensive information, including the status of the solar panel before and after the cleaning process, alongside details such as the time of cleaning initiation and the method utilized for cleaning. Additionally, the page displays the voltage generation following the cleaning process, showcasing the effectiveness of the proposed system in restoring optimal performance. All data pertaining to these parameters are securely stored on the cloud, enabling thorough evaluation of the cleaning system's efficacy over time. Through this cloud-based monitoring and storage approach, customers gain valuable insights into the maintenance of their solar panels, ensuring sustained efficiency and longevity of their renewable energy investments.

3. Conclusion

Solar energy makes up a sizable portion of renewable energy resources. PV is the key technology for converting solar energy into usable energy. This study examines how dust accumulation on photovoltaic panels negatively affects their energy efficiency, leading to a noticeable decrease in output energy yield. It is concluded by the extensive real time measurements, that the dust accumulation significantly impacts the expected power output of photovoltaic panels, particularly over extended periods. Neglecting this factor will likely result in a substantial discrepancy between the actual and estimated energy yield of these systems.

A low-cost IoT-based automatic cleaning mechanism for photovoltaic modules is designed and tested for a day, a week, and a month of exposure to dust. The experimental findings show an average increase in efficiency of 12.37% while using this proposed cleaning system. By automating cleaning processes and providing real-time voltage and power monitoring, IoT reduces manpower, maintenance costs, and the risk of damage associated with manual cleaning. This low-cost solution with inbuilt microcontrollers and IoT-based automation aligns with the Sustainable Development Goals, promoting sustainable and energy-efficient next-generation PV systems in the future.

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