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Revolutionizing Solar Efficiency Harnessing Iot Innovation For Intelligent Dust Monitoring And Cleaning Solutions

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Abstract- Solar photovoltaic (PV) panels were a broadly implemented renewable energy source but their efficiency was substantially influenced by dust accumulation which hindered sunlight absorption and reduced power output Regular cleaning and monitoring were essential to sustain their performance Traditional cleaning mechanisms such as manual or semiautomatic cleaning were often inefficient labor-intensive and costly which demanded the development of automated solutions This research introduced an IoTbased cleaning and monitoring system designed to enhance the efficiency of solar PV panels The system combined realtime data acquisition through IoT sensors to detect dust accumulation and environmental conditions activating an automated cleaning mechanism when necessary Additionally machine learning algorithms analyzed historical data to optimize cleaning schedules maintaining minimal energy loss and improved reliability A review of prevalent dust removal techniques such as passive coatings electrostatic cleaning and robotic solutions revealed that many methods were either highmaintenance or not costeffective for largescale deployment IoTbased solutions when integrated with predictive analytics provided a potential substitute by enabling realtime monitoring and analytical decisionmaking for panel maintenance The outlined methodology enhanced energy output while reducing operational costs and minimizing manual intervention making solar energy systems more efficient and sustainable This innovation contributed to the prolonged effectiveness of solar power by addressing one of its key operational challenges thereby fostering a cleaner and more reliable renewable energy future.

Keywords- Solar Photovoltaic Monitoring & Cleaning System for Dust Deposition IoT & Machine Learning.

I. INTRODUCTION

11 Basics of Solar Energy and Renewable Energy

The expanding global demand for energy driven by urbanization and industrialization has highlighted the limitations of traditional fossil fuels which are exhaustible and contribute significantly to environmental degradation To resolve this challenge renewable energy sources such as hydropower solar biomass wind and geothermal have developed into viable substitutes Among these solar energy is the mostample and widely accessible offering a clean and scalable solution for power generation By capturing sunlight solar technology provides an environmentally friendly technique to reduce reliance on fossil fuels mitigate climate change and enhance global energy security

Solar energy is obtained from the sun which functions as a massive nuclear fusion reactor emitting an immense amount of energy In just an hour the sunlight received by Earth is enough to meet global electricity demands for an entire year This makes solar power one of the most optimistic energy sources for the future The two primary approaches of harnessing solar energy are photovoltaic (PV) technology which directly converts sunlight into electricity using semiconductor materials and solar thermal systems which adopt solar heat to generate steam for turbinedriven power production Due to advancements in PV technology solar panels have become the most widely implemented method for electricity generation in commercial residential and industrial applications.

The significance of solar energy extends beyond its abundance as it offers multiple environmental technical and economic advantages Environmentally solar power generates Zero Carbon emissions helping to mitigate global warming while substantially reducing water and air pollution compared to fossil fuelbased energy sources Economically it minimizes electricity costs offers energy independence by enabling decentralized power generation and has become a key catalyst for employment generation in installation manufacturing and maintenance sectors From a technical perspective solar energy systems are highly scalable with applications ranging from small rooftop panels to largescale solar farms and require minimal maintenance distinctly from occasional cleaning and monitoring

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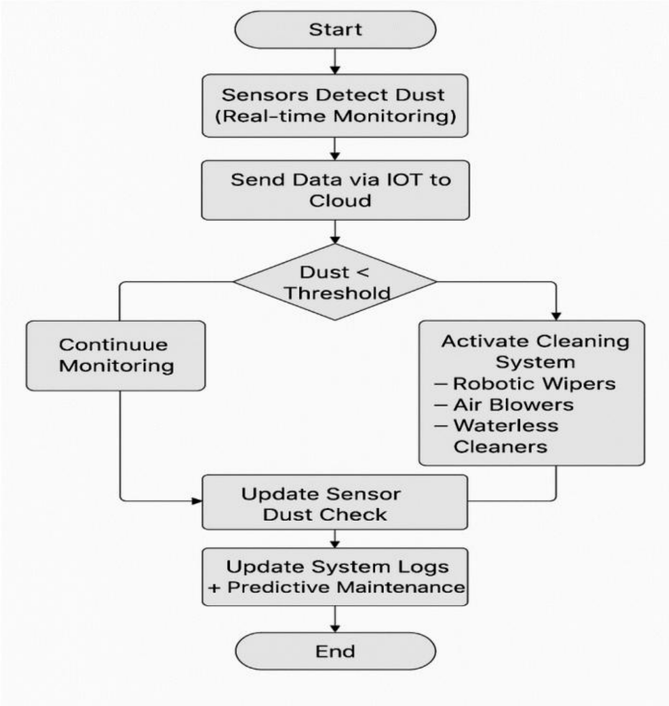

Figure. 1Workflow of IoTBased System

Fig1 The flowchart illustrates an IoTbased system where sensors monitors dust on solar panels send data to the cloud and automatically trigger cleaning when dust exceeds set limits ensuring maximum energy efficiency.

On the other hand its numerous advantages solar energy efficiency is affected by external environmental factors such as dust accumulation shading and temperature variations Dust accumulation is a major challenge that affects the efficiency of solar panels by obstructing sunlight and reducing their energy output Dust which includes fine particles such as soil sand pollen and pollutants gathers on the surface of solar panels due to natural environmental conditions wind patterns and human activities The pace of dust accumulation is influenced by various conditions including geographical locations climate conditions seasonal variations and closeness to construction sites or industrial areas In arid and semiarid regions where dust storms are frequent the impact on solar panel efficiency can be even more evident.

The buildup of dust creates a hindrance between the solar cells and sunlight reducing photon absorption and afterward lowering power generation efficiency Research has shown that even a thin layer of dust can substantially decrease the performance of PV systems with efficiency reduction ranging from 10% to 50% depending on the severity of dust accumulation To resist this issue various cleaning techniques such as manual cleaning autonomous cleaning robots and selfcleaning coatings have been invented Moreover smart monitoring systems prepared with IoTbased sensors can help detect dust buildup in real time and trigger cleaning mechanisms accordingly.

The merging of these advanced technologies is vital to maintain the optimal performance of solar panels and ensures longterm reliability By addressing dust collection and other environmental challenges solar power can become an increasingly feasible and sustainable energy solution for the future The ongoing development of innovative solutions for dust mitigations will play an important role in maximizing the efficiency of solar energy systems and helping the global transition towards renewable energy sources The unification of these technologies can considerably enhance solar panel efficiency ensure longterm reliability and optimize the energy output making solar power an even more feasible and sustainable energy solution for the times ahead

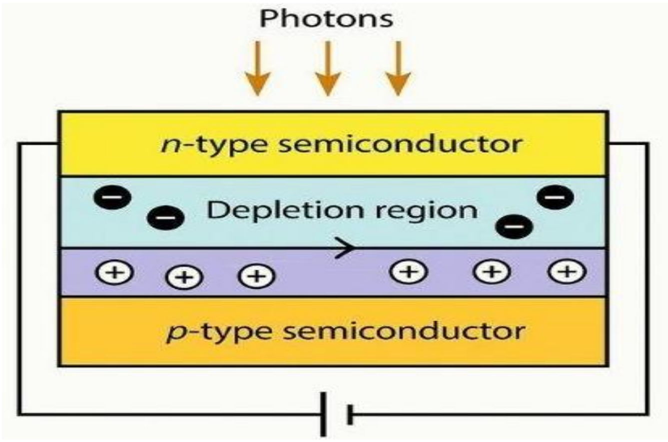

Figure 2 Structure and Working Principle of a Photovoltaic (Solar) Cell

Fig 2 illustrates the structure and functioning of a photovoltaic cell based on a pn junction When the photons strike the cell they generate pairs of electronholes in the depletion region The internal electric field across the junction forces electrons to move towards the ntype semiconductor and holes towards the ptype semiconductor This movement of charge carriers creates a potential difference which results in the generation of electrical energy

12 Mathematical Introduction

The photovoltaic (PV) effect is the method by which a semiconductor material adapts sunlight into electrical energy The phenomena are based on the interaction of light photons with the semiconductor material causing the generation of an electric current The efficiency and performance of a solar rely

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on several mathematical parameters comprising power output efficiency and maximum power point tracking.

121 Fundamental Equations of the Photovoltaic Effect

1211 Generation of ElectronHole Pairs

When photons with energy greater than or equal to the forbidden energy gap (E_g) of the semiconductor material hit the solar cell they excite electrons from the valence band to the conduction band generating free electrons and holes The energy required for this transition is given by.

$$Eg = hf = hc/\lambda \quad (1)$$

Where
h = 6626 × 1034 Js (Plancks constant)
c = 3 × 108 m/s (speed of light)
f = frequency of the photon (Hz)
λ = wavelength of the incident photon (m)

If E_g of the material (eg Silicon = 11 eV) is lower than the incoming photon energy the electrons get excited leading to current generation.

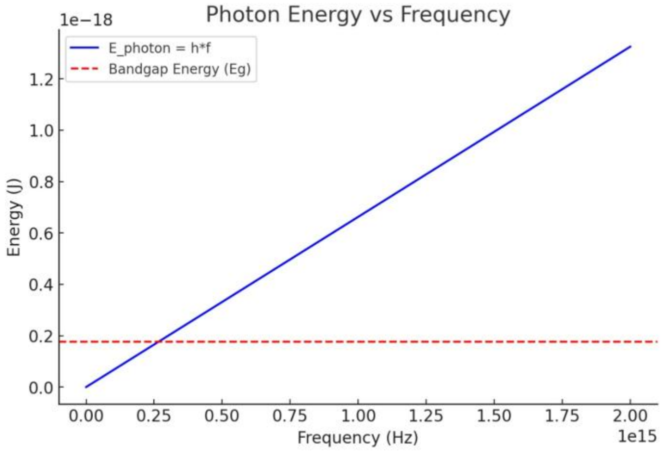

Figure 3 Photon Energy as a Function of Frequency with Bandgap Energy Threshold

Fig 3 shows the linear relation between the photon energy and the frequency as shown by the equation Eg = hf The blue line represents the increasing photon energy with frequency while the red dashed line marks the bandgap energy (Eg) of a material which indicates the minimum amount of energy required for electrons to transition from the valence band to the conduction band

1212 Generation of Photocurrent

The separation of electronhole pairs creates a potential difference generating an electric field at the pn junction of the solar cell The current produced by the photovoltaic effect is given by

$$I_{ph} = q\,G\,W \quad (2)$$

Where

Q = elementary charge (16×10^{19} C)

G = photon generation rate (photons per unit volume per second)

A = active area of the solar cell

W = width of the depletion region

1213 Solar Cell CurrentVoltage (IV) Characteristics The output characteristics of a solar cell are given by the Shockley diode equation with a lightgenerated current term.

$$I = I_L - I_0(e^{qV/nkT} - 1) \quad (3)$$

Where

I_L = Lightgenerated current (A)

I_0 = Reverse saturation current (A)

q = 1602×10^{19} C (Charge of an electron)

V = Output voltage(V)

n = Ideality factor (ranges from 1 to 2)

k = 138×10^{23} J/K (Boltzmann constant)

T = Temperature (K)

At opencircuit voltage (V_{oc}) I = 0 giving

$$V_{oc} = nkT/q \ln (I_L/I_0 + 1) \quad (4)$$

At shortcircuit current (I_{sc}) V=0 meaning

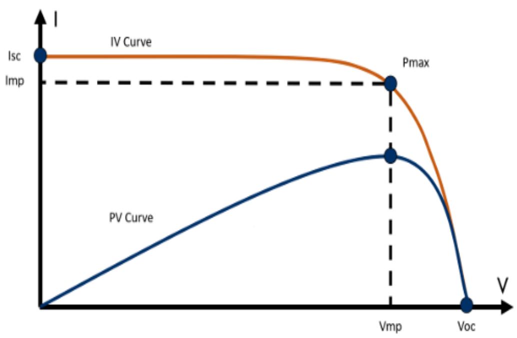

Figure 4 CurrentVoltage and PowerVoltage Characteristics of a Photovoltaic Cell [6]

The graph illustrates the currentvoltage (IV) and powervoltage (PV) characteristics of a photovoltaic cell The IV curve (shown in orange) shows the relationship between the output current and the voltage The PV curve (shown in blue) represents the output power peaking at the maximum power point (P_{max}) corresponding to V_{mp} and I_{mp} where the cell operates with highest efficiency

1214 Power Output of a Solar Cell The electrical power output of a solar cell

$$P = IV \quad (6)$$

The maximum power point (MPP) is the operating point where the product IV is maximum determined by

$$dP/dV = 0 \quad (7)$$

The fill factor (FF) is a crucial parameter measuring how well a solar cell performs

$$FF = V_{mp}I_{mp}/V_{0c}I_{sc} \quad (8)$$

where V_{mp} and I_{mp} are the voltage and current at the maximum power point

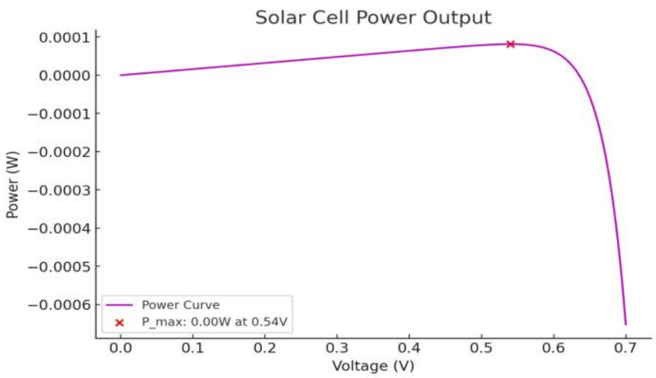

Figure 5 Power Output of a Solar Cell as a Function of Voltage

Fig 5 shows the PowerVoltage (PV) characteristics of a solar cell The power output increases with the increasing voltage reaching a peak at the maximum power point (P_{max}) and then drops sharply The overall low power output shows that the solar cell may be functioning under poor illumination or experiencing a malfunction

1215 Solar Cell Efficiency The efficiency (η) of a solar panel is the ratio of its electrical output power to this incident solar power (P_{in})

$$\eta = P_{max}/P_{in} \times 100 \quad (9)$$

Where

$$P_{in} = E \times A \quad (10)$$

E = Solar irradiance (W/m^2 typically 1000 W/m^2 under standard test conditions)

A = Area of the solar cell (m^2)

$P_{max} = V_{mp} \times I_{mp}$

Higher efficiency means better energy conversion from sunlight to electricity

II. LITERATURE SURVEY

The Literature Survey reviews already existing research papers on IoTdriven monitoring and cleaning systems for solar panels It inspects different sensor technologies data processing techniques and automated cleaning methods that have been suggested in recent years The aim is to understand the effectiveness of these solutions identify research gaps and highlight emerging trends in IoTbased solar panel maintenance

TABLE 1 IoTBased Models for Monitoring Dust Accumulation on Solar Panels

SNo	Author Name	What has been done (Methodology)	Results	Pros	Cons
1	Saeed Iqbal Muhammad Sajid Syed Maaz Hasan Yasar Ayaz Emaduddin Adeel	Investigated the effects of temperature dust and micro crackers on photovoltaic panels using Electrical	Achieved high classification accuracy with F1 scores of 0856 for temperature	Costeffective monitoring enhances predictive maintenance and solar panel	Requires panel disconnections for testing frequency scans are

	Waqas [1] [2025]	Impedance Spectroscopy (EIS) combined with machine learning for realtime monitoring	classification and 0975 for detecting dust and microcracks	efficiency	resourceintensiv e
2	Salman Hossain All Mumtahina Arika Iffat Nowshin Fahim Jamal Uddin Ataee Ashik Ahmed Hasan Jamil Apon Muhammad Arshadul Hoque [2] [2025]	Researchers developed an MLbased dust detection and automated sprinkler cleaning system for PV panels An ANN model achieved 9811% accuracy in detection and cleaning restored efficiency to 1487% matching clean panels Economic analysis confirms viability for PV setups above 289kWp	A machine learningbased dust detection system for solar PV panels achieves 9811% accuracy with ANN triggering an automated sprinkler to restore efficiency Economically viable for PV capacities above 289kWp	Enhances PV efficiency reduces energy loss enables automated maintenance and proves costeffective	Water reliance limits use in arid regions requires initial investment and performance varies with environmental conditions
3	PK Dhala C Jaswanth Reddy R S Aswin Kumar S Sabareesh [3] [2024]	The paper introduces a 55W solar power monitoring and automated cleaning system using Pythonbased embedded technology for optimizing solar panel efficiency	A 55W solar system with automated monitoring and cleaning detects dust and triggers a brush for efficiency using Arduino Uno Node MCU and remote monitoring	Smart systems optimize solar panel efficiency with realtime monitoring remote control and automated cleaning reducing labor and maximizing energy output	Smart systems face limited validation high costs and integration challenges impacting realworld deployment
4	Aadel Mohamed Alatwi Hani Albalawi Abdul Wadood Hafeez Anwar Hazem MElHageen [4] [2024]	Developed a deep learningbased framework for detecting dust on solar panels using image classification models to enhance solar power generation	Achieved a maximum classification accuracy of 8697% using DenseNet169 with a linear SVM for dusty solar panel detection	Lowcost Solution improves efficiency and sustainability of solar panels	Limited dataset requires further validation for diverse environmental conditions

5	Mangalam H Karun Harshaini H Kavya Shree S S Pavithran P [5] [2024]	Developed an IoTbased hybrid monitoring system for solar panels that integrates physical modelling and machine learning to optimize performance defect faults and automate cleaning	Hybrid IoT system boosts solar efficiency via realtime monitoring ML autocleaning with solar tracking maximizing energy output for sustainable power	The system maximizes solar efficiency by tracking sunlight cleaning dusts and detecting faults early with hybrid modelling It is affordable and scalable	The system relies on the internet needs regular sensor maintenance and has ML integration complexity requiring expertise
6	Mehmet Rida Tur Rami AlHajj Sanjeevikumar Padmanaban Mohammed Wadi Eklas Hossain Abdulfetah Shobole [6] [2024]	Analyzed factors like dust accumulation and shading affecting solar panel efficiency using a modelbased approach supported by real system data	Demonstrated that dust accumulation and shading significantly reduces solar panel efficiency with recommendatio n for mitigating these effects through optimized tilt angles and cleaning methods	Provides insights into optimizing solar panel performance highlights the impacts of environmental factors	Limited to specific conditions requires further validation for diverse climates
7	Siti Nur Afifah Mohd Suhaimi Mohd Nasri Jasmie Nor Aira Zambri Omar Abu Hassan Farahiya Mustafa Sim Sy Yi Norhafiz Slim [7] [2024]	Developed an IoTbased dust monitoring system for solar panels using ESP32 dust sensors and Blynk app to track cleanliness and notify users for maintenance	Dust accumulation drops efficiency from 616% to 241% with cleaning recommended below 485W output The system ensures realtime tracking and peak power generation	Improves solar efficiency enables realtime monitoring supports systematic maintenance and enhances accessibility with IoT	No cleaning function relies on connectivity sensor accuracy varies and has an initial setup cost
8	Mrs S Tejaswi U Balaji Dinesh PNarasimha Yadav Sri Charan GK Vamshi Kumar [8] [2024]	Developed an IoTbased solar panel management system for realtime dust detection and automated cleaning to enhance energy	Successfully demonstrated improved solar panel efficiency and reduced maintenance costs through	Reduces manual cleaning efforts improves energy output and panel lifespan	Limited regional data requires further testing for diverse conditions

		efficiency	automated cleaning and realtime monitoring		
9	P Samourn Lakshmi Manjula Sri Rayudu K Bapuji [9] [2024]	IoTbased dust detection for solar panels using a modified DesnseNet121 deep learning model Images are captured via IoT devices analyzed for dust accumulation and processed for efficient maintenance	IoTdriven systems detect dust on solar panels using a modified DenseNet121 model improving accuracy and enabling timely maintenance for optimal efficiency	The model ensures accurate dust detection efficient feature reuse realtime tracking and costeffective maintenance for solar panels	The system demands high computational power relies on data quality for accuracy faces scaling challenges in IoT deployment and experiences detection variability across environments
10	Benjamin Oluwamuyiwa Olorunfemi Omolola A Ogbolumani Nnamdi Nwulu [10] [2022]	The study reviews smart systems for detecting dirt and cleaning solar panels to enhance energy output comparing them with manual and autonomous methods	Smart systems enhance solar panel efficiency through realtime monitoring and automated cleaning optimizing energy output They enable remote supervision reducing labor reliance	Smart systems boost solar panel efficiency with realtime monitoring for optimal cleaning They enable remote control for easy management and use automation to cut labor costs	Smart systems face limited realworld validation making performance uncertain High initial costs pose financial challenges and technical complexity makes integration difficult

TABLE 2 IoTBased Models for Cleaning Dust from Solar Panels

SNo	Author Name	What has been done (Methodology)	Results	Pros	Cons
1	Dr S Satthiyaraj Dr R Sugashini [11] [2025]	This paper introduces an IoTbased automated cleaning system for solar panels leveraging sensors and microcontrollers to optimize cleaning with water and	The IoTbased automated cleaning system improved solar panel efficiency by up to 32% providing a scalable and costeffective	Paper presents an IoTbased automated solar panel cleaning system with notable advantages including a 32% improvement in	The cons include dependency on IoT infrastructure requiring maintenance and stable connectivity higher initial

		wipers enhancing solar panel performance by reducing dust accumulation and ensuring realtime monitoring for better efficiency and usability	solution for maintaining optimal performance	efficiency reduced manual labor and realtime monitoring for better usability and accessibility	setup costs and limited suitability for environments beyond dusty or desert regions
2	Muhammadin Hamid Micael Frans Simamora Maria Derani Ester Vania Putri Cholillah [12] [2024]	Developed an IoTbased system with wipers for cleaning solar panels integrating dust sensors servo motors and RTC modules The system automates cleaning twice daily and enables realtime monitoring via Android devices	Improved solar panel efficiency by approximately 8933% in a hot desert climate demonstrating the systems effectiveness in maintaining optimal energy output	Boosts solar panel efficiency automates cleaning and is costeffective	Minimal voltage improvement under strong sunlight requires skilled maintenance
3	A Mellit Mo Chourouk MZennaro [13] [2024]	Proposed a predictive method for scheduling cleaning of photovoltaic plants in desert areas using a TinyML model Visual images were classified into clean panels dust accumulation and sand deposits The system determines cleaning frequency (daily weekly or monthly) based on classification results and posts the information to an Arduino IoT platform	Achieved a classification accuracy of 8656% effectively assisting in decisionmaking for cleaning intervals preserving PV plant performance in harsh environments	Costefficient reduces water and energy wastage effective for desert regions	Limited to two anomalies small dataset constrained by microcontrollers memory
4	Mukundswamy M S C RajnikantShankarling appa C B [14] [2024]	Developed an IoTbased automated system for cleaning and cooling solar panels The system includes a microcontroller that monitors dust and	Enhanced power generation and efficiency by 63% with cleaning and cooling showcasing its effectiveness in	Improves solar panel efficiency automates maintenance and enables realtime monitoring via IoT	Complexity in system setup and maintenance requires further integration for diverse environmental

		temperature automates cleaning with gear motordriven wipers and integrates a watercooling mechanism using copper tubes to prevent overheating	maintaining optimal photovoltaic performance		conditions
5	Muzzam Ghafoor Arslan Ahmed Amin Muhammad Shoaib Khalid [15] [2024]	The methodology involves designing an IoTbased automated solar panel cleaning system using an ESP32 microcontroller sensors and motorized brushes integrated with Adafruit IO for realtime monitoring and control enhancing efficiency by 30%	IoTbased automated cleaning systems improved the efficiency of a 30W solar panel by 30% ensuring optimal energy generation and reducing downtime	Its IoTbased automated cleaning system which enhances solar panel efficiency by 30% reduces manual labor enables realtime monitoring via Adafruit IO and offers a costeffective scalable solution for dusty environments	The papers limitations include reliance on IoT infrastructure requiring maintenance higher initial costs and limited adaptability to climates beyond dusty regions
6	Josephin Sundah Johan F Makal Johan Pongoh Ronny Katuuk Ali Ramschie [16] [2024]	Designed and implemented an IoTbased system for automatic solar panel cleaning and cooling The system uses sensors to detect dirt and temperature microcontrollers to automate cleaning and cooling processes and integrates monitoring via web servers for realtime updates and control	Successfully maintained solar panel voltage above 15V optimizing power output and efficiency	Improves solar panel efficiency automates maintenance extends panel lifespan and reduces manual maintenance costs	Requires skilled setup and maintenance may need further testing under varied environmental conditions
7	Maha Anber Bassam W Aboshosha [17] [2024]	This paper develops an IoTbased automated cleaning system for solar panels to combat efficiency losses caused by dust achieving an 8933%	IoTbased automatic solar panel cleaner raised solar panel efficiency by 8933% ensuring optimal energy	The key advantage of this paper is the development of an IoTbased automated cleaning system that improves	The cons include reliance on IoT infrastructure requiring maintenance higher initial costs and limited adaptability to

		improvement in performance particularly in hot desert climates	performance in hot desert climates	solar panel efficiency by 8933% especially in dusty climates while reducing manual labor and ensuring consistent energy output through costeffective and scalable automation	climates beyond dusty desert regions
8	Abhishek G Abhishek C Rahul Ravikiran Deepak Ghode [18] [2024]	Developed an IoTbased automatic solar panel dust cleaning system using NodeMCU a 12V DC gear motor L293D motor drive IR sensor and the Blynk application The system detects dust levels via IR sensors and initiates cleaning automatically using a motorized mechanism ensuring realtime monitoring via a mobile app	Successfully demonstrated reduced power loss due to dust accumulation improved cleaning efficiency and increased solar power output	Enhances solar panel efficiency reduces manual maintenance conserves energy by cleaning only when needed and extends panel lifespan	Requires an initial setup may need further improvements for extreme weather conditions and limited cleaning efficiency in certain dust types
9	Md Tanvir Islam Mim Md Asif Imtiaz Anik Riadul Islam Shaharier Kabir Md Ashikul Islam Abu Shufian [19] [2023]	Designed a timescheduled automatic cleaning system for solar panels using aluminum alloybased mechanical design and a controlling unit Tested in a 375kW solar power plant achieving a notable enhancement in energy output	Increased energy output by 1015% proving the cleaning systems efficacy in optimizing solar power generation	Enhances efficiency by 1015% automates cleaning and is costeffective	Limited adaptability to weather further optimization needed
10	Milan Vaghani Jayesh Magtarpara Keyur Vahani Jenish Maniya Prof Rajiv	Developed an IoTbased solar panel cleaning system using water sprays	Improved power generation by 32% effectively reducing losses	Enhances energy output by approximately 32% reduces	Limited applicability to different panel setups and

	Kumar Gurjwar [20] [2019]	and a wiper mechanism controlled via a mobile application The system operates using a rechargeable battery and improves solar panel efficiency	caused by dirt and particles	manual labor and is lightweight and costeffective	weather conditions requires further design optimization for varied installation

III. METHODOLOGY

This review paper followed a structured literature review approach to evaluate existing studies on IoTbased cleaning and monitoring of dust on solar panels The main objective was to analyze multiple IoT models sponsor technologies communication protocols and automated cleaning mechanisms that contributed to sustaining solar panel efficiency To accomplish this a welldefined methodology was adopted including an extensive literature search from referred journals and conference proceedings The gathered research was categorized based on cleaning mechanisms monitoring techniques data processing approaches and performance evaluation metrics A relative analysis was performed to assess the advantages limitations and practical applications of these IoT models

31 Commonly used Methodologies for Monitoring

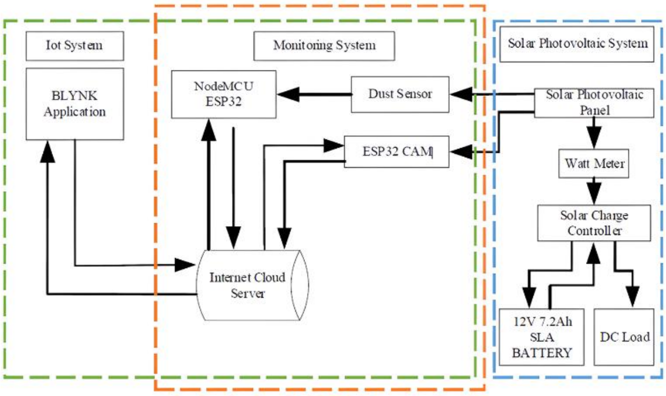

Figure 6 Block diagram displaying Monitoring System [7]

Fig 6 explained about a system that combined IoT and monitoring to optimize solar photovoltaic (PV) panel efficiency by detecting dust accumulation and guaranteeing efficient energy production It consisted of three main subsystems the Solar Photovoltaic System which was responsible for power generation and storage using a solar panel watt meter solar charge controller a 12V 72Ah SLA battery and a DC load the Monitoring System which included a dust sensor to detect dust on the panel and an ESP32 CAM for realtime video both administered by a NodeMCU ESP32 that transmitted data and the IoT System which facilitated remote monitoring via a BLYNK app cloud server and WiFi communication The system ensured continuous power generation detected dust accumulation and transmitted realtime data for remote monitoring reducing manual inspections By systematizing panel cleanliness tracking it maximized solar efficiency prevented energy loss and offered costeffective and sustainable solutions for solar maintenance [7]

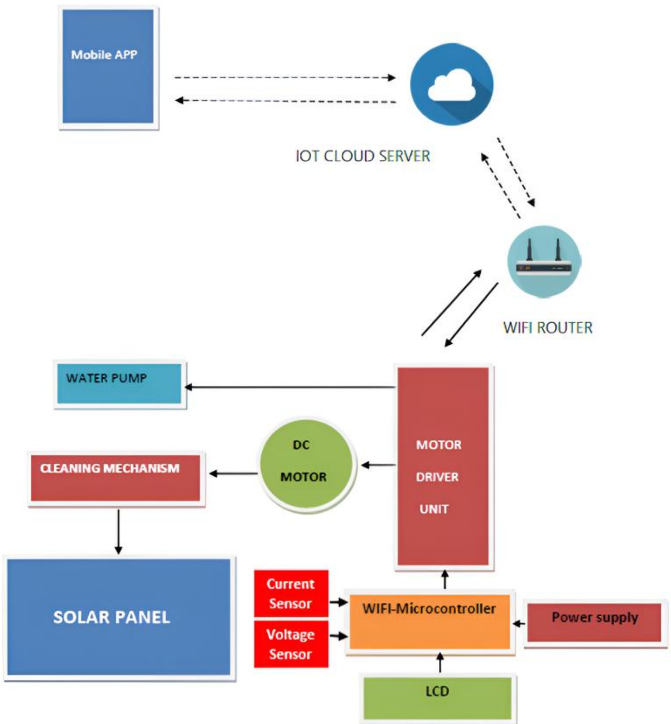

Figure7 Block diagram displaying workflow of Monitoring and Cleaning System [11]

Fig 7 suggested a system that automated solar panel cleaning by applying IoT and sensorbased monitoring to maintain efficiency It included three main sections Power generation & monitoring a cleaning mechanism and IoTbased remote monitoring The solar panel generated electricity to enable system operation while a WiFienabled microcontroller

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consistently observed performance using current and voltage sensors displaying realtime data on an LCD When dust accumulation was detected the cleaning mechanism driven by a DC motor and motor driver unit activated to remove debris If further cleaning was required a water pump sprayed water onto the panel The microcontroller conveyed sensor data via a WiFi router to an IoT cloud server allowing remote monitoring and control through a mobile app The framework followed a structured process Realtime data collection automated cleaning activation water pump control (if required) and IoTbased monitoring ensuring efficient and remotecontrolled solar panel sustenance This reduced manual oversight and maximized energy output making the system reliable and sustainable [11]

32 Commonly used Methodologies for Cleaning

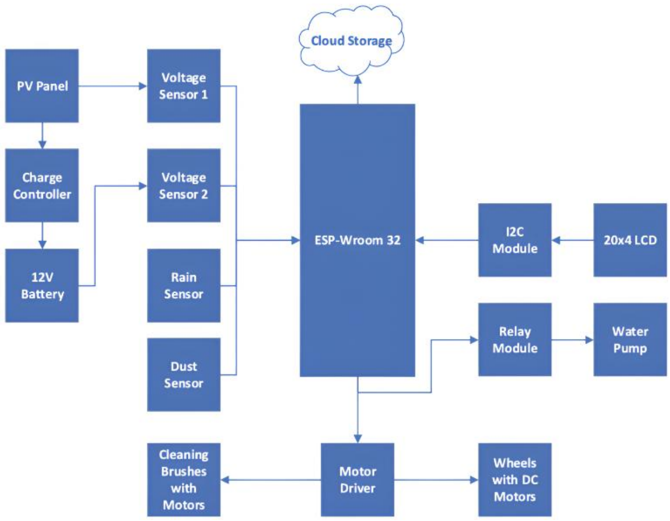

Figure8 Block diagram displaying Advanced Cleaning System [15]

Fig 8 showed an IoTbased solar panel cleaning system that optimized maintenance and streamlined energy efficiency using ESPwroom 32 as the central controller It collected data from dust (GP2Y101) rain (FC37) and voltage (F031) sensors to monitor cleaning operations The dust sensor triggered motorized soft nylon brushes and a water pump ensuring efficient cleaning while minimizing water wastage The rain sensor prevented unnecessary cleaning and voltage sensors regulated panel and battery health

A 10W solar panel charge controller and 12V battery powered alongside energy stored in the battery for sustained operation Motorized wheels and gear motors revolved panels for thorough cleaning and improved sun exposure An LCD with an I2C module displayed realtime system data while cloud storage facilitated remote monitoring and control The structure efficiently integrated sensors systemized cleaning mechanisms and IoT connectivity to improve solar panel performance and reduce maintenance efforts [15]

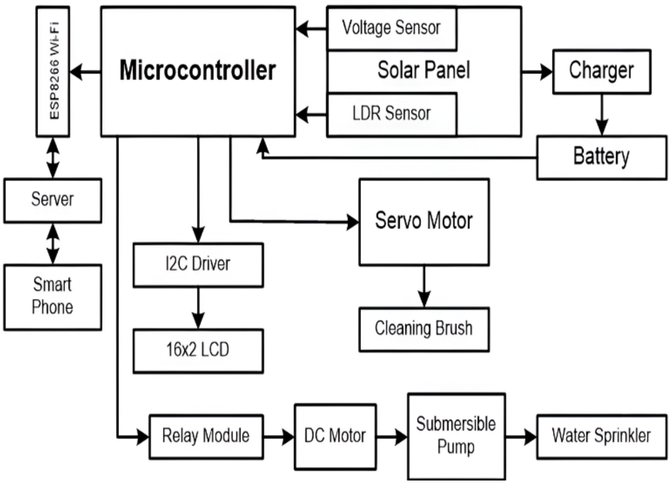

Figure9 Block diagram of IoTbased Automated Solar Panel Cleaning Scheme [23]

Fig 9 displayed an IoTenabled automated solar panel cleaning and monitoring system that elevated energy efficiency by automating cleaning and tracking power output It was composed of an ESP8266 NodeMCU microcontroller sensors actuators and IoT connectivity for realtime optimization The solar panel generated power which has stored in a battery via a charger A voltage sensor and LDR sensor tracked power output and sunlight intensity Dust accumulation reduced efficiency and once the voltage droped below a set threshold the system determines if cleaning was required The cleaning mechanism contained a servo motor that moved a cleaning brush and a submersible water pump controlled by a DC motor and transmit module to spray water when needed The I2C LCD display illustrated realtime data while IoT connectivity allowed remote monitoring via a smartphone or cloud server This system secured minimal waste usage energyefficient cleaning and realtime performance tracking minimizing maintenance efforts and enhancing solar panel efficiency in various conditions [23]

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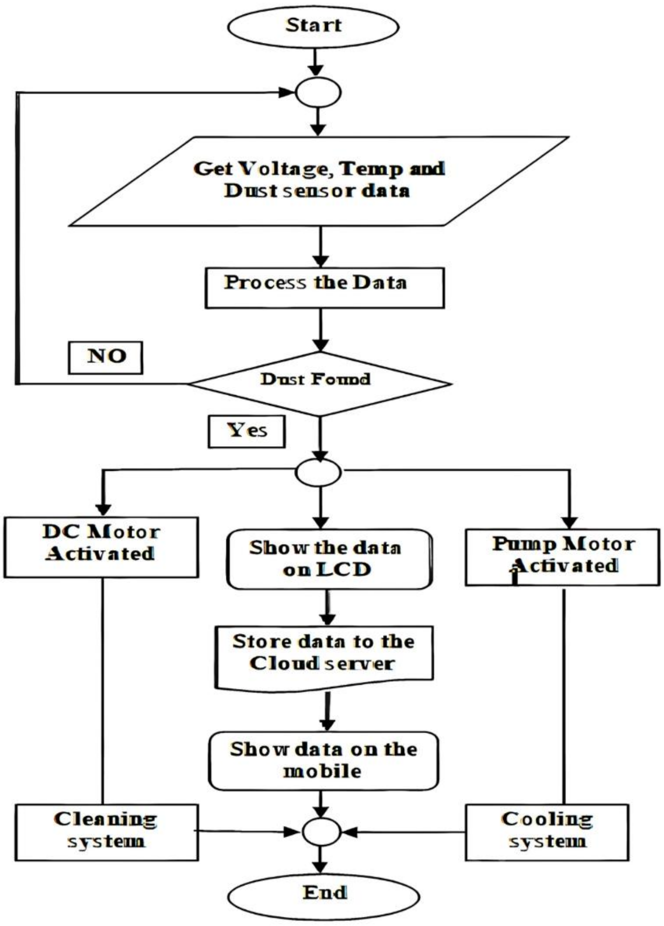

Figure10 Flow chart displaying Automated Cleaning and Cooling for Solar Panel using IoT [14]

Fig 10 explained an IoTbased selfoperating solar panel cleaning and cooling system that improved energy efficiency by addressing dust accumulation and overheating The system began by initializing variables and acquiring voltage temperature and dust sensor data which the microcontroller processed to determine the requirement for cleaning and cooling .

Upon detection of dust the DC motor activated stimulating the cleaning system while realtime data was displayed on an LCD stored in the cloud and forwarded to a mobile device for remote monitoring If the panel temperature exceeded 35°C the pump motor activated triggering the cooling system to maintain optimal performanceThis IoTbased system automated cleaning and cooling this facilitated better energy output reduced manual maintenance and enabled realtime monitoring for proactive maintenance and sustainability [14].

IV. RESULTS AND DISCUSSION

The IoTenabled automated solar panel cleaning and monitoring system depicted an innovative advancement in photovoltaic (PV) maintenance by integrating realtime environmental sensing advanced automation and remote accessibility to optimize solar energy efficiency By consistently detecting dust accumulation and environmental factors the system validated optimal sunlight absorption minimized energy losses and enhanced power output Its costeffective selfregulating cleaning mechanism operated by multiple sensors and an adaptive microcontroller eliminated the requirement for frequent manual intervention reduced labor costs and minimized system inactivity The integration of IoT and cloudbased analytics enabled effortless remote monitoring allowing users to track performance metrics receive automated servicing alerts and optimize cleaning schedules based on realtime conditions Moreover its resourceconcious design minimized water and energy consumption by automatically adjusting the cleaning process according to dust levels weather patterns and temperature variations Developed for scalability and future expansion the system was capable of being implemented across residential commercial and largescale solar farms incorporating AIdriven anticipatory maintenance and machine learning algorithms to further optimize energy output and system longevity By delivering smart sustainable and highperformance solutions this innovation defined a new standard for autonomous solar panel maintenance ensuring reliability efficiency and longterm viability in renewable energy applications.

Moreover besides its direct benefits in enhancing solar panel efficiency this system presented a versatile and scalable approach to various applications In residential solar installations householders ensured continuous high energy efficiency without manual cleaning efforts making solar implementation more convenient and sustainable Mercantile and industrial buildings with extensive rooftop solar panels benefited from selfmonitoring systems reducing operational breaks and extending panel longevity Extensive solar farms significantly enhanced energy output with predictive AIdriven monitoring and automated cleaning ensuring minimal efficiency losses over immense installations In remote and isolated locations where manual maintenance was complicated this IoTenabled system provided a reliable and independent solution ensuring seamless power generation It also corresponded with smart city initiatives and green buildings supporting energyefficient facilities while reducing reliance on fossil fuels In agriculture where dust buildup on solarpowered irrigation systems was a major concern this autonomous cleaning mechanism enhanced performance in harsh environmental conditions Beyond its potential extended to aerospace and space applications where selfregulating and automated maintenance of solar panels on satellites and extraterrestrial structures was crucial for steady power supply.

By effortlessly integrating IoT automation and AIdriven maintenance this system not only improved the performance of solar panels but also revolutionized the way solar energy systems were sustained across various sectors As solar energy adoption continued to spread globally such intelligent solutions played a crucial role in ensuring highefficiency power generation with minimal human intervention This innovation ultimately reinvented the standards for sustainable and autonomous solar panel maintenance making renewable energy sources more reliable costeffective and approachable in diverse environments

V. CONCLUSION

Renewable energy is very important for addressing global energy demands while lowering environmental impacts Unlike fossil fuels which contribute to pollution and climate change renewable resources like solar wind and hydro are sustainable ecofriendly and abundant They provide various benefits including reduced greenhouse emissions enhanced energy security economic growth and longterm sustainability Among these solar energy is widely adopted but its efficiency can be affected by external factors like dust accumulation on panels necessitating effective monitoring and maintenance solutions The Internet of Things plays an important role in upgrading renewable energy systems by integrating smart sensors cloud computing and AI to improve efficiency and automation IoT enables realtime monitoring predictive maintenance smart energy management and remote control ensuring effective performance of renewable energy infrastructure Specifically in solar energy applications IoTbased models are used for monitoring dust levels and automating cleaning processes thereby maintaining panel efficiency and maximizing energy output By utilizing IoT renewable energy systems become more intelligent costeffective and sustainable contributing to a cleaner and more efficient energy future

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