IoT-enabled Smart Monitoring and Cleaning Techniques for Enhancement of Solar Panel Efficiency

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Abstract

The rapid adoption of solar energy as a clean and sustainable power source has led to an increased deployment of solar panel installations worldwide. However, solar panels' efficiency is affected by various factors including dust accumulation, shading and malfunctioning cells. To address these challenges and optimize solar panel performance, this research focuses on the development of an IoT-enabled Smart Monitoring and Cleaning System. The proposed system integrates Internet of Things (IoT) technology with advanced monitoring sensors to continuously collect real-time data on the performance and health of solar panels. The system incorporates smart cleaning techniques. Traditional solar panel cleaning methods can be costly and time-consuming. Therefore, this research explores the integration of automated cleaning mechanisms such as robotic cleaners or self-cleaning coatings. These techniques can efficiently remove dust and debris, mitigating the adverse effects of soiling on solar panel efficiency. The benefits of the proposed IoT-enabled Smart Monitoring and Cleaning System are twofold: First, it optimizes solar panel efficiency, leading to increased energy generation and improved financial returns on investments. Second, it reduces the environmental impact by promoting the use of renewable energy and minimizing water consumption, as the automated cleaning methods do not rely on water-intensive processes.

Keywords- Solar Panel, IoT- Real Time Monitoring, Cleaning Techniques, Efficiency, Maintenance, Performance Parameters

1. INTRODUCTION

1.1 Solar Panel

Solar panels, commonly referred to as "PV panels," are a technology that transforms solar light, which is made up of energy particles called "photons," into electricity that may be utilised to power electrical loads. In addition to producing electricity for household and commercial solar electric systems, solar panels can also be used for a wide range of other purposes, such as remote power systems for cabins, telecommunications equipment, remote sensing, and many others. The efficiency varies between different panel types but generally ranges from 15% to 20% for most commercial panels [1]. Solar panels are usually mounted on rooftops, ground-mounted racks, or integrated into building facades. They require a location with ample sunlight exposure to maximize energy production. He cost of solar panels has been declining over the years, making solar energy more accessible to homeowners and businesses. Government incentives and tax credits in some regions can further reduce the upfront costs. Solar panels are generally low-maintenance. Regular cleaning and occasional inspection for damage or debris are recommended to ensure optimal performance [2].

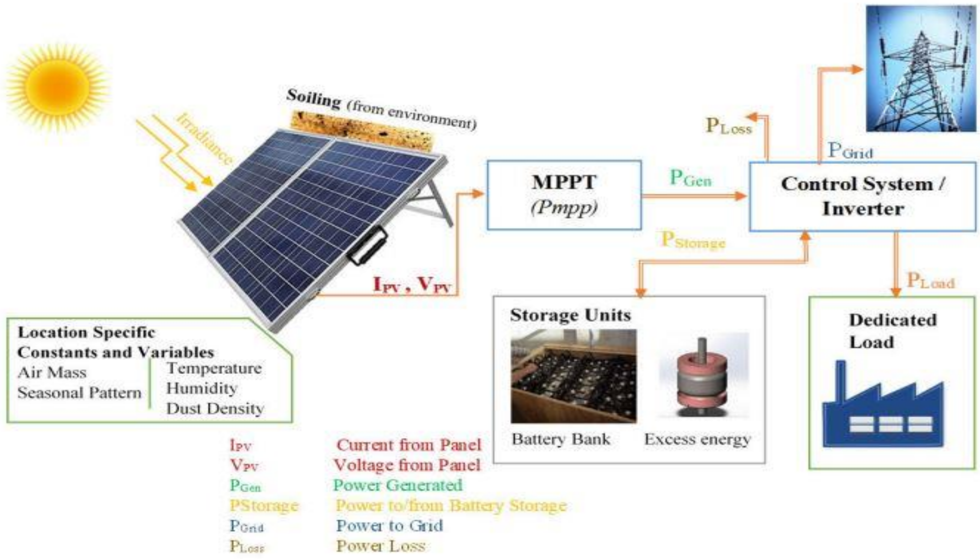

Figure1: Typical Solar PV System Block Diagram

1.2 Types of Solar Panel

1.2.1 Monocrystalline Solar Panels (Mono-SI):

Monocrystalline solar panels are frequently used for bigger energy systems in commercial and residential buildings. Panel sizes do, however, vary. Monocrystalline can therefore also be employed in smaller installations.

Advantages

- ✓ Silicon is used in their construction, and it has a high purity rating, increasing their efficiency to 15% to 22%.
- ✓ Take up less room than thin-film and polycrystalline panels.
- ✓ Due to the steady and inert nature of silicon, monocrystalline panels can last up to 25 years.

Disadvantages

- ✓ They are expensive due to their intricate design, and they are not recommended for cold climates since snowfall might harm the solar cells and lead to system failure.
- ✓ The manufacturing process for monocrystalline panels involves more complex and precise techniques, such as the growth of single crystal structures.
- ✓ Monocrystalline panels are rigid and lack flexibility, which can limit their applications in certain situations where flexible or curved solar panels are required.

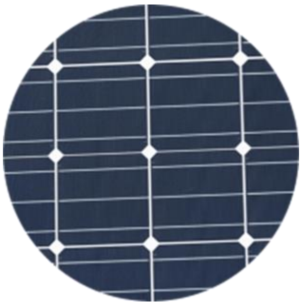

Figure2: Single-crystalline Solar Panel

1.2.2 Polycrystalline Solar Panels (Poly-SI):

Polycrystalline solar panels, as its name suggests, are made by melting many pure silicon crystals together. However, having more crystals isn't necessarily better [3]. The efficiency of polycrystalline panels is actually lower than that of monocrystalline panels. However, given that they are available in a range of power levels from 5W to 250W and above, they make a viable choice for both modest and large-scale installations.

Advantages

- ✓ Because of the simpler manufacturing process, they are less expensive than monocrystalline.
- ✓ They are more environmentally friendly since they produce less waste during the melting process
- ✓ They are also just as strong and long-lasting as monocrystalline solar panels, making them a suitable option for households on a tight budget.

Disadvantages

- ✓ Because the silicon used to build them is less pure, they have poorer efficiency (13% to 17%)
- ✓ They require more space to produce the same amount of electricity as monocrystalline cells.

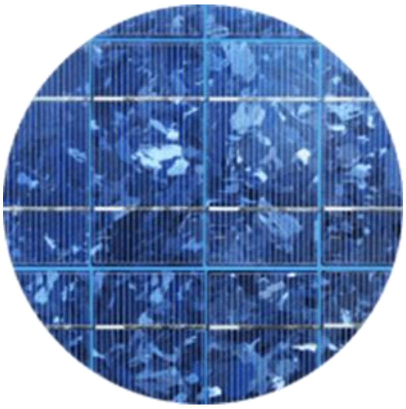

FIGURE3: Polycrystalline Solar Panel

1.2.3 Recommended for Using in Transportation: Thin-Film

Despite being portable and lightweight, thin-film PV cells that are not silicon-based are the least effective kind of solar panel. Use them only in installations where they won't need to generate a lot of power; their flexibility and portability are their two main advantages.

Advantages

- ✓ Easy and inexpensive to construct
- ✓ Perfect for solar-powered transportation applications, such as bus rooftop panels and cold-storage trucks

Disadvantages

- ✓ Not an excellent option for rooftops because they need a lot of room to collect enough solar energy to produce energy.
- ✓ They are weaker and degrade more quickly than crystalline panels. For thin-film panel installations, there are only limited warranties available, which homeowners should take into account depending on how long they intend to live in their houses. 7% to 18% efficiency.

Figure4: Thin Film Solar Panel

1.2.4 A-Si: amorphous silicon solar cell

Among the several varieties of solar panels, the amorphous silicon solar cell is the one that is primarily employed in such pocket calculators. The best thin film technology is used in this kind of solar panel, which has three layers in total. In this scenario, the thickness is 1 micro metre (one millionth of a metre), just to give you a quick idea of what "thin" means. These cells are less efficient than crystalline silicon ones, which have efficiency rate of about 18%, with just 7%, but the advantage is that A-Si-Cells are more affordable.

1.2.5 CdTe: Cadmium Telluride Solar Cell

This photovoltaic technology uses cadmium telluride, which permits the production of solar cells at a comparatively low cost and hence a shorter payback period (less than a year), among the variety of other types of solar panels. This solar energy technology uses the least quantity of water during production compared to the others. Your carbon footprint will be as small as feasible using CdTe solar cells because of the quick energy payback time. The fact that Cadmium Telluride is poisonous if consumed or inhaled is the only drawback of using it. This is one of the biggest obstacles to be overcome, especially in Europe, where many people are quite hesitant to use the technology that underlies this kind of solar panel.

1.2.6 HCVP and CVP Concentrated PV Cell

Concentrated photovoltaic cells produce electricity in the same way as traditional solar systems. These multi-junction solar panel types have the highest efficiency rate of all existing photovoltaic systems, up to 41%. Such CVP cells get their name from the features that make them more effective than other kinds of solar panels: curved mirror surfaces, lenses, and occasionally even cooling systems are employed to concentrate sunlight and boost performance [4]. As a result, CVP cells, which have a high performance and efficiency rate of up to 41%, have evolved into one of the most effective solar panels.[4] What is still true is that CVP solar panels can only be as effective if they are facing the sun at the ideal angle. The solar panel's solar tracker is in charge of tracking the sun in order to achieve such high efficiency rates.

2. Methodology used to improve the efficiency of Solar Panel

2.1 Manual Cleaning

This technique calls for manual cleaning by a human operator using any wipers equipped with adequate support structures, as indicated in Figure 5. The operator himself evaluates the cleanliness of the surface using a visual approach until it is suitable or until all traces of dust have been eliminated. The solar power plants consist of several panels put at a height of 12 to 20 feet or more above the ground, making the operation exceedingly time-consuming and difficult. The required amount of time and the panel's and person's safety are at jeopardy. Manually cleaning panels requires the use of fluids like cleansers or gels, which act on the panel and lessen the surface transparency if cleaning is not done correctly. The PV panels are highly susceptible to physical damage, which cannot be prevented. When cleaning solar panels, there are a few tools that will be very helpful in getting the job done correctly. On the one hand, the soil is removed from the panel using a variety of specialised brushes that revolve. We might also use any straightforward cleaning tool, such the ones used on car windscreens.

FIGURE5: Manual Cleaning

2.2 Vacuum Suction Cleaning

An air pump is used by hoover suction cleaners to partially hoover up dust and other particles, typically from floors, window panes and other surfaces. The hoover cleaner motor typically receives an electrical feed in order to generate suction pressure. The vacuum cleaners wattage consumption does not correspond to how effective the device is. The output power, which is measured in air watts, is a conversion of the input power into airflow. Only the surfaces other than the corners of the panel may be fully cleaned by the hoover, and this must be done manually as illustrated in Figure 6. Given that the operator would inevitably need to move physically while using the cleaner on the panel, thorough training is required. Scratches and collected dust over time result in ineffective absorption of solar insolation.

Figure6: Vacuum Suction Cleaning

2.3 Automatic Wiper Based Cleaning

A rubber wiper and a water pot are used in the automatic wiper-based cleaning system to spray water with cleaning agents. The procedure is just like cleaning the windows of a car, and it needs an automatic mechanism to run and finish the job. Battery power powers the mechanism, as seen in Figure 7. This approach works in a similar way to the preceding one and is automatically [5] activated by the appropriate control mechanism.

Figure7: Automatic Wiper Based Cleaning

2.4 Cleaning using Electrostatic Repulsion

Without using water or brushes, the new device employs electrostatic repulsion to cause dust particles to separate and almost leap off the panel's surface. The dust particles receive an electrical charge from a simple electrode that passes just above the solar panel's surface to turn on the device. The dust particles are subsequently repelled by a charge placed on the solar panel itself. A straightforward electric motor and guide rails along the edge of the panel can be used to automate the system's operation. The newly created system just needs an electrode, which can be a straightforward metal bar, to pass over the panel in order to produce an electric field that charges the dust particles as it moves over it. The particles are then repelled by an opposite charge applied to a thin, transparent conductive layer that has been deposited on the solar panel's glass surface. By calculating the proper voltage to use [6], the researchers were able to determine a voltage range that was strong enough to counteract gravity and adhesion forces and cause the dust to lift away.

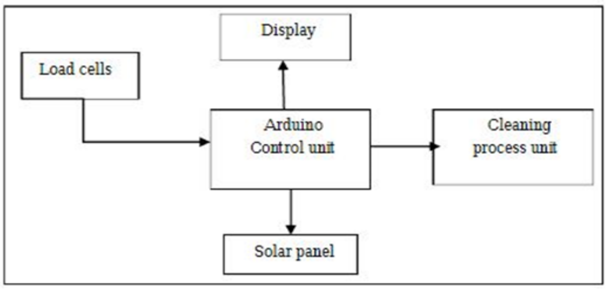

Figure8: Electrostatic Repulsion

2.5 Drones with mapping cameras and sensors

Solar panels need to be cleaned, but doing so is challenging because they continuously gather dust, grime, and other debris and are frequently found on top of large buildings or in isolated locations. A drone-based setup is created as a result. It will include a quad copter that is contained in a weather proof docking station that is placed close to the disputed solar panels. Two doors on top of the station will slide open at regular intervals, and the drone will emerge from them on a motorised platform before the plane lifts off and flies up to the panel's figure9. The drone will then line itself above each panel, spray it with cleaning fluid, then move on to the next one using tools such Lid AR sensors and mapping cameras. The aeroplane will return to the docking station after the cleaning work is finished and be lowered into it [7]. A robotic system will then swap out its batteries if necessary and swap out its empty cleaning fluid tank with one that is full.

Figure9: Drones with Mapping Cameras and Sensors

2.6 Internet of Things (IOT) Based

ARDUINO- Internet based system to continuously Monitor the solar panel parameters to detect any faults in connections & circuit failures. It will then inform for it to timely get repaired. It transmits the power output to IOT system. For maximum power generation, solar power plants need to be closely watched. This aids in obtaining power from power plants in an effective manner while keeping an eye out for damaged solar panels, loose connections, dust accumulation on panels reducing output, and other similar problems impacting solar performance.[8] The automated solar power monitoring solution that we suggest here is based on the Internet of Things and enables automatic solar power monitoring from anywhere over the internet. To track the parameters of a 10Watt solar panel, we use an Arduino-based system [9]. The solar panel is continuously monitored by our system, which also sends the power output to an IOT system over the internet (see fig.6)

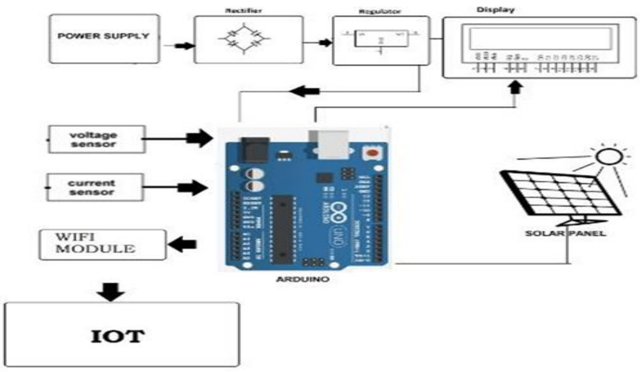

Figure10: Arduino based System

2.7 Robotics

Companies like Italy's Wash Panel are now able to make automatic and semi-automatic robots that are specifically made for cleaning solar panels thanks to advancements in robotics technology. For panels put on locations like carports, greenhouses, and shed roofs, it supplies transportable semi-automatic robots. Additionally, it provides fixed roof robots for substantial installations in dusty settings that need regular cleaning.

2.8 Nanoparticle coatings

An anti-dirt solar panel coating has been created by researchers at the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) division of India's Department of Science and Technology. In India, a trifecta of high temperatures, high humidity, and severe pollution reduces the efficiency of PV panels. The nanoparticle-based technology is highly clear and repels dust, allowing it to be easily removed with water without affecting the effectiveness of the panel. The coating is created by Indian company Marichin Technologies for commercial use.

Table1: An analysis of various solar panel cleaning systems

Technology	**Procedure f Cleaning**	**Cleaning Efficiency**	**Special Qualities**	**Drawbacks**	**Remarks**	**Refer.**
Cleaning Manually	Hand Washing	removes all types of dust, including oil layer and bird droppings	Cleaning Assisted by Humans	(i) Manpower Is Needed (ii) Large Solar Farms Are Ineffective (iii) The solar panel's surface may be harmed.	Small Solar Home Systems	[10]
	Kit for Cleaning	Removes all types of dust, including oil layer and bird droppings.	Additional shafts and a unique cleaner		Implementable Useful for large-scale rooftop solar plants with arbitrary array configurations	

	Misting Water	removes particles of dust	Water house applied manually		Better suited for locations with lots of water	
	Rainwater Purification	removes particles of dust	Using Natural Cleaning		PV Site situated in Tropical regions	
Self-Cleaning Approach	translucent Nano film with a coating	cleaner than a natural method using rainwater	A thin film covering has no impact on a panel's effectiveness.	Low system reliability across a range of site conditions	Useful for installing remote sensor networks powered by PV	[11], [12]
Water Cleaning Robots	automatic sprinkler system	removes dust particles and bird droppings	Regular water rinses prevent accumulated filth from adhering.	Not appropriate in areas with a lack of water	Useful for rooftop solar power systems	[13]
Robotic System	Water Based Cleaning	Clean hard dirt and dust deposits	After cleaning, the smoothness of the panel surface is still present.	Sophisticated and complicated system, additional costing of water	Useful for Large-Scale Solar Plants with Plenty of Water Resources	[14-17]
	Without Water Cleaning	Without using any water, remove both clean and difficult dirt	low cost of operating	limited to a specific module Configuration	Useful for Large-Scale Solar Plants with Limited Water Resources	[18,19]
	Robotics with IoT Integration	Cleaning efficacy varies depending on the methodology utilised, which might include both water-based and waterless methods.	(i) Remotely tracking current plant conditions (ii) Needs no human involvement	Complex system, high initial investment, and requirement for a skilled and qualified supervisor	Suitable for remote big solar plants and semi-arid regions	[20,19]

3. Solar Panel Cleaning using Artificial Intelligence

Cleaning solar panels is a critical task to ensure their efficiency and maximize energy production [21]. Traditionally, manual cleaning or automated cleaning systems like water sprinklers or brushes have been used. However, artificial intelligence (AI) can revolutionize the way solar panels are cleaned by making the process more efficient and cost-effective.

Here's how AI can be utilized for solar panel cleaning:

- **Automated Drones**: Drones equipped with AI-powered image recognition can fly over solar panel arrays, identify dirty or shaded areas, and schedule cleaning based on real-time data. AI algorithms can also optimize the cleaning route to minimize energy loss during the cleaning process.

- **Computer Vision**: AI can be used to analyse images captured by cameras mounted on the ground or on drones. By recognizing dirty or faulty solar panels, the AI system can automatically trigger cleaning operations.
- **Weather Prediction and Scheduling**: AI algorithms can analyze weather forecasts and plan cleaning schedules during periods of low solar power generation or predict when panels are likely to get dirty, optimizing cleaning efforts.
- **Robotics and Automation**: AI-powered robotic systems can be designed to move autonomously on the solar panels' surface, using soft brushes or other cleaning mechanisms to remove dust and debris.
- **Machine Learning and Predictive Maintenance**: By applying machine learning to historical data, AI can predict when solar panels are likely to get dirty based on location, weather conditions, and other factors. This allows for proactive cleaning before performance degradation occurs.
- **Autonomous Cleaning Vehicles**: AI can be integrated into specialized vehicles that move along the rows of solar panels and use various cleaning techniques to keep them clean.
- **Drone Swarms**: Multiple drones equipped with AI can work collaboratively to cover large solar farms efficiently, identifying and cleaning panels as a team.
- **Energy Yield Optimization**: AI algorithms can analyze the impact of dirt and other environmental factors on energy generation. By continually monitoring and cleaning panels, AI can maximize the solar farm's overall output.

3.1 Benefits of using AI for solar panel cleaning:

- Increased Efficiency: AI can optimize cleaning schedules and methods, reducing energy losses due to dirty panels.
- Cost Savings: Automated cleaning with AI can lower labor costs and improve the longevity of solar panels, leading to overall cost savings.
- Real-Time Monitoring: AI can continuously monitor the performance of solar panels and alert operators in case of faults or inefficiencies.
- Environmental Impact: By maximizing energy production, AI-powered cleaning contributes to reducing reliance on fossil fuels, thus having a positive impact on the environment.
- Scalability: AI can easily scale to handle large solar panel installations, making it ideal for utility-scale solar farms.

4. Schematics for Machine Learning Implementation in PV Cleaning System that have been suggested

Machine learning is most suited to address this specific issue due to its capacity to inherit specific behaviours, the trend of the dataset and its ability to confidently classify or anticipate the comparable behaviours that it has learned through.

- ✓ **Data Selection:** As was covered in the sections before, there are a number of factors that affect a solar photovoltaic module's efficiency. Dust Density, Module Temperature (Tpv), Ambient Temperature and Humidity. The influencing factors are air mass. Solar irradiance (Gpv), a measurement of the amount of solar energy input, is referred to as the input parameter. Solar irradiance (Gpv), a measurement of the amount of solar energy input, is referred to as the input parameter. Array voltage (Vpv) and Array current (Ipv) are the output parameters. The more parameters that are included, the more accurate the model may be; as a result, the system will be more complex and expensive. Due to the various soiling circumstances at different times of the year, it is seen in the study conducted in Middle Eastern nations [22, [23] that seasonal meteorological data are of utmost relevance in deciding the cleaning intervention.
- ✓ **Data Processing:** Processing the data that was gathered and appears to be inaccurate is necessary before casting the calibration model for the decision-making. The simplest data processing method is time series, which treats each parameter input as a separate entity. In contrast, simple featuring interprets a set of input data as a statistical interpretation (mean, mode, median, variance), grouping multiple instances of data that share a feature into a single instance. Principal Component Analysis (PCA) is more complicated than the other two and is typically employed when there are many parameters to consider and accuracy is crucial. Similar to this, there are more advanced data processing methods that can be employed effectively.
- ✓ **Model Selection:** One of the easiest calibration modelling methods used to define the linear relationship between the parameters is logistic regression. Numerous sophisticated machine learning methods, including as support vector machines, artificial neural networks, random forests, transfer learning, and deep learning, can be examined, and the best among them should be used, depending on the quality of the processed data, the parameters involved, and the level of accuracy necessary.
- ✓ **Evaluation of Performance:** After evaluating various combinations of machine learning models and data processing tools, the best combination is chosen among them based solely on the system's accuracy, cost, energy consumption and computational time, particularly as required by the solar photovoltaic system's specification.

5. Conclusion

Solar panels have proven to be a highly viable and sustainable solution for generating clean and renewable energy. Solar panels harness energy from the sun, a virtually limitless and clean source of power. By converting sunlight into electricity, solar panels help reduce greenhouse gas emissions, air pollution and reliance on fossil fuels, reducing the effects of climate change in the process [24]. The automation of cleaning operations reduces the dependence on human intervention, minimizing the likelihood of errors and ensuring a reliable and consistent performance of the solar panels over time. The integration of IoT technology provides real-time monitoring capabilities, enabling the system to assess the cleanliness status of panels and determine the most appropriate cleaning schedules. Through data-driven analytics and sensor feedback, the cleaning process becomes highly adaptable to prevailing weather conditions. For instance, the system can intelligently avoid cleaning during rainy periods but prioritize cleaning after dusty days, maximizing the effectiveness of each cleaning cycle [25]. This increased reliability translates to greater confidence in the solar energy system's overall performance and a reduced need for manual maintenance, ultimately contributing to lower operational costs. As renewable energy sources like solar power become more integral to global energy strategies, the adoption of IoT-enabled automatic cleaning systems becomes a crucial step towards sustainable and efficient energy production. By harnessing the power of optimization techniques and IoT connectivity, solar panel cleaning can be streamlined, efficient and environmentally friendly, solidifying the place of solar energy as a key player in the transition to a greener and more sustainable future.

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