

Solar Panel Monitoring by Temperature and Dust Maintenance

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Abstract—The efficiency of photovoltaic (PV) panels is significantly affected by environmental factors such as temperature rise and dust accumulation. This paper presents an active cooling and dust mitigation system that employs water spraying controlled by Arduino-based sensors. Mathematical models for heating and cooling were developed, and MATLAB simulations were conducted to analyze the effect of temperature on power output. Hardware experiments validated the simulation results, showing a decrease in efficiency from 15.71% at 23°C to 12.29% at 40°C for clean modules, and further losses due to dust deposition. Powder-like dust caused up to 25.64% efficiency loss compared to 22.44% for sand. The proposed system effectively maintains panel performance by reducing overheating and cleaning dust, thereby enhancing efficiency and extending panel lifespan.

Index Terms—Solar irradiance, Photovoltaic (PV) efficiency, Temperature coefficient, Dust accumulation, Active cooling, MATLAB simulation, Arduino monitoring, Water spraying system.

I. INTRODUCTION

Solar energy has emerged as one of the most promising renewable energy resources due to its abundance, sustainability, and cost-free availability. Photovoltaic (PV) technology plays a pivotal role in harnessing solar energy by converting sunlight directly into electricity. However, the efficiency of PV panels is highly sensitive to environmental conditions, particularly temperature variations and dust accumulation on the panel surface. These factors significantly reduce the energy conversion efficiency, thereby limiting the overall performance and reliability of solar power systems.

The temperature of a solar panel directly influences its output characteristics. As the operating temperature

rises above the nominal value (typically 25 °C), the electrical resistance within the semiconductor material increases, leading to a reduction in voltage and overall power output. The temperature coefficient of PV modules quantifies this effect, indicating that for every 1 °C rise in temperature, efficiency decreases by approximately 0.5%. This overheating phenomenon is particularly critical in tropical regions such as India, where high ambient temperatures and intense solar irradiance are common.

Dust deposition is another major challenge affecting PV performance. Airborne particles such as sand, soil, and industrial pollutants settle on the panel surface, blocking solar irradiance from reaching the cells. The severity of efficiency loss depends on particle size and density; finer particles such as powder form a compact layer that reduces irradiance penetration more effectively than larger particles like sand. Studies have shown that dust accumulation can cause efficiency losses ranging from 10% to 30%, depending on environmental conditions.

To address these challenges, researchers have proposed various cooling and cleaning techniques. Passive cooling methods, such as natural convection, are simple but often insufficient under high irradiance conditions. Active cooling approaches, including water spraying, air circulation, and hybrid photovoltaic/thermal (PV/T) systems, have demonstrated significant improvements in efficiency, with water-based cooling reducing panel temperature by up to 8 °C and increasing efficiency by 3%. Similarly, automated cleaning systems have been developed to mitigate dust deposition, ensuring consistent panel performance without manual intervention.

II. FACTORS AFFECTING THE SOLAR PANEL EFFICIENCY

A. Overheating effect

One of the most critical factors influencing the performance of photovoltaic (PV) modules is overheating. PV cells are designed to operate optimally at a nominal temperature of around 25 °C. When the operating temperature rises beyond this threshold, the semiconductor properties of the solar cell are adversely affected. Specifically, the bandgap energy decreases with increasing temperature, which reduces the open-circuit voltage (V_{oc}) and, consequently, the maximum power output. Although the short-circuit current (I_{sc}) may increase slightly with temperature, this effect is negligible compared to the significant voltage drop, resulting in an overall decline in efficiency.

The temperature coefficient of PV modules quantifies this relationship, typically indicating a loss of about 0.5% efficiency per 1 °C rise above 25 °C. For example, in tropical regions such as Kerala, India, where ambient temperatures frequently exceed 35 °C, PV panels can experience efficiency losses of more than 5–10% during peak irradiance hours. This thermal stress not only reduces instantaneous energy conversion but also accelerates material degradation, leading to long-term reliability issues such as delamination, solder joint fatigue, and reduced lifespan of the module.

Experimental and simulation results from this study confirm the severity of overheating. MATLAB simulations demonstrated a reduction in output power from 49.5 W at 23 °C to 40.23 W at 40 °C, representing an 18.7% loss. Hardware experiments showed similar trends, with efficiency dropping from 15.71% at 23 °C to 12.29% at 40 °C for a clean module. These findings highlight the direct correlation between temperature rise and efficiency degradation, validating the theoretical predictions.

Overheating is therefore a dual challenge: it reduces the immediate energy yield and accelerates long-term wear of PV systems. Effective cooling strategies, such as water spraying, air circulation, or hybrid photovoltaic/thermal (PV/T) systems, are essential to mitigate these effects. Among these, water-based cooling has proven to be the most effective, reducing panel temperature by up to 8 °C and improving efficiency by approximately 3%. By integrating active

cooling mechanisms with real-time monitoring, PV systems can maintain stable performance even under high irradiance and ambient temperature conditions, ensuring both higher energy conversion rates and extended operational lifespan.

B. Dust effect

Dust deposition on photovoltaic (PV) panels is a major environmental factor that significantly reduces energy conversion efficiency. When airborne particles such as sand, soil, or industrial pollutants settle on the surface of solar modules, they obstruct solar irradiance from reaching the semiconductor cells. This obstruction reduces the effective input energy, thereby lowering the output power. The severity of efficiency loss depends on the type, size, and density of dust particles. Larger particles such as sand create partial shading, while finer particles such as powder form a compact layer that blocks irradiance more effectively, leading to greater efficiency degradation.

The mechanism of dust-induced losses can be explained by optical and thermal effects. Optically, dust reduces transmittance by scattering and absorbing incident light, which decreases the short-circuit current (I_{sc}). Thermally, dust accumulation increases localized heating on the panel surface, further compounding efficiency losses due to the temperature coefficient effect. This dual impact makes dust one of the most critical challenges in maintaining PV performance, especially in regions with high particulate matter concentration.

Experimental results from this study clearly demonstrate the impact of dust on PV efficiency. When sand particles were deposited on the panel, efficiency losses ranged from 11.63% at 23 °C to 22.44% at 40 °C. In contrast, powder-like dust caused even higher losses, starting at 17.56% at 23 °C and reaching 25.64% at 40 °C. These findings confirm that smaller particles have a more detrimental effect due to their compactness and ability to form a uniform layer that blocks irradiance penetration. The comparison between sand and powder highlights the importance of particle size in determining the severity of efficiency reduction.

Dust accumulation is not only a short-term performance issue but also a long-term reliability concern. Persistent deposition can lead to surface abrasion, chemical reactions with moisture, and uneven heating, which accelerate material

degradation. In regions with high dust density, such as industrial zones or arid climates, PV panels may lose up to 30% of their efficiency if not regularly cleaned. Manual cleaning methods are labor-intensive and water-consuming, making them impractical for large-scale installations.

III. SCHEMATIC BLOCK DIAGRAM

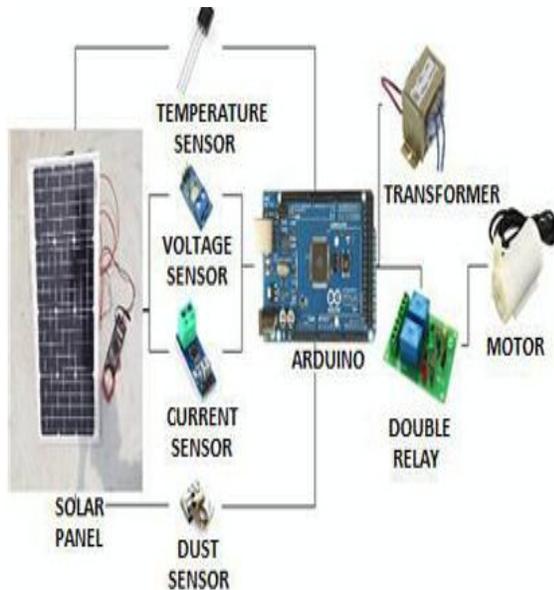


Figure describes the schematic block diagram of the experiment. Here the solar Panel is connected with temperature sensors, dust sensors, current sensors and voltage sensors to measure the required data. These sensors are connected to the Arduino where a certain code is dumped into it to monitor the solar panel and if any of the data from the temperature or dust sensor goes beyond the reference amount, then the relay turns on. Then the motor pumps some water over the panel until it reaches the value required, where the efficiency is high.

IV. COOLING TECHNIQUE

To mitigate the adverse effects of overheating in photovoltaic (PV) modules, several cooling strategies have been developed to maintain optimal operating temperatures and enhance efficiency. Passive cooling methods, such as natural convection and computational fluid dynamics (CFD) designs, rely on ambient airflow but are often insufficient under high

irradiance conditions. Active cooling approaches, on the other hand, employ external agents such as air or water to dissipate excess heat more effectively. Air-based cooling systems can reduce panel temperature by approximately 4.7 °C, resulting in a 2.6% efficiency improvement, while water-based cooling systems achieve greater performance, lowering temperature by up to 8 °C and increasing efficiency by 3%. Hybrid photovoltaic/thermal (PV/T) systems further integrate cooling with energy recovery, using circulating fluids to simultaneously generate electricity and thermal energy. More advanced solutions, such as micro-heat pipe arrays and thermoelectric coolers, transfer heat away from the PV surface with high precision, though they may involve higher costs and complexity. Among these techniques, water spraying has proven particularly effective in regions with high ambient temperatures and dust accumulation, as it not only cools the panel but also cleans the surface, thereby addressing both thermal and optical losses. The choice of cooling method depends on environmental conditions, resource availability, and system design, but active water-based cooling remains one of the most practical and efficient solutions for enhancing PV performance.

V. TYPES OF COOLING TECHNIQUES

The efficiency of photovoltaic (PV) panels is strongly influenced by their operating temperature, making cooling strategies essential for maintaining optimal performance. Several techniques have been proposed and implemented to address overheating, ranging from passive methods to advanced active cooling systems.

- **Passive Cooling Approaches:**
Passive cooling relies on natural convection and radiation to dissipate heat without external energy input. Computational Fluid Dynamics (CFD) models have been used to design panel structures that enhance airflow and promote natural convection. While these methods are simple and cost-effective, their effectiveness is limited under high irradiance and elevated ambient temperatures, where heat dissipation is insufficient to prevent efficiency losses.
- **Active Cooling Approaches:**
Active cooling techniques employ external agents such as air or water to remove excess heat more effectively. Air-based cooling systems use forced convection, often with fans, to circulate air across the

panel surface. Experimental studies show that air cooling can reduce panel temperature by approximately 4.7 °C, resulting in a 2.6% increase in efficiency. Water-based cooling systems, on the other hand, achieve greater performance by spraying or circulating water over the panel surface. This method can lower panel temperature by up to 8 °C and improve efficiency by 3%. In addition to cooling, water spraying simultaneously removes dust particles, thereby addressing both thermal and optical losses.

- **Hybrid Photovoltaic/Thermal (PV/T) Systems:**
PV/T systems integrate cooling with energy recovery by circulating fluids such as water or air through heat exchangers attached to the PV modules. These systems not only reduce panel temperature but also capture thermal energy for secondary applications such as water heating. Although PV/T systems offer dual benefits, they involve higher installation costs and complexity compared to standalone cooling methods.

- **Advanced Cooling Solutions:**
Innovative techniques such as micro-heat pipe arrays, phase change materials (PCM), and thermoelectric coolers (TEC) have been explored to enhance cooling efficiency. Micro-heat pipes transfer heat away from the PV surface with high precision, while PCM absorbs excess heat during peak irradiance and releases it gradually. TEC devices actively pump heat using electrical energy, offering precise temperature control. However, these advanced solutions are often expensive and less practical for large-scale deployment.

- **Proposed Water-Based Cooling System:**
In this study, a water-based cooling system integrated with real-time monitoring was developed. Sensors continuously measure temperature, dust deposition, voltage, and current, and when threshold values are exceeded, an Arduino-controlled relay activates a pump motor to spray water across the panel surface. This approach simultaneously cools the panel and removes dust, ensuring stable performance under varying environmental conditions. Simulation and hardware results confirm the effectiveness of this technique, with efficiency losses reduced significantly compared to uncooled and dusty modules.

- **Comparative Analysis:**
Among the techniques studied, water-based cooling provides the most practical balance between

performance improvement and resource utilization. While air cooling offers moderate gains, its inability to address dust accumulation limits its effectiveness. Hybrid PV/T systems and advanced cooling technologies deliver superior results but at higher costs and complexity. The proposed water spraying system, by combining cooling and cleaning functions, emerges as a cost-effective and efficient solution for enhancing PV performance, particularly in regions with high ambient temperatures and dust density.

TECHNIQUES	PERFORMANCE
Computational Fluid Dynamics (CFD)	It promotes natural convection cooling.
PVT / Air system	Influence of forced or natural convection on the cooling of PV modules.
Spraying water with a fan	It is inefficient because the entire panel may not be sprayed with water, which also results in a significant amount of water loss.
Micro-heat pipe array	It transfers the heat from the PV panels to the water or air.
Air as a coolant	The temperature is reduced by 4.7° and its efficiency is increased by 2.6 %.
Water as a coolant	The temperature is decreased by 8° and its efficiency is increased by 3%.

VI. CONCLUSION

This study has demonstrated that the performance of photovoltaic (PV) panels is significantly influenced by environmental factors such as temperature rise and dust deposition. Both simulation and hardware experiments confirmed that as the operating temperature increases beyond the nominal value of 23–25 °C, the output power and efficiency of PV modules decrease sharply. For instance, efficiency dropped from 15.71% at 23 °C to 12.29% at 40 °C in clean modules, validating the theoretical predictions of the temperature coefficient effect. Similarly, dust accumulation was shown to cause substantial efficiency losses, with powder-like particles reducing efficiency by up to 25.64% compared to 22.44% for sand at 40 °C. These findings highlight the dual challenge of thermal and optical degradation in solar panels.

To address these issues, an intelligent hardware system was developed that integrates temperature, dust, voltage, and current sensors with an Arduino-based controller. The system automatically

activates a water pump when threshold values are exceeded, thereby cooling the panel and removing dust simultaneously. This active cooling and cleaning technique proved effective in mitigating efficiency losses, ensuring stable performance under varying environmental conditions.

The proposed solution offers a practical, low-cost, and energy-efficient method to enhance PV performance, particularly in regions with high ambient temperatures and dust density. By maintaining optimal operating conditions, the system not only improves instantaneous energy yield but also extends the operational lifespan of solar panels. Future work may focus on optimizing water usage, integrating advanced cooling technologies such as phase change materials or hybrid PV/T systems, and scaling the design for large-scale solar farms. Overall, the findings contribute to sustainable energy transition by improving the reliability and efficiency of solar power systems

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