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Development of Floating Solar Panel Efficiency and Their Maintenance

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Abstract

Floating photovoltaic (FPV) systems offer a promising alternative to traditional ground-mounted solar panels by leveraging water surfaces to improve efficiency, conserve land, and reduce water evaporation. Despite their advantages, FPV systems face challenges such as overheating, dirt accumulation, and increased maintenance needs, which hinder their widespread adoption. This study addresses these limitations through the development of an innovative FPV system equipped with a 12V water pump for automated cooling and cleaning, monitored via an Internet of Things (IoT) platform. The methodology involves integrating the cooling and cleaning mechanisms into the FPV system, utilising IoT for real-time monitoring and control. Experiments were conducted to evaluate the system's performance under varying environmental conditions. Key performance metrics, such as temperature regulation, energy output, and cleaning efficiency, were compared to those of ground-mounted PV systems. Results demonstrate that the FPV system, with automated cooling and cleaning, consistently outperforms traditional systems. Cooling mechanisms reduced panel temperatures by up to 5°C, leading to a 10–15% increase in energy output. The cleaning system effectively removed up to 90% of dust, restoring panel efficiency within seconds. This research highlights the potential of FPV systems in advancing renewable energy technologies by improving efficiency, reducing maintenance, and promoting sustainability. Future work will focus on optimising materials for harsh environments, scaling the system for diverse aquatic settings, and evaluating its environmental impact. The findings underline the importance of supportive policies to drive the adoption of FPV systems as a viable solution for global energy demands.

1. Introduction

The transition to renewable energy is essential to address environmental challenges, improve energy security, and reduce greenhouse gas emissions. Among renewable sources, solar energy plays a vital role due to its abundance and accessibility. However, traditional ground-mounted photovoltaic (PV) systems face significant limitations, including land constraints and reduced efficiency caused by overheating (Silva & Branco, 2018).

Floating photovoltaic (FPV) systems offer a novel solution by positioning solar panels on water surfaces. These systems leverage water's cooling properties to enhance efficiency while conserving valuable land resources. Additionally, FPV systems help reduce water evaporation, making them particularly advantageous in arid regions (Dzamesi et al., 2024; Hammoumi et al., 2022). Despite these benefits, FPV systems encounter challenges such as dirt accumulation, algae growth, and increased maintenance needs, which negatively impact energy output and raise operational costs (Syafiq et al., 2018).

To address these issues, this study develops an automated cooling and cleaning mechanism for FPV systems using a 12V water pump. This system cleans dirt and debris from the panels while regulating their temperature through water-based cooling, thereby improving overall efficiency. IoT integration enables real-time monitoring and maintenance, ensuring reliability and sustainability. The study's objectives include evaluating the impact of these mechanisms on energy output, temperature regulation, and pollutant removal and comparing the performance of FPV systems with ground-mounted PV systems under various environmental conditions.

By tackling these challenges, this research contributes to advancing renewable energy technology, reducing carbon emissions, and promoting sustainable energy practices. It aligns with global efforts to address energy challenges and highlights FPV systems as a viable solution for sustainable energy generation.

2. Literature Review

Photovoltaic (PV) systems, which convert sunlight into electricity using semiconductors, have become a widely adopted technology for renewable energy generation due to their efficiency and reliability. Among the various types, monocrystalline and polycrystalline silicon solar cells dominate the market for their high performance, while thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) offer cost efficiency and flexibility but lower efficiency. Emerging technologies, like perovskite solar cells, hold the potential for high efficiency but face challenges related to stability and degradation (Parida et al., 2020; Chen et al., 2019). Floating photovoltaic (FPV) systems represent an innovative approach to address the limitations of land-based PV systems. By utilising water surfaces, FPVs overcome land scarcity issues while benefiting from water's cooling effect, which can enhance efficiency by reducing panel temperatures. Studies indicate that FPVs can improve energy output by 5–15% compared to ground-mounted systems, while also reducing water evaporation, making them particularly useful in arid regions (Hammoumi et al., 2022; Dzamesi et al., 2024). For examples, Fig 1 (a) ground-mounted solar, and Fig 1 (b) floating solar.


(a) (b)

Fig. 1: (a) Ground-mounted solar, (b) Floating solar (Dzamesi et al., 2024).

Furthermore, FPVs integrated with hydropower plants can maximise renewable energy output without additional land usage (Da Silva & Branco, 2018). Despite these advantages, FPV systems face significant challenges, including corrosion, biofouling, and dirt accumulation, which increase maintenance costs and reduce efficiency. Environmental impacts, such as disruption to aquatic ecosystems, must also be considered. Floating platforms that permit natural water flow can mitigate ecological concerns (Hammoumi et al., 2022; Elminshawy et al., 2022). Additionally, innovative materials and designs are being explored to improve the durability and efficiency of FPVs in harsh environments (Amer et al., 2023).

The integration of advanced technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), further enhances the potential of FPV systems. These technologies enable real-time monitoring and predictive maintenance, ensuring system reliability and scalability. As demand for renewable energy grows, advancements in materials, system designs, and integrated technologies are expected to strengthen FPVs' role in achieving global energy goals (Dzamesi et al., 2024; Dai et al., 2020).

Future research must focus on addressing existing challenges, such as optimising cooling and cleaning mechanisms, mitigating environmental impacts, and improving system longevity. The use of IoT-driven automated cleaning systems, as developed in this study, represents a promising solution to overcome these obstacles and promote the wider adoption of FPV systems for sustainable energy generation.

3. Methodology

This system combines solar energy, electronics, and remote monitoring to ensure efficient solar panel cooling and cleaning. The process begins with the solar panel, which turns sunlight into electrical energy. This energy is handled by a charge controller, which ensures that the attached 12V battery charges safely without overcharging or deep drain. The battery provides a dependable energy supply for components such as the ESP8266 Wi-Fi module, temperature sensor, and water pumps, allowing the system to operate constantly even in the absence of sunlight. Fig 2 illustrates a block diagram that provides an overview of the system's key components and their interactions.

Fig. 2: System block diagram.

The following components were utilised to develop the floating photovoltaic (FPV) system:

- **Solar Panels:** Convert sunlight into electricity.
- **12V Water Pump:** Enables cooling and cleaning of the panels.
- **ESP8266 Wi-Fi Module**: Facilitates IoT integration for remote monitoring and controls overall system.
- **Temperature Sensor:** Monitors panel surface temperature.
- **12V Battery:** Stores energy for continuous operation.
- **Charge Controller:** Protects the battery from overcharging and deep discharge.

3.1 Cooling and Cleaning Mechanism

A water pump was programmed to activate when the panel temperature exceeded 35°C, as monitored by the temperature sensor. The pump sprayed water on the panel surface, reducing its temperature and cleaning accumulated dirt. A flowchart of the process is shown in Fig 3, where the system checks temperature, establishes Wi-Fi connectivity, and performs cooling and cleaning operations.

It begins with a test and setup. If the temperature is above 35°C, the water pump cools the panels. The system connects to Wi-Fi for remote control, and if successful, the pump cleans the panels. If Wi-Fi fails, troubleshooting is required. The process ensures the panels stay efficient automatically.

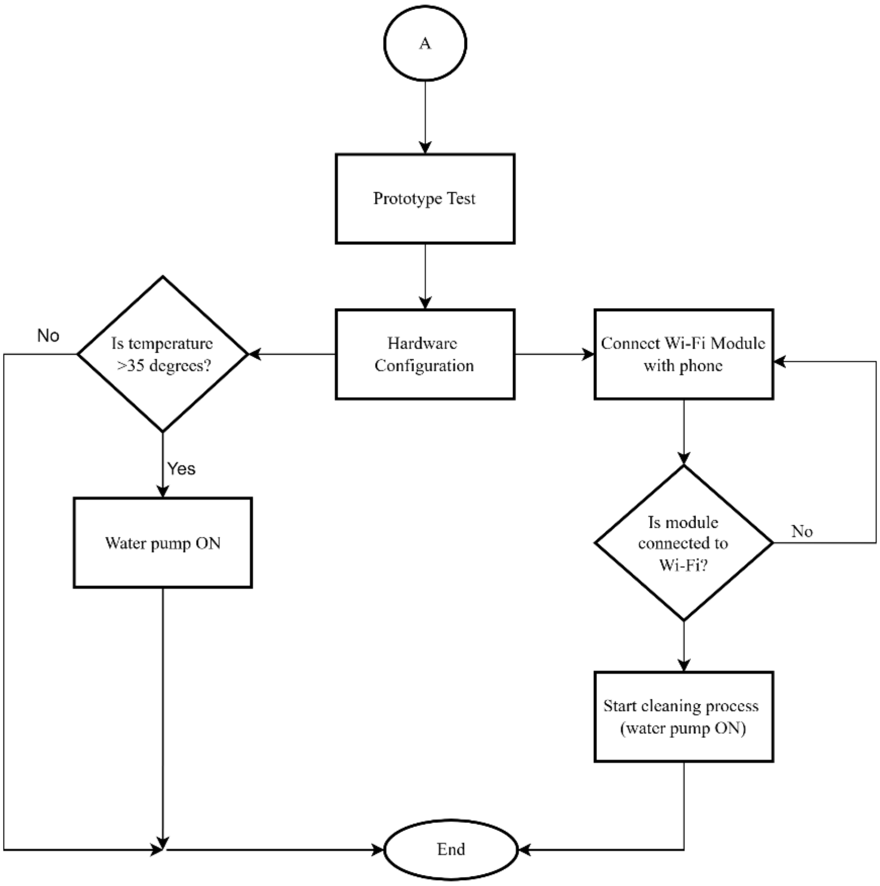


***Fig. 3*: Flowchart system.**

3.2 Data Analysis

The performance of the FPV system was evaluated under controlled environmental conditions. Key metrics included:

- **Temperature Regulation:** Measured panel temperature before and after cooling.
- **Energy Output:** Recorded voltage and current to calculate power generation under varying irradiance levels.
- **Cleaning Efficiency:** Assessed power recovery after cleaning at different levels of dust coverage.

Data were collected in intervals and analysed using statistical methods to identify trends and performance improvements compared to ground-mounted PV systems.

4. Results and Discussions

The project outcomes were assessed through controlled experiments to evaluate the functionality and performance of the floating photovoltaic (FPV) system. A key innovation was the use of a 12V water pump for cooling and cleaning, ensuring the panels remained efficient and free of debris. These experiments provided valuable insights into the system's effectiveness and durability under various conditions, including temperature changes and performance metrics.

4.1 Actual Prototype

A floating photovoltaic (PV) prototype was developed to evaluate the performance of renewable energy systems under real-world conditions. The prototype consisted of the following key components:

Buoyant Materials: These supported the PV panels on a stable metal frame, ensuring floatation on water surfaces.

PV Panels: Installed to convert sunlight into electricity efficiently.

MPPT Charge Controller: Used to optimise energy conversion by maintaining the panels at their maximum power point under varying irradiance conditions.

12V Battery: Stored energy for continuous system operation, especially during low sunlight conditions.

12V Water Pumps: Deployed for cooling the panels and load testing, ensuring stable operation and efficiency.

The system was designed to collect real-time data on energy output, panel temperature, and system performance. The integration of buoyant materials and robust structural components allowed the prototype to remain operational in various environmental conditions.

Data recorded from the prototype highlighted the effectiveness of the cooling mechanism in regulating temperature and maintaining optimal energy output. This setup addressed common challenges such as overheating and dirt accumulation, demonstrating the feasibility of floating PV systems as a sustainable energy solution. Fig 4 shows the prototype of floating solar panel.

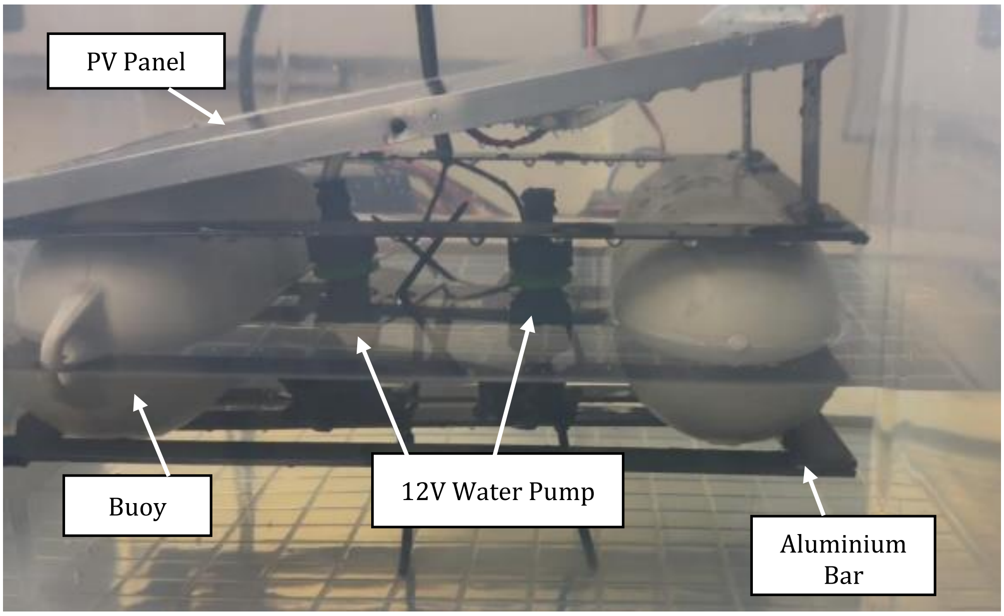


Fig. 4: The prototype floating solar panel.

4.2 Analyzing Front and Back Water Cooling on Solar Panel Output

The performance of solar panels was tested under two distinct cooling conditions: water applied to the front surface and water applied to the back surface. Each test was conducted for 60 minutes, and the total power output was recorded to evaluate the impact of temperature regulation on energy efficiency.

The experiment was carried out both with and without the cooling system to quantify its effectiveness. The cooling mechanism aimed to lower panel temperatures, as excessive heat reduces photovoltaic efficiency by increasing internal losses and decreasing voltage output. Table 1 and Table 2 present the measured results for the cooling system's performance under various irradiance levels, temperatures, and cooling methods. The results indicate that water cooling consistently improved power output by reducing panel temperature.

Table 1: *Performance with water applied to the front panel surface.*

	Irradiance (W/m²)	Temperature (°C)	Voc (V)	Isc (A)	Power (W)
Without Cooling Mechanism	451	36	19.8	0.48	9.50
With Cooling Mechanism	451	34	20.3	0.49	9.95
Without Cooling Mechanism	670	38	19.5	0.52	10.14
With Cooling Mechanism	670	37	20.0	0.53	10.60
Without Cooling Mechanism	734	40	19.20	0.56	10.75
With Cooling Mechanism	734	37	19.70	0.56	11.03

Table 2: Performance with water applied to the back panel surface.

	Irradiance (W/m²)	Temperature (°C)	Voc (V)	Isc (A)	Power (W)
Without Cooling Mechanism	442	36	20.3	0.47	9.54
With Cooling Mechanism	442	35	21.4	0.49	10.47
Without Cooling Mechanism	675	38	19.2	0.55	10.56
With Cooling Mechanism	675	37	20.75	0.56	11.62
Without Cooling Mechanism	725	39	18.97	0.57	10.82
With Cooling Mechanism	725	38	20.20	0.59	11.92

Key findings include:

Front Cooling: Increased power output by approximately 5% compared to no cooling.
Back Cooling: Achieved higher efficiency gains, with power output increasing by up to 10%, particularly under higher irradiance levels.

Fig 5 illustrates the power output comparison for both cooling methods, highlighting that back cooling consistently outperformed front cooling. The improved efficiency is attributed to better temperature regulation when cooling is applied to the back surface, which reduces thermal stress more effectively. These results demonstrate the significant role of temperature management in optimising solar panel performance, particularly in floating photovoltaic systems. Future optimisation of cooling designs may yield further efficiency improvements.

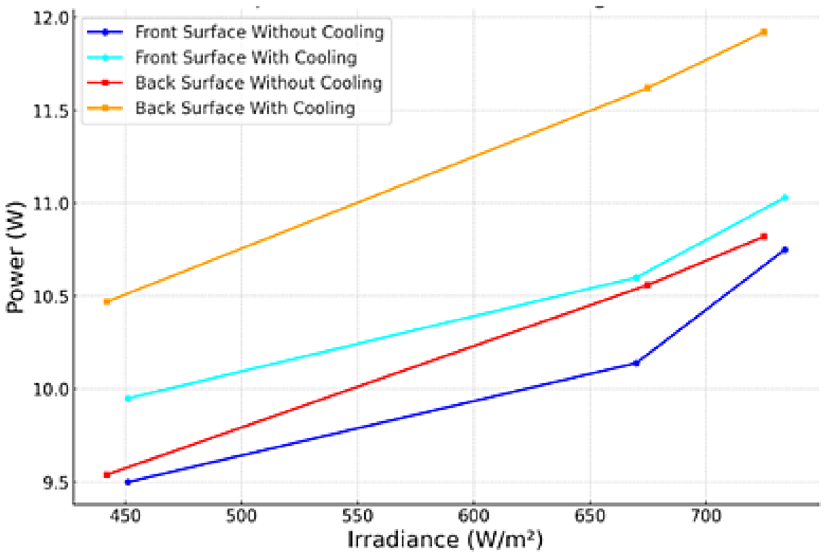


Fig. 5: Generated output for for both with and wihout cooling systems.

The data compares the power output of solar panels with water cooling applied to the front or back surface. Both cooling methods increase power output as irradiance rises. For front surface cooling, power improves from 9.50W at 451 W/m^2 to 11.03W at 734 W/m^2. For back surface cooling, power increases from 9.54W at 442 W/m^2 to 11.92W at 725 W/m^2, consistently outperforming front cooling, especially at medium to high irradiance. Cooling reduces panel temperature, improving efficiency by boosting voltage and current generation. Figure 5.1 illustrates the power output comparison for both cooling methods.

4.3 Performance Analysis of a Solar-Powered Water Pump

The performance of the solar-powered water pump was analysed to determine the relationship between irradiance, panel temperature, and system efficiency. The results demonstrate that as irradiance increases, the load voltage (V load) remains relatively stable. However, the load current (I load) and power consumption increase significantly, particularly when the water pump is active.

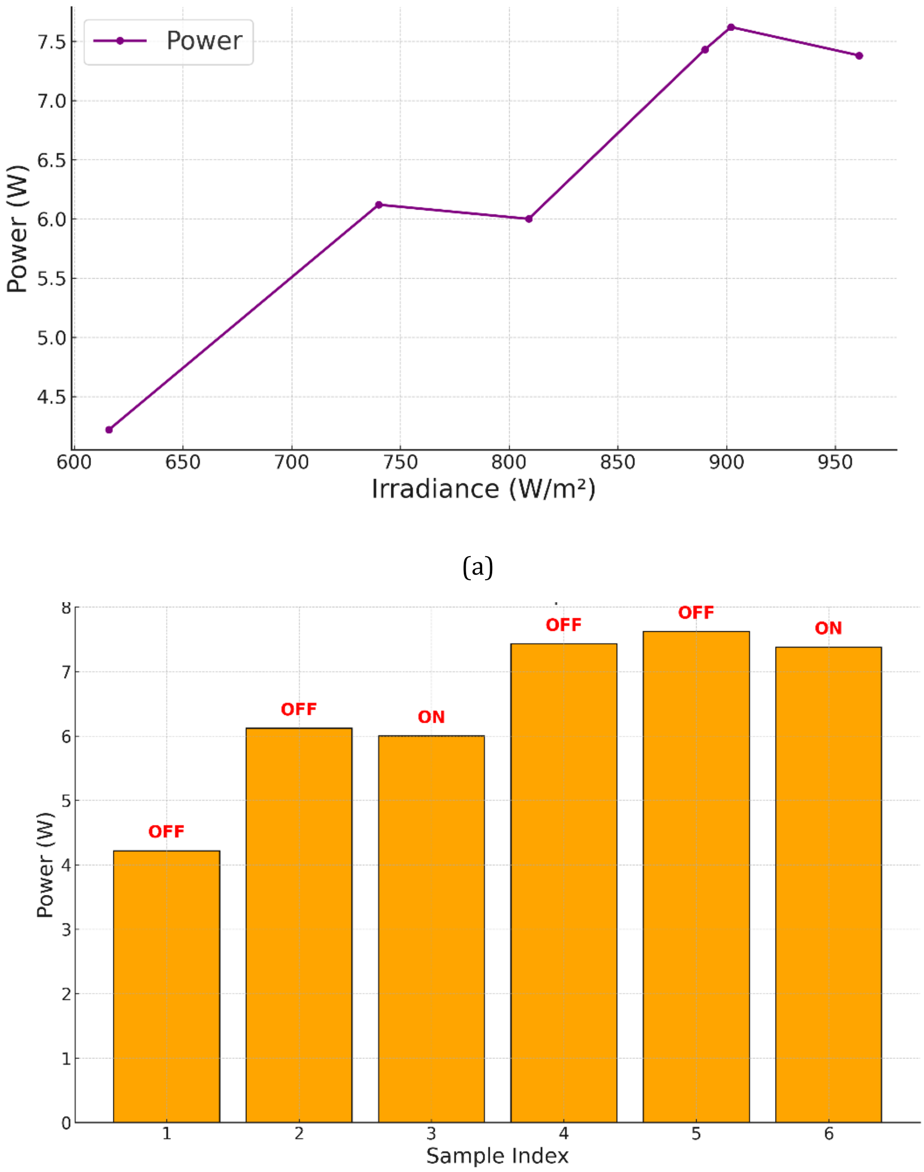
At higher irradiance levels, the increased energy generation enables the water pump to operate efficiently, while at lower irradiance levels, the system shows minimal activity with the pump switched off. This dynamic illustrates the dependency of pump functionality on available solar energy. Table 3 summarises the measured performance of the solar-powered water pump under varying irradiance conditions. Key findings include:

i. Higher irradiance levels (e.g., 809 W/m^2 and 961 W/m^2) resulted in higher power consumption by the pump due to increased current demand.
ii. During pump operation, the load voltage dropped slightly (e.g., from 13.6 V to 12.5 V) due to additional energy requirements, but the system maintained stable functionality.
iii. At lower irradiance levels (e.g., 616 W/m^2 and 740 W/m^2), the pump remained off, consuming negligible power.

***Table 3*: Measured results of solar-powered water pumps.**

Irradiance (W/m²)	Temperature Sensor (°C)	V_load (V)	I_load (A)	Power (W)	Battery Current (A)	Water Pump Condition
616	32.56	13.6	0.31	4.22	0.30	OFF
740	34.6	13.6	0.45	6.12	0.32	OFF
809	35.34	12.5	0.48	6.0	2.42	ON
890	34.50	13.5	0.55	7.43	0.46	OFF
902	33.75	13.6	0.56	7.62	0.48	OFF
961	35.19	12.5	0.6	7.38	2.45	ON

Fig 6 provides a visual representation of the results:



(a)

(b)

***Fig. 6*: (a) Generated output power under different irradiance levels, (b) Power consumption of the water pump during operation.**

At higher irradiance levels (616, 740, 890, and 902 W/m²), with the water pump off, the system maintains stable conditions with increased load voltage (V_load), current (I_load), and power output proportional to irradiance. When irradiance rises further (809 and 961 W/m²), the water pump activates, causing a drop in load voltage (from 13.6V to 12.5V) due to the pump's additional power demand. During pump operation, battery current increases (2.42–2.45A), whereas it is much lower when the pump is off (0.30–0.48A)

4.4 Cleaning Mechanism

The cleaning mechanism was developed to ensure optimal solar panel performance by effectively removing dust and dirt from the panel surface. This mechanism is controlled remotely through the Blynk app, providing users with flexibility and convenience in managing the cleaning process. Although the system is not fully automated, it offers an efficient manual solution for maintaining solar panel efficiency and minimising energy losses caused by dirt accumulation.

The cleaning system was tested under varying levels of dust coverage to evaluate its effectiveness. Table 4 summarises the cleaning duration and corresponding panel performance for different dust levels. Key findings include:

1. Increased dust coverage significantly reduced the open-circuit voltage (Voc), short-circuit current (Isc) and power output of the panels. For instance, at 90% dust coverage, the power output dropped to 3.93 W compared to 9.2 W at 20% dust coverage.

2. The cleaning process successfully restored panel performance, with cleaning durations ranging from 4 seconds for 20% dust coverage to 15 seconds for 90% dust coverage.

Table 4: Measured results of cleaning duration.

Dust Coverage (%)	Voc (V)	Isc (A)	Power (W)	Cleaning Duration (s)
20% Dust	18.8	0.49	9.2	4
40% Dust	17.9	0.46	8.23	6
60% Dust	16.1	0.41	6.60	9
80% Dust	14.2	0.35	4.97	12
90% Dust	13.1	0.30	3.93	15

These results emphasise the critical role of regular cleaning in maintaining the efficiency of floating photovoltaic systems. The integration of the Blynk app allows users to initiate the cleaning process remotely, which is particularly beneficial in inaccessible or large-scale installations. Future improvements could focus on automating the cleaning mechanism entirely, reducing the need for manual intervention while enhancing operational efficiency. Additionally, exploring alternative materials or designs for cleaning components may further optimise the system's performance.

5. Conclusion

This project demonstrated the feasibility and efficiency of floating photovoltaic (FPV) systems, which outperform traditional ground-mounted systems by leveraging water-based cooling to enhance energy output and conserve land. The integration of an effective cleaning mechanism restored panel efficiency, reduced manual maintenance, and extended operational lifespan. While initial costs are higher, FPV systems offer significant environmental and economic benefits, including reduced water evaporation and minimised habitat disruption. Future work should focus on scaling deployments to diverse environments, improving material durability for harsh conditions, and integrating IoT for real-time monitoring and maintenance. Comprehensive studies on environmental impacts and supportive policies, such as subsidies and incentives, are crucial to driving the widespread adoption of this innovative and sustainable energy technology.

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