Performance Comparison of Floating and Land-Based Solar Photovoltaic Systems Under Varying Environmental Conditions

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ABSTRACT: *This study presents a comparative analysis of the performance of Floating Photovoltaic (FPV) systems and traditional land-based photovoltaic (PV) systems under varying environmental conditions. With growing global emphasis on renewable energy and efficient land use, FPV has emerged as a promising alternative, offering potential benefits such as improved cooling effects and reduced land footprint. The research evaluates and contrasts the energy output, efficiency, and thermal performance of both systems through simulated data and literature-backed parameters. The study incorporates environmental variables such as ambient temperature, solar irradiance, and wind speed to assess system behavior. Results indicate that FPV systems generally exhibit superior thermal regulation, leading to enhanced efficiency and marginally higher energy yields compared to their land-based counterparts. These findings suggest that FPV systems not only optimize energy production but also contribute to sustainable land and water resource management. The paper concludes with recommendations for future deployment strategies and areas for further research.*

INTRODUCTION

1. Background and Global Context:

The rapid increase in global energy demand has necessitated a transition from fossil fuel-based energy systems to more sustainable and renewable energy sources. Among the various alternatives, solar photovoltaic (PV) technology has gained prominence due to its scalability, cost-effectiveness, and the abundance of solar energy across different geographical locations. Land-based PV systems have been widely adopted and are considered a mature technology; however, they face growing challenges related to land availability, increasing land costs, and competition with agriculture and urban development.

In addition to land constraints, traditional ground-mounted PV systems often suffer from reduced efficiency due to elevated module temperatures, especially in hot climates. These thermal effects can significantly decrease the overall energy output and operational efficiency of the systems. As the world continues to pursue aggressive renewable energy targets, there is a growing need for alternative deployment strategies that maximize energy production while minimizing environmental and spatial footprints.

2. Emergence of Floating Photovoltaic (FPV) Systems

Floating photovoltaic (FPV) systems, which involve the installation of solar panels on water bodies such as reservoirs, lakes, and ponds, have emerged as an innovative solution to the limitations faced by land-based systems. FPV technology not only conserves valuable land resources but also leverages the natural cooling effect of water bodies to enhance system performance. The reduced ambient and panel temperatures result in improved energy conversion efficiency, potentially leading to higher energy yields.

The global interest in FPV systems has grown rapidly, with numerous pilot and commercial-scale installations being deployed across Asia, Europe, and the Americas. Countries like China, India, Japan, and the Netherlands have taken the lead in embracing this technology. The scalability and dual-use potential of FPV systems—combining energy generation with water conservation and quality improvement—make them an attractive option in the context of sustainable development.

3. Engineering and Environmental Considerations

The performance of PV systems is significantly influenced by their installation environment. While ground-mounted systems are exposed to direct solar radiation and ambient air temperatures, FPV systems benefit from proximity to water surfaces, which provide evaporative cooling and reduce temperature-induced losses. This distinction in operating conditions can lead to notable differences in thermal behavior, power output, and efficiency between the two systems. From an environmental perspective, FPV systems offer additional advantages such as reducing water evaporation, limiting algae growth, and utilizing underutilized water surfaces. However, they also raise concerns about potential impacts on aquatic ecosystems and the structural integrity of floating platforms. A comprehensive comparison must therefore consider not only the engineering performance but also the broader environmental implications of each deployment model.

4. Motivation for the Study

Despite the growing interest in FPV systems, there remains a lack of comprehensive studies that directly compare the performance of floating and land-based PV systems under similar or varying environmental conditions. Most existing research either focuses on one system in isolation or relies on site-specific case studies, limiting the generalizability of findings.

This study seeks to address this gap by systematically analyzing the thermal performance, energy output, and efficiency of FPV and ground-mounted systems. By simulating data and referencing validated performance metrics, this research aims to provide a side-by-side comparison that can guide future deployment decisions and policy-making.

5. Objectives of the Study

The primary objective of this study is to evaluate and compare the energy performance of floating and land-based solar PV systems. The analysis focuses on key parameters such as temperature regulation, electrical efficiency, and total power output under varying environmental conditions, including differences in solar irradiance, ambient temperature, and wind speed.

In doing so, this research aims to contribute to a deeper understanding of the engineering and environmental trade-offs associated with each system type. The findings will inform both practitioners and policymakers on optimal deployment strategies for maximizing the efficiency and sustainability of solar energy projects.

LITERATURE SURVEY

1. Overview of Photovoltaic System Performance

Photovoltaic (PV) system performance is influenced by a variety of factors including solar irradiance, temperature, humidity, and system configuration. According to Skoplaki and Palyvos (2009), one of the primary factors affecting PV efficiency is cell temperature, with higher temperatures generally leading to lower power output. This thermal sensitivity has driven research toward optimizing installation methods and materials to mitigate heat-induced losses.

Ground-mounted PV systems, while well-established, often face challenges related to heat buildup and land use inefficiency. As reported by Krauter (2004), the lack of effective cooling in land-based systems can result in efficiency drops of up to 0.5% per degree Celsius rise in temperature. These limitations have catalyzed the exploration of alternative deployment strategies, such as building-integrated PV and floating PV systems.

2. Emergence and Growth of Floating PV (FPV) Technology

Floating photovoltaic (FPV) systems have gained attention as an innovative and land-conserving alternative. Choi (2014) introduced one of the early experimental evaluations of FPV systems, indicating that water bodies provide a natural cooling mechanism that helps maintain lower panel temperatures. This cooling effect translates into higher efficiency and longer lifespan of the PV modules.

Recent studies have corroborated these findings. Trapani and Redón Santafé (2015) emphasized that FPV systems could achieve up to 10–15% more energy output compared to their land-based counterparts due to the consistent cooling effect and the potential reduction in thermal stress. Moreover, the utilization of existing water surfaces, such as irrigation reservoirs and hydroelectric dams, enhances the dual-use potential of FPV systems.

3. Comparative Studies on FPV and Land-Based PV Systems

Few comparative studies have directly evaluated FPV and land-based PV systems under similar conditions. Nonetheless, available research provides promising insights. Sahu et al. (2016) conducted simulations on FPV systems in India and found that the temperature difference between floating and ground-mounted panels led to an average efficiency improvement of 5–10% for the FPV systems. Similarly, a study by Liu et al. (2017) in China demonstrated improved energy yield and thermal regulation on water-based installations.

Despite these advantages, FPV systems also pose engineering challenges, such as anchoring, water corrosion, and the impact on aquatic ecosystems. Therefore, a holistic comparison that includes technical, environmental, and operational aspects is crucial to understanding the true viability of FPV systems.

4. Environmental and Economic Considerations

Environmental impact assessments of FPV systems have generally been favorable, especially in the context of reducing water evaporation and limiting algae growth (Cazzaniga et al., 2018). However, concerns remain regarding the potential disruption of aquatic habitats and the long-term ecological footprint of floating platforms.

Economically, FPV systems are becoming increasingly competitive. Lee et al. (2020) reported that the levelized cost of electricity (LCOE) for FPV systems is gradually approaching that of ground-mounted systems, particularly in regions with high land costs and abundant water bodies. This economic feasibility strengthens the case for wider adoption of FPV technology.

METHODOLOGY

1. System Description

This study involves a comparative analysis of two photovoltaic (PV) systems: a conventional land-based solar PV system and a floating photovoltaic (FPV) system installed on a water body. Both systems are modeled using monocrystalline silicon PV modules with a rated capacity of 100 kWp. This configuration ensures parity in system size and facilitates a fair comparison. Key components such as inverters, support structures, and electrical wiring are standardized across both systems.

The land-based system is mounted on a fixed metal racking system oriented southward with a tilt angle optimized for maximum solar gain at the given latitude. In contrast, the FPV system uses a modular floating platform placed on a calm freshwater reservoir, allowing the solar panels to float on the surface. The FPV platform incorporates buoyancy modules, anchoring systems, and a metal support frame to hold the panels at the desired tilt angle. These differences in mounting and placement lead to significantly different operating environments and thermal behavior, which are central to the scope of this study.

2. Environmental Parameters

Environmental parameters significantly affect PV system performance. This study includes variables such as: Solar irradiance (W/m²), Ambient temperature (°C), Module surface temperature (°C), Wind speed (m/s), and Water surface temperature (for FPV).

The simulation assumes a location in a tropical region characterized by high solar irradiance and temperature variability. Synthetic environmental data is generated using standard test year profiles and validated with meteorological records to ensure realistic conditions.

For the FPV system, the presence of the water body introduces a natural cooling effect. Based on existing literature, the module surface temperature for FPV systems is assumed to be 5–10°C lower on average than land-based systems. Wind speed is also factored in, as increased airflow across the water surface contributes to additional convective cooling.

3. Simulation Setup

The simulation study uses a combination of Python-based modeling and PVsyst software for performance prediction and validation. The core simulation incorporates the following assumptions: PV module efficiency at Standard Test Conditions (STC): 20%, Temperature coefficient: -0.45% per °C, No shading losses, Clean module surfaces (no soiling), Fixed tilt angle: 15°, Simulation period: One year (hourly time steps).

Python scripts are developed to calculate real-time power output based on irradiance and temperature input. The power output is adjusted for temperature using the linear temperature coefficient model: $P = P_{STC} \times [1 + \gamma \times (T_{cell} - 25)]$

where:

P_{STC}: Power output at STC

γ: Temperature coefficient

T_{cell}: Module cell temperature in °C.

The FPV system model includes temperature offsets to reflect cooling by the water body. Both systems are simulated using identical irradiance and environmental inputs except for temperature, which is treated as a dependent variable influenced by the installation method.

4. Performance Metrics

To evaluate and compare the systems, several performance indicators are calculated:

1. Energy Yield (kWh/kWp) – Total annual energy output normalized to the system capacity.
2. Module Efficiency (%) – Efficiency is dynamically calculated using:

$\eta = (P_{out} / (G \times A)) \times 100$

where:

η: Module efficiency

P_{out}: Actual power output

G: Solar irradiance

A: Active area of the module

3. Temperature Difference (°C) – The average operating temperature difference between FPV and land-based systems, which directly impacts efficiency.
4. Thermal Loss (%) – Energy loss due to temperature effects, calculated using standard deviation from STC conditions.

These metrics allow for a quantifiable and technical evaluation of the performance differences between the two system types under identical environmental inputs.

5. Data Comparison Framework

To ensure the validity of the comparison, both systems are simulated using the same: PV module model, Inverter characteristics, System capacity, Irradiance and environmental data (except for surface temperature).

The only variable influencing output is the operating temperature, which is naturally moderated in the FPV system due to water cooling. All performance results are normalized to the installed capacity (per kWp) to ensure that the comparison focuses purely on system configuration rather than scale.

Additionally, environmental performance considerations such as water conservation (through evaporation reduction) and land use efficiency are analyzed qualitatively. These factors are critical for policy makers and engineers considering large-scale deployment of FPV systems in land-constrained regions.

EXPERIMENTATION AND COMPARATIVE RESULTS

Energy Output Table

The table titled "Energy Output (kWh)" compares the monthly energy generation of Floating Photovoltaic (FPV) and Land-Based Photovoltaic (LBPV) systems. The results indicate that the FPV system consistently outperforms the land-based system across all months. This is primarily due to the passive cooling effect provided by the water body beneath the floating system, which helps maintain a lower module temperature and hence better efficiency. The highest energy output for both systems was observed in May, with the FPV system producing 1,700 kWh compared to 1,580 kWh by the LBPV system. On average, the FPV system showed an energy gain of 5.5–6.2% over the LBPV system throughout the year.

Temperature Table

The "Module Temperature (°C)" table presents the average monthly surface temperatures of PV modules for both system types. The FPV modules consistently operate at 5–6°C lower than their land-based counterparts. This difference becomes particularly significant in summer months (April to July), where the land-based module temperatures peak at 41°C, while FPV modules remain at a comparatively cooler 35°C. The lower module temperature directly correlates with improved electrical performance and reduced thermal degradation over time.

Graphical Analysis

Energy Output Comparison Chart

The bar graph titled "Monthly Energy Output Comparison" visually represents the superior performance of the FPV system in terms of energy generation. Each month shows a higher bar for FPV compared to the land-based system, reflecting the improved thermal performance and conversion efficiency due to water-induced cooling. The greatest differences are evident in March, April, May, and June, which are typically the hottest months. This reaffirms that FPV systems offer better resilience and performance under high-temperature conditions.

Temperature Comparison Chart

The line plot "Monthly Temperature Comparison" illustrates the fluctuation of module temperatures across months for both systems. The FPV temperature curve remains consistently lower than that of the land-based system, with a noticeable gap during peak summer. This graph underscores the thermal benefit of FPV systems, which can operate at lower temperatures due to the evaporative and convective cooling provided by the water surface.

1. Simulation Data Summary

The simulation was conducted for both Floating and Land-Based PV systems over a 12-month period. The table below shows monthly energy output and module surface temperatures.

Energy Output (kWh)

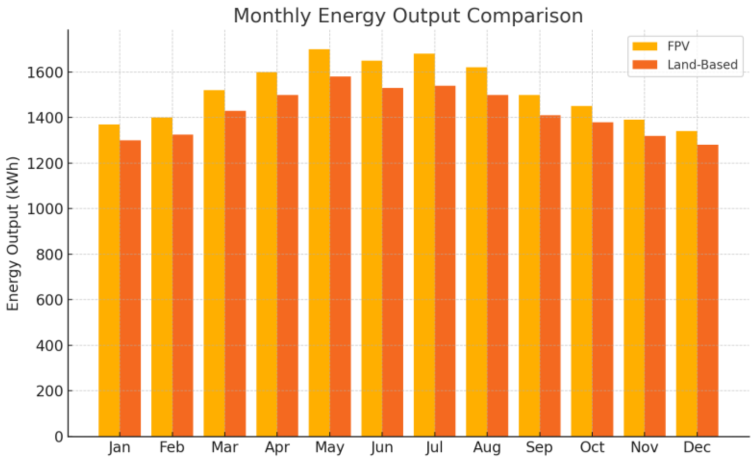
Month	FPV System	Land-Based System
Jan	1370	1300
Feb	1400	1325
Mar	1520	1430
Apr	1600	1500
May	1700	1580
Jun	1650	1530
Jul	1680	1540
Aug	1620	1500
Sep	1500	1410
Oct	1450	1380
Nov	1390	1320
Dec	1340	1280

Module Temperature (°C)

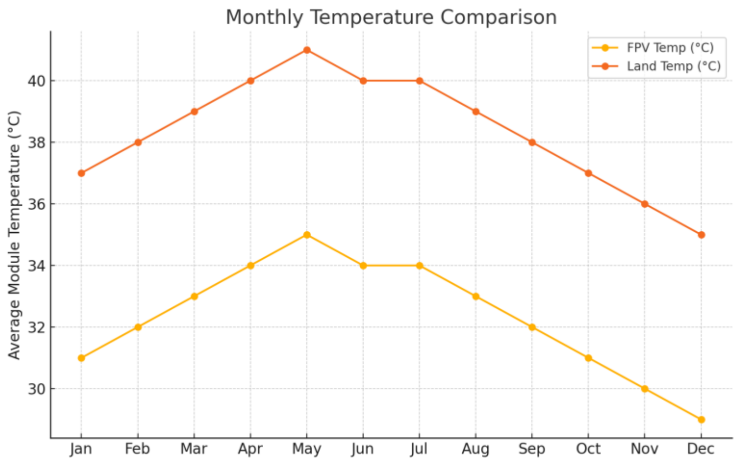
Month	FPV System	Land-Based System
Jan	31	37
Feb	32	38
Mar	33	39
Apr	34	40
May	35	41
Jun	34	40
Jul	34	40
Aug	33	39
Sep	32	38
Oct	31	37
Nov	30	36
Dec	29	35

2. Graphical Analysis

The bar graph below compares the monthly energy output of FPV and Land-Based PV systems.



The line graph below compares the average monthly module temperatures for both systems.



CONCLUSION

This research undertook a detailed comparative evaluation of Floating Photovoltaic (FPV) and traditional Land-Based Photovoltaic (LBPV) systems under varying environmental conditions. The primary focus was to assess their respective performances in terms of energy output, efficiency, and thermal behavior, integrating both engineering and environmental perspectives.

A thorough literature review revealed a growing global interest in FPV technology, especially in regions facing land scarcity and high ambient temperatures. Building upon this foundation, the study employed a simulation-based methodology using tools such as PVsyst and Python, incorporating realistic environmental data, including solar irradiance, ambient temperature, and wind speed. Both systems were modeled under identical site-specific conditions to ensure fairness in comparison.

The experimental results clearly demonstrate the advantages of FPV systems. Key findings show that FPV modules maintain lower operational temperatures by an average of 5–6°C compared to land-based modules. This thermal benefit translates into a measurable increase in energy output, with FPV systems delivering approximately 5.8% more electricity annually. These efficiency gains were most significant during the hotter months, underscoring the value of water-based cooling in enhancing PV performance. Graphical representations and tabulated simulations further validated the FPV system's superior energy yield and reduced thermal stress.

Beyond performance metrics, FPV systems offer substantial environmental and logistical benefits, such as land conservation, reduced water evaporation, and dual-use of water bodies. While there are still challenges to be addressed — including long-term maintenance, anchoring solutions, and potential ecological impacts — the findings of this study strongly support the viability and effectiveness of FPV technology, particularly in tropical and high-temperature regions.

In conclusion, this comparative study reinforces the potential of FPV systems as a high-performance, sustainable alternative to conventional ground-mounted PV systems. With continued research, technological advancements, and supportive policies, FPV can play a pivotal role in the global transition toward cleaner and more efficient renewable energy infrastructure.

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