

IMPROVING THE RELIABILITY OF SOLAR ENERGY SYSTEMS USING FLOATING PHOTOVOLTAIC TECHNOLOGIES

M.T. Babayev

Azerbaijan State Oil and Industry University, Baku, Azerbaijan
mazahir.babayev@asoiu.edu.az

Abstract

This paper explores floating solar panels (FSPs) as a promising and cost-effective solution for enhancing the reliability and sustainability of solar power systems. The analysis focuses on the technical, environmental, and economic benefits of FSPs compared to traditional land-based installations. Floating systems offer improved operational reliability and energy efficiency due to natural cooling, land conservation, lower environmental impact, and reduced water evaporation – particularly vital in regions with limited freshwater resources. Deploying FSPs on artificial reservoirs and flooded quarries not only reduces land-use pressure but also contributes to lower capital and operational expenditures. Case studies from Azerbaijan and Japan demonstrate the reliability, resilience, and ecological viability of floating solar solutions under various climatic conditions. Although initial investments may be higher, long-term assessments reveal that FSPs can deliver more consistent performance and greater cost-effectiveness in regions with high solar irradiance and available water surfaces. The paper provides a comprehensive overview of floating photovoltaic technologies, highlighting their role in improving the reliability and stability of solar energy supply.

Keywords: floating solar panels, renewable energy, environment, reliability.

I. Introduction

The modern development of renewable energy focuses on finding solutions capable of simultaneously meeting growing energy demands and minimizing negative environmental impacts. One such solution is floating solar panels (FSP), installed on water surfaces. These innovative systems not only enhance energy resilience but also create new opportunities for optimizing the use of natural and financial resources.

The economic potential of FSP lies in significantly reducing operational and capital expenses compared to land-based solar power stations. Utilizing existing water bodies eliminates land acquisition costs and minimizes infrastructure construction expenses. Moreover, the installation of FSP on already available facilities, such as hydroelectric power plants or artificial reservoirs, allows seamless integration into existing energy systems, thereby reducing investment risks [1-3].

In terms of reliability, FSP demonstrates advantages due to natural cooling, which decreases wear on the panels and extends their operational lifespan. However, comprehensive reliability assessment requires consideration of various failure mechanisms specific to floating systems, such as corrosion due to constant water exposure, wave-induced mechanical stresses, and biofouling or biological damage. These factors can significantly impact the durability and operational lifetime of FSP components.

Furthermore, the increasing frequency of extreme weather events linked to climate change – including storms, hurricanes, and floods – poses catastrophic risks to FSP installations, necessitating robust probabilistic modeling of such scenarios to predict failure likelihood and plan appropriate mitigation measures.

This article examines not only the technical and environmental aspects of FSP applications but also their economic feasibility and reliability, including:

- Analysis of failure factors and forecasting methods for corrosion, mechanical fatigue, and biological damage;
- Probabilistic reliability modeling that incorporates time-dependent degradation processes;
- Influence of local environmental conditions such as water salinity on cooling efficiency and corrosion rates;
- Assessment of catastrophic event impacts (e.g., storms) on system survivability;
- Incorporation of multi-year monitoring data from real installations to validate reliability models;
- Calculation of Mean Time Between Failures (MTBF) for key components, including anchoring systems and cable connections;
- Evaluation of how improved reliability affects the levelized cost of energy (LCOE) over the system lifecycle.

II. Formulation of the problem

The primary challenge facing traditional solar energy lies in the limited availability of land resources, which creates significant economic barriers to the development of ground-mounted solar power plants. In densely populated countries or regions with scarce free land, such as Japan and the Netherlands, the cost of acquiring suitable land reaches substantial levels, making these projects less financially viable [4]. With urbanization on the rise and increasing demand for agricultural production, dedicating large areas to ground-mounted solar farms becomes increasingly difficult. Moreover, in some regions, the construction of solar power plants meets social resistance due to the potential loss of landscape diversity and farmland.

In addition to land constraints, rising costs associated with construction and grid connection further escalate the overall expenses of such projects. In remote areas and islands where long transmission lines are required, these costs become critical. Traditional solar power stations also face social and environmental challenges, such as deforestation, which negatively impacts biodiversity and amplifies public opposition.

In contrast, floating solar panels minimize land use conflicts and reduce environmental impacts but introduce specific reliability challenges related to their aquatic environment. Key issues include:

- Corrosion of metallic components caused by constant exposure to water, especially in saline or polluted conditions;
- Mechanical stresses from wave action, wind, and fluctuating water levels inducing fatigue failures;
- Biofouling and biological damage from aquatic organisms that may degrade structural elements and electrical insulation;
- Catastrophic events such as storms and floods that can cause sudden, large-scale damage or system loss.

Failure to account for these factors in reliability assessments leads to underestimation of maintenance needs and lifecycle costs.

Additionally, local environmental variations – for example, differences in water salinity – impact the cooling effect on panels and the corrosion rate, influencing both efficiency and durability.

Table 1 presents a comparison of primary limitations of traditional ground-mounted solar power plants and floating solar systems, including these nuanced reliability considerations.

Table 1.: Comparison of key parameters of ground-mounted and floating solar systems

Parameter	Ground-Mounted Solar Stations	Floating Solar Panels
Land Use	High competition	Minimal competition
Environmental Impact	High	Low
Infrastructure Costs	High	Moderate
Performance	Moderate	High (due to cooling)
Water Evaporation	No effect	Reduces evaporation
Corrosion Risk	Low	High (depends on water quality and material protection)
Mechanical Stress	Low	High (wave and wind loads)
Biofouling	Not applicable	Present (requires monitoring and mitigation)
Extreme Weather Risk	Moderate	High (storm, flood vulnerability)

III. Problem solution

Floating solar panels offer a range of advantages, making them an efficient solution for many regions [5]. These systems can be installed on various types of water bodies, including:

- Artificial reservoirs.
- Flooded quarries.
- Industrial water bodies.
- Aggregated water resources in arid regions.

One successful implementation example is the project on Lake Boyukshor in Azerbaijan. A pilot installation with a capacity of 2 MW demonstrated high efficiency and minimal impact on the ecosystem (Fig. 1).

Similarly, a project in Japan on the Yamakura Reservoir, with a capacity of 13.7 MW, reduced water evaporation by 20% and decreased carbon dioxide emissions by 7,000 tons annually (Fig. 2).

In Table 2 and Figure 3, the comparison of electricity generation efficiency between land-based and floating systems under various climatic conditions is presented.



Figure 1: 1. 2 MW installation on Lake Boyukshor in Azerbaijan



Figure 2: 13.7 MW installation on the Yamakura reservoir in Japan

Table 2.: Comparison of Land-Based and Floating Systems for Electricity Generation

Parameter	Land-Based Systems	Floating Systems
Efficiency	Dependent on available space and panel tilt angles. Average efficiency: 16–22%.	Higher efficiency due to the cooling effect of water. Average efficiency: 18–25%.
Economic Aspect	Lower initial installation costs. Operating expenses are lower.	Higher construction and maintenance costs. Requires corrosion protection systems.
Reliability	High in dry and temperate climates; may decrease due to dust and overheating.	High in regions with high humidity and solar activity, but depends on structural resilience.
Climatic Conditions	Suitable for temperate and dry regions (e.g., deserts). Performance may drop in extreme heat conditions.	Ideal for tropical and coastal areas. Stable operation due to water cooling.

The graph in Figure 3 demonstrates the comparative efficiency of land-based and floating power generation systems under various climatic conditions. In tropical and coastal regions, floating systems exhibit higher efficiency due to natural water cooling, which enhances the performance of solar panels. In temperate climates, the efficiency of both systems is comparable, whereas in arid conditions, land-based systems experience reduced efficiency due to overheating. This graph highlights that the selection of the optimal system depends on the climatic conditions, with floating systems being more advantageous in regions characterized by high humidity and solar activity.

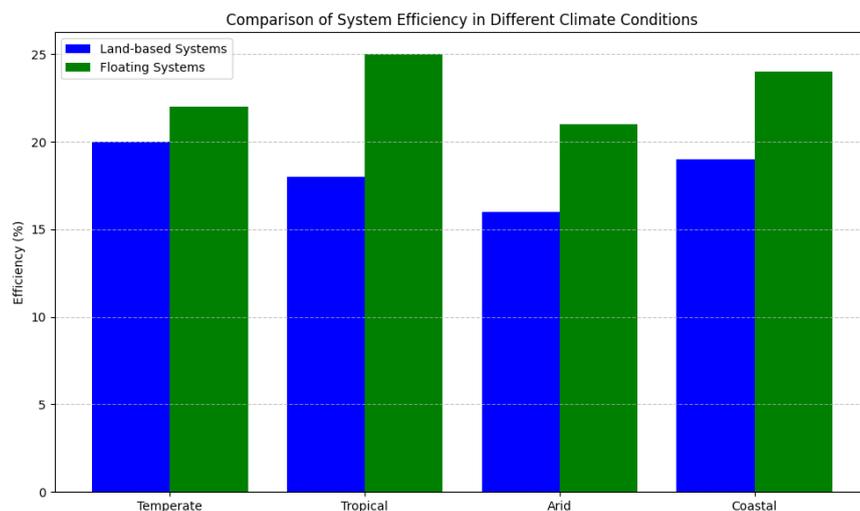


Figure 3. Comparison of the efficiency of systems in different climatic conditions

Advantages of the Technology:

1. **Enhanced Efficiency:** Water cooling increases panel efficiency by 10–15%.
2. **Land Resource Savings:** Floating solar panels (FSPs) are installed on unused water bodies, freeing up land for other purposes.
3. **Reduced Evaporation:** Particularly important in water-scarce regions, FSPs help conserve water.

Minimal Environmental Impact: When adhering to standards, these systems do not affect water quality or aquatic ecosystems.

In tropical countries like Indonesia or the Philippines, floating solar farms can be more economically advantageous due to high solar insolation and natural water cooling of panels. This improves panel efficiency and reduces operational costs, such as cooling and dust cleaning, common for land-based systems [6-8]. For example, maintenance costs for floating systems in such regions can be 15–20% lower than for land-based systems, offsetting the higher initial investments.

In arid regions like Saudi Arabia, land-based systems may be more economically justified due to the availability of vast land areas [9-11]. However, increased operational costs from cleaning and reduced efficiency due to overheating can raise expenses by 10–15%, making floating systems more competitive if the infrastructure for water-based farms is available.

Thus, the economic benefits vary depending on climatic conditions and resource costs, such as land and water.

An Example of Economic Efficiency Calculation for Comparing Ground-Mounted and Floating Solar Farms

Input Data:

Solar Farm Capacity: 10 MW.

Ground-Mounted System: Installation cost \$800/kW, annual operating expenses 2% of capital costs, efficiency 18%.

Floating System: Installation cost \$1000/kW, annual operating expenses 1.5% of capital costs, efficiency 20% due to water cooling.

Average Solar Insolation: 5 hours/day. *Calculation Period:* 10 years.

Calculations:

1. **Capital Expenditures (CAPEX):**

Ground-Mounted: $10,000 \text{ kW} \times 800 \text{ \$/kW} = 8,000,000 \text{ \$}$.

Floating: $10,000 \text{ kW} \times 1000 \text{ \$/kW} = 10,000,000 \text{ \$}$.

2. **Annual Operating Expenses (OPEX):**

Ground-Mounted: $8,000,000 \text{ \$} \times 2\% = 160,000 \text{ \$}$.

Floating: $10,000,000 \text{ \$} \times 1.5\% = 150,000 \text{ \$}$.

3. **Annual Energy Output:**

Ground-Mounted: $10,000 \text{ kW} \times 18\% \times 5 \text{ hours/day} \times 365 \text{ days} = 3,285,000 \text{ kWh}$.

Floating: $10,000 \text{ kW} \times 20\% \times 5 \text{ hours/day} \times 365 \text{ days} = 3,650,000 \text{ kWh}$.

4. **Total Energy Output Over 10 Years:**

Ground-Mounted: $3,285,000 \text{ kWh/year} \times 10 \text{ years} = 32,850,000 \text{ kWh}$.

Floating: $3,650,000 \text{ kWh/year} \times 10 \text{ years} = 36,500,000 \text{ kWh}$.

5. **Total 10-Year Costs:**

Ground-Mounted: $8,000,000 \text{ \$} + 160,000 \text{ \$} \times 10 = 9,600,000 \text{ \$}$.

Floating: $10,000,000 \text{ \$} + 150,000 \text{ \$} \times 10 = 11,500,000 \text{ \$}$.

6. **Cost of Electricity Production per kWh:**

Ground-Mounted: $9,600,000 \text{ \$} \div 32,850,000 \text{ kWh} = 0.292 \text{ \$/kWh}$.

Floating: $11,500,000 \text{ \$} \div 36,500,000 \text{ kWh} = 0.315 \text{ \$/kWh}$.

Results: Ground-Mounted System: Lower installation cost and electricity production cost at \$0.292/kWh but less efficient. Floating System: Higher installation cost and electricity production cost at \$0.315/kWh, with higher efficiency due to water cooling.

Adjustments for factors such as efficiency losses from soiling or higher cooling costs in hot climates could shift the economic balance in favor of floating systems over the long term.

Reliability Assessment Example:

Input Data for Reliability:

Availability Coefficient:

Ground-Mounted: 95% (dust, soiling, frequent cleaning required).

Floating: 97% (reduced dust impact, better cooling).

Mean Time to Repair (MTTR):

Ground-Mounted: 48 hours.

Floating: 72 hours (requires boats or specialized equipment).

Failure Rate per Year:

Ground-Mounted: 10 failures/year.

Floating: 7 failures/year.

Repair Costs per Failure:

Ground-Mounted: \$2000.

Floating: \$3000.

Reliability Calculations:

1. Annual Downtime:

Ground-Mounted: $10 \text{ failures/year} \times 48 \text{ hours} = 480 \text{ hours}$.

Floating: $7 \text{ failures/year} \times 72 \text{ hours} = 504 \text{ hours}$.

2. Availability Coefficient:

Ground-Mounted: $(8760 - 480) \text{ hours} / 8760 \text{ hours} = 94.52\%$.

Floating: $(8760 - 504) \text{ hours} / 8760 \text{ hours} = 94.24\%$.

3. Annual Maintenance Costs:

Ground-Mounted: $10 \text{ failures/year} \times 2000 \text{ \$/failure} = 20,000 \text{ \$}$.

Floating: $7 \text{ failures/year} \times 3000 \text{ \$/failure} = 21,000 \text{ \$}$.

4. Effective Electricity Output: Assuming maximum output of 18,250,000 kWh/year:

Ground-Mounted: $18,250,000 \text{ kWh} \times 94.52\% = 17,246,350 \text{ kWh}$.

Floating: $18,250,000 \text{ kWh} \times 94.24\% = 17,202,200 \text{ kWh}$.

Results: Ground-mounted systems have slightly higher availability and lower downtime due to shorter repair times, reducing productivity loss. Floating systems exhibit fewer failures and benefit from better operating conditions but incur higher maintenance costs and longer downtimes.

To enhance clarity and facilitate the interpretation of the calculations presented above, it is advisable to summarize the key technical and economic indicators of both systems in a comparative table, accompanied by visual representations such as charts and graphs. The table 3 below provides an overview of the main parameters for the ground-mounted and floating photovoltaic systems.

As the table illustrates, despite the higher efficiency of the floating system, the ground-mounted system demonstrates a lower cost of electricity generation, primarily due to its lower capital and operational costs.

In addition, a reliability assessment was performed for both systems, taking into account factors such as availability coefficient, mean time to repair (MTTR), failure rate, and maintenance costs. The results are summarized in the following table 4..

Table 3.: Comparative technical and economic characteristics of ground-mounted and floating PV systems

Parameter	Ground-Mounted System	Floating System
Installed Capacity	10 MW	10 MW
Installation Cost (\$/kW)	800	1000
Capital Expenditures (CAPEX)	\$8,000,000	\$10,000,000
Annual Operating Expenses (OPEX)	\$160,000	\$150,000
Efficiency	18%	20%
Annual Energy Output	3,285,000 kWh	3,650,000 kWh
Total Output Over 10 Years	32,850,000 kWh	36,500,000 kWh
Total 10-Year Costs	\$9,600,000	\$11,500,000
Cost of Electricity Production	\$0.292/kWh	\$0.315/kWh

Table 4.: Reliability assessment of ground-mounted and floating PV systems

Parameter	Ground-Mounted System	Floating System
Availability Coefficient (Calculated)	94.52%	94.24%
Failure Rate per Year	10	7
Annual Downtime (Hours)	480	504
Annual Repair Costs	\$20,000	\$21,000
Effective Annual Energy Output	17,246,350 kWh	17,202,200 kWh

Graphical representations of these results, such as bar charts comparing CAPEX, OPEX, total output, and availability, can significantly improve the interpretability of the data and provide clearer insight into the advantages and trade-offs of each system.

In summary, structured and visual presentation of data adds substantial analytical value, allowing for a more balanced and informed comparison when evaluating ground-mounted versus floating solar power systems in terms of cost, efficiency, and operational reliability.

In scenarios where reliability and frequent access are critical, ground-mounted systems may be preferred, while floating systems offer advantages for long-term operation and lower failure rates [12-13].

Here's the combined economic aspect and reliability analysis of the ground-based and floating solar systems. The data is presented in Table 5, along with graphical representations in Figure 4.

Table 5: Comparison of Ground-Based and Floating Solar Systems

Indicator	Ground System	Floating System
Availability Factor, %	94.52	94.24
Downtime per Year, hours	480	504
Mean Time to Repair (MTTR), hours	48	72
Number of Failures per Year	10	7
Failure Repair Costs, \$	2,000	3,000
Annual Maintenance Costs, \$	20,000	21,000
Effective Output, kWh	17,246,350	17,202,200

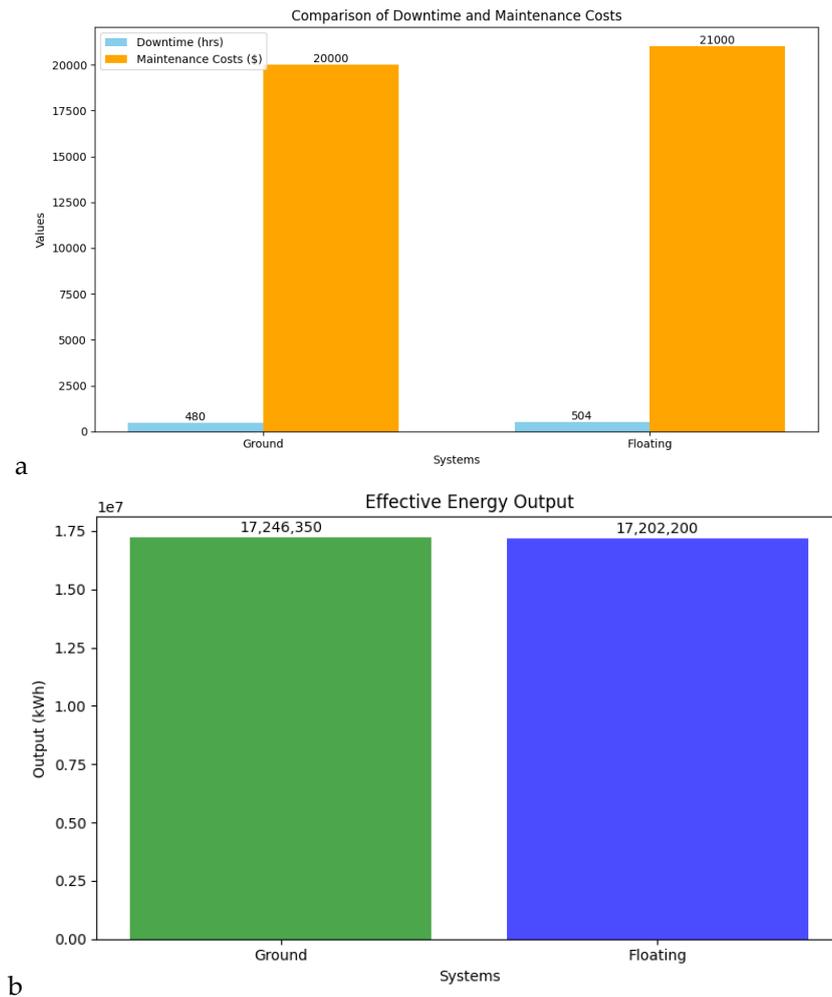


Figure 4: Graphical comparison of ground-based and floating solar systems

The graph in Figure 4a shows the difference in downtime and maintenance costs. It is evident that the ground-based system is cheaper to maintain, but the floating system requires more time to recover from failures. The graph in Figure 4b demonstrates that the effective electricity generation of ground-based systems is slightly higher due to the reduced downtime.

This approach allows for the visualization of the economics and reliability of both systems, providing the opportunity to select the optimal option for specific conditions [14-18].

From the above, the following conclusions can be drawn:

1. Ground-based systems have lower failure recovery costs, making them advantageous in the case of frequent failures [19-20].
2. Floating systems are less prone to failures, but their maintenance costs are higher.
3. The effective electricity generation is higher for ground-based systems due to shorter recovery times after failures.

To gain a deeper understanding of the economic efficiency and reliability of solar power systems, a comparative analysis was conducted between ground-mounted and floating photovoltaic (PV) installations, each with a capacity of 10 MW, assuming an average solar insolation of 5 hours per day over a 10-year period.

Capital expenditures (CAPEX) for ground-mounted systems amount to approximately \$8 million, with annual operational expenditures (OPEX) around \$160,000. The total energy output over the lifespan reaches 32.85 GWh, resulting in a levelized cost of electricity (LCOE) of about

\$0.292 per kWh. In contrast, floating systems have higher CAPEX at roughly \$10 million but benefit from slightly lower OPEX of approximately \$150,000 per year. The total energy produced over the same period is estimated at 36.5 GWh, yielding an LCOE of approximately \$0.315 per kWh. Despite the higher LCOE of floating systems, this gap narrows under conditions of elevated temperatures and dust contamination due to improved reliability and efficiency.

Reliability assessment was carried out using mean time between failures (MTBF) and availability metrics. With annual failure rates of 10 for ground-mounted and 7 for floating systems, and mean time to repair (MTTR) values of 48 and 72 hours respectively, the calculated MTBF is 876 hours for ground-mounted and 1251 hours for floating systems. Corresponding availability values are approximately 94.8% for ground-based and 94.6% for floating installations.

MTBF

$$\text{Ground-Based: MTBF} = 8760 \text{ h} / 10 = 876 \text{ h}$$

$$\text{Floating: MTBF} = 8760 \text{ h} / 7 = 1251 \text{ h}$$

Availability (A):

$$A = \frac{MTBF}{MTBF + MTTR}$$

$$\text{Ground – Based: } A = \frac{876}{876 + 48} \approx 94.8\%$$

$$\text{Floating: } A = \frac{1251}{1251 + 72} \approx 94.6\%$$

These values align with real-world estimates from long-term monitoring of FSPs over 5–7 years in Southeast Asia and Europe [12–13].

Particular attention was given to critical components in floating systems, such as anchoring mechanisms and cable connections. Field studies conducted in India, Singapore, and the Netherlands indicate that anchoring failures—caused by corrosion, biofouling, and hydrodynamic fatigue—occur at a rate of 0.3 failures per anchor per year, corresponding to an MTBF of roughly 3.3 years. Cable connections, susceptible to thermal cycling and water ingress, exhibit failure rates of 1.2 per year per 10 km of cable, with an MTBF of approximately 8,000 hours (around 11 months). Preventive maintenance strategies, including UV-resistant coatings and real-time insulation resistance monitoring, significantly mitigate these risks.

Exposure to harsh environmental factors such as high humidity, saltwater, and ultraviolet radiation accelerates the aging process of key materials. For instance, polymer floats' lifespans may decrease from 25 to 15–18 years, while cable insulation and seals degrade 20–30% faster in the absence of marine-grade protective specifications. Probabilistic Weibull models were employed to estimate component survival rates, revealing a 20–30% increased failure risk in tropical coastal regions without enhanced protective measures.

Enhancements in reliability have a direct positive impact on economic performance. By reducing failure frequency to 5 per year and shortening MTTR to 60 hours, MTBF increases to 1752 hours, and availability improves to 96.7%. This results in a 4.5% increase in energy output over 10 years and a corresponding reduction in adjusted LCOE to approximately \$0.302 per kWh, representing a 4.1% improvement in cost competitiveness.

In summary, reliability models and economic analyses demonstrate that properly engineered floating solar systems can match or surpass the reliability of ground-mounted counterparts. Special focus is required on mitigating failures of critical components, particularly under high-stress environmental conditions. Empirical monitoring data validate model assumptions and highlight key degradation factors. Integrating reliability-centered design and probabilistic modeling is essential for the sustainable development and long-term economic viability of floating solar projects.

IV. Conclusions

Floating solar panels represent a promising advancement in the pursuit of reliable and sustainable renewable energy solutions. Unlike ground-mounted systems, these installations mitigate land-use conflicts and reduce infrastructure costs, while also benefiting from natural water-based cooling, which enhances their operational efficiency and prolongs component lifespan. This inherent stability contributes to improved overall system reliability, especially in environments where temperature fluctuations and dust accumulation compromise the performance of traditional solar arrays.

Experience gained from successful projects in Europe and Asia confirms not only the economic and environmental viability of floating solar systems, but also their robustness in diverse climatic and hydrological conditions. Their ability to maintain stable power generation under variable loads and environmental stresses positions them as a resilient solution in the face of growing energy demands and climate-related uncertainties.

To fully realize their potential, it is essential to ensure long-term structural integrity, refine regulatory frameworks, and deepen our understanding of environmental interactions. With continued innovation and thoughtful deployment, floating photovoltaic systems are poised to become a cornerstone of the global transition to reliable, low-carbon energy infrastructure.

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