Floating Photovoltaic Power Plants: A Review of Energy Yield, Reliability, and Maintenance

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Executive Summary

Photovoltaic (PV) systems are essential for the transition to sustainable energy, reducing fossil fuel dependence and mitigating climate change. Although PV requires minimal land area —PV can meet the European Union's energy needs using only 0.26% of its land — space for deployment is often scarce in densely populated regions. Floating photovoltaics (FPV) provides an effective dual-use solution by mounting PV system on floats. FPV is a growing niche within PV with cumulative installed capacity reaching 7.7 GW globally by 2023. FPV shows strong potential to support climate targets, but still faces challenges like regulatory barriers, cost competitiveness compared to ground-based PV (GPV), and uncertainties about environmental impacts and system reliability. FPV systems are currently installed mainly on sheltered inland waters, such as quarry lakes, irrigation ponds and reservoirs.

FPV technical standards are still developing. Guidelines have been published by the World Bank, DNV, and Solar Power Europe, and emerging national standards from South Korea, China, and Singapore address design, components, and safety. The International Electrotechnical Commission (IEC) is working on formal standards for floats, mooring systems, and electrical connectors. However, the published best practices lack quantitative guidance for yield modelling and reliability, which this report aims to address. It provides data-driven insights, models, and parameters essential for accurate energy yield, reliability, and maintenance predictions over FPV systems' lifetimes.

The report provides guidelines and quantitative recommendations for accurately assessing energy yield (EYA) in FPV systems, a key factor for determining the levelized cost of electricity and project profitability. Current models for EYA are insufficient, lacking reliable data for critical parameters like module temperature, wave-induced losses, soiling losses, and performance loss rates. Standard modelling tools do not adequately cover FPV-specific needs, and existing meteorological databases often exclude sea and coastal areas, which limits FPV yield estimation. Chapter 2 identifies essential parameters and highlights knowledge gaps in meteorological data, energy production modelling, and uncertainty analysis that distinguish FPV EYA from that of GPV.

1. Meteorological Data Requirements: The report highlights the need for improved meteorological data tailored to FPV, as the water-based environment affects variables like irradiance, wind, and temperature. It is uncertain how this affects prediction accuracy for FPV.
2. Thermal Losses: Thermal performance depends on the FPV system design. Modelling tools, such as PVsyst® and pvlib, need to incorporate these specifics for more accurate yield estimates.

3. Wave-Induced Losses: Wave motion affects irradiance by altering module tilt and creating irradiance non-uniformity. No complete model for wave-induced losses currently exists and the report encourages field data collection to improve accuracy in yield modelling.
4. Soiling Losses: FPV systems may experience unique soiling challenges, including bird droppings and other debris from surrounding ecosystems.

The report underscores that FPV yield estimation tools and methods are still evolving, and it encourages improved empirical studies and data-sharing to refine modelling approaches and align them with the distinctive characteristics of FPV installations.

When assessing the reliability of an FPV system, one faces important knowledge gaps and challenges. First, the stress profiles experienced by components in a FPV installation are neither well understood nor quantified and will vary a lot depending on float technology and water body conditions. Second, open information and systematic studies on observed degradation and field failures remain scarce, as are studies of performance loss rates. And third, as a result of the first two points, there is no accelerated stress testing protocol developed for component reliability evaluation. In the following, each of these three topics will be further discussed.

The term *degradation* denotes the gradual process of change in characteristics with operational time of a material / component / system triggered by stress impact. Typically, we distinguish between three types of degradation: reversible degradation, irreversible degradation, and failures. For FPV, the balance of system components may be even more critical than the PV modules. Junction boxes, cables, connectors, and related protecting materials may suffer from additional stress compared to GPV systems. Chapter 3 provides an overview of environmental stressors in the operating environment of FPV systems, and finally discuss three different sources for quantification of degradation effects:

Field data: collection of long-term field data is indispensable for accurate identification of failure modes and the design of appropriate testing protocols. As the available field data on failures and degradation is very limited, performance stability is measured through long-term trends in historical production data. Three commonly used statistical methods are deployed to calculate the PLR through historical PV performance and climatic data: Ordinary Least Squares (OLS), seasonal and trend decomposition using locally weighted scatterplot smoothing (STL), as well as Year-on-Year (YoY). These methods are based on determining trends in the historical data. The major drawback of statistical methods is that they do not trace the correlation of the evaluated degradation rates with the climatic variables and degradation processes. Despite the significant number of FPV systems that has now been operated over several years, long-term FPV performance studies are rare. A study by SERIS using three years of data from a large FPV test bed found PLRs between -0.7% and -0.5% per year, like those of nearby rooftop PV.

Laboratory: in the lab environment, accelerated stress tests enable reliability screening of key components in short timeframes, to identify and mitigate quality issues before they manifest as problems in actual installations. A challenge with laboratory testing for FPV is that there are no IEC standards, and few field measurements of stressors and field degradation. IEC standards that can be relevant for FPV components are summarized in this section.

Simulation Models: simulations are one convenient option to overcome the lack of experimental (long-term) data, and to capture the correlations between the degradation rates and the stressors/climatic variables. However, we emphasize the importance of using validated simulation models to obtain reliable results. For FPV, four types of simulations are of particular interest to study the influence of single stressors: a) Wind loads through Computational Fluid Dynamics (CFD) and mechanical simulations, b) Moisture ingress through mass transport simulations, c) Hotspot formation through electrical and thermal simulations, d) Thermally Induced Stress through thermal and mechanical simulations.

There are currently no standards available that describe the recommended sensors and procedures for monitoring of FPV power plants. Instrumentation requirements for GPV power plants, including requirements with respect to accuracy and number according to the size of the plant, can be found in IEC 61724-1.

Chapter 4 introduces a preliminary failure and effects analysis of technical and operational challenges, and how these impact operation and maintenance (O&M). Available data is limited, and one can only anticipate that the occurrence and degree of severity for the different events may change as more data is collected. A list of key aspects and considerations when budgeting for FPV O&M projects is also provided.

FPV technology faces key R&D challenges, and hence possibilities, in its O&M framework, especially as installations scale up and offshore projects expand. Major areas include:

- Monitoring and Remote Sensing: Remote FPV sites, especially offshore, struggle with data transmission reliability and high communication costs. Advanced solutions using drones, satellites, cloud storage, and Internet of things can enhance monitoring and reduce O&M costs.
- Expert Dependence: FPV's complexity requires specialized experts (e.g., divers, marine engineers) for maintenance and inspections, increasing costs and time. AI-driven data analytics, Unmanned Aerial Vehicle (UAV) based inspections, and autonomous systems offer potential to reduce human intervention.
- Extreme Weather and Degradation: Marine environments introduce severe stressors like corrosion and UV exposure, accelerating FPV component degradation. R&D in advanced materials, protective designs, and robust emergency-response plans is crucial to improve FPV durability.
- Environmental Impact and Regulations: Concerns on FPV effects on aquatic ecosystems, such as water quality and habitat shading, call for eco-friendly designs and regulatory standards that minimize harm and adapt O&M practices for sustainability.

In conclusion, FPV offers a promising solution for expanding renewable energy without increasing land use pressures. However, the absence of regulatory frameworks and limited long-term data creates uncertainty for developers, regulators, and investors, slowing FPV adoption. Rapid innovation in the field often prioritizes confidentiality, limiting data sharing crucial for industry growth. This report aims to support FPV development by building a knowledge base on energy yield, reliability, and O&M — areas where FPV diverges from GPV. Key research priorities include understanding FPV-specific stressors, improving predictive models, automating O&M, and assessing environmental impacts. Addressing these gaps can lead to a more mature, sustainable FPV industry, ready for broader deployment.

Key Takeaways

1. The potential of FPV to expand solar capacity without land constraints is very promising, but uncertainties related to environmental impacts, complex or missing regulatory frameworks, and cost barriers slow its adoption.
2. The report provides guidance to improve engineering judgements of FPV specific losses in energy yield assessments (EYA). The accuracy of EYA for FPV can be further improved by closing gaps in meteorological data and gaining more quantitative knowledge on loss mechanisms and degradation.
3. Improvements and automation of monitoring and O&M practices, combined with more open sharing of data, can reduce costs during operation and support assessment of FPV specific stressors and reliability, ultimately leading to faster scalability.

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