

WAVE PERFORMANCE STUDY OF A RAPIDLY DEPLOYABLE AND FOLDABLE OFFSHORE FLOATING PHOTOVOLTAIC SYSTEM

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ABSTRACT

Based on completed and planned installed capacity, offshore photovoltaics (PV) have emerged as a new form of “Marine plus Renewable Energy” productivity, ranking second only to offshore wind power in China. Existing offshore floating PV solutions typically adopt semi-submersible platform derived from the traditional marine engineering industry, with a few based on overseas thin-film technologies. Conventional solutions suffer from several limitations: (1) semi-submersible platforms are large and heavy, with complex construction organization, low efficiency, high costs, strong dependence on nearshore fabrication sites and marine engineering production capacity; (2) transport efficiency is low, with only hundreds of kilowatts per shipment (compared to megawatts per shipment for offshore wind); and (3) thin-film solutions rely on non-standard, customized PV modules. To address these challenges, a rapidly deployable and foldable offshore floating photovoltaic system TK-FFPV has been developed, based on first-principles thinking and the KISS (Keep It Simple and Stupid) design philosophy. By leveraging prefabrication, modularization, and foldable structures, TK-FFPV transforms the high-risk, costly, and complex outdoor construction paradigm of large marine engineering equipment into a safe, economical, and efficient indoor intelligent manufacturing model for small electromechanical equipment. The approach is more conducive to exploiting industrial supply chain advantages, enabling large-scale deployment and export, reducing costs, improving efficiency, and accelerating the development of offshore PV. This paper presents the real-sea field tests conducted for the wave performance of TK-FFPV system.

Keywords: *Offshore floating photovoltaics; Foldable structures; Rapid deployment; Wave resistance*

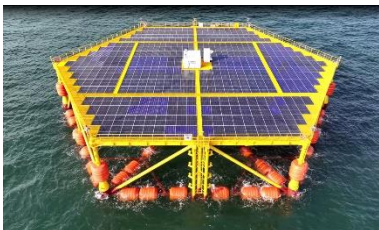
I. INTRODUCTION

“Marine plus Renewable Energy” has become a critical pathway for coastal regions to build new energy systems, achieve carbon peaking and carbon neutrality goals, develop green and low-carbon industries, and strengthen the blue economy. Based on completed and planned installed capacity, offshore photovoltaics (PV) have become the second-largest “Marine plus Renewable Energy” technology after offshore wind power, as reflected in policy documents such as the Shanghai Offshore Photovoltaic Development Plan under the Wind-Solar Co-location system ^[1] and Jiangsu Offshore Photovoltaic Development Implementation Plan (2025-2030) ^[2]. Similar to the offshore wind industry’s transition from fixed foundations in nearshore shallow waters to floating foundations in deeper and farther offshore areas with richer wind resources^[3], offshore PV is evolving from pile-supported fixed installations in tidal flats and

shallow coastal waters toward floating PV systems in deeper and wider marine regions. Owing to its vast development potential and strong market prospects, offshore floating PV has become a key focus for governments, industry, academia, and investors worldwide.

Offshore floating PV power generation has been identified as one of the Top Ten Engineering Research Frontiers in the mechanical and transportation engineering domain in the Global Engineering Frontiers 2024 report ^[4]. Policy support is further accelerating its development. For example, the Guangdong Action Plan for Cultivating and Developing Future Green and Low-Carbon Industrial Clusters (2024) ^[5] calls for enhanced resource assessment and pilot demonstrations of offshore floating PV. In China, multiple power generation enterprises have initiated offshore floating PV demonstration projects (Table 1). Internationally, companies across Europe and Southeast Asia, including

Table 1. China's Offshore Floating PV Technology Demonstration Projects

Companies, Locations, and Years	Project Overview	Installed Capacity, Technology Type, Total Investment, and Unit Cost
State Power Investment Corporation (SPIC) Shandong 2022		500 kW Thin-Film Type Investment: 1.41 million USD (≈ 2.83 USD/W)
State Power Investment Corporation (SPIC) Tianjin 2023		254 kW Tensioned-Floating-Island Type Investment: 0.45 million USD (≈ 1.77 USD/W)
China Energy Investment Corporation Jiangsu 2024		100 kW Semi-Submersible Type Investment: 0.62 million USD (≈ 6.22 USD /W)
China Huaneng Group Shandong 2024		300 kW Semi-Submersible Type Investment: 4.45 million USD (≈ 14.84 USD/W)

Oceans of Energy and SolarDuck (Netherlands), Ocean Sun and Fred. Olsen 1848 (Norway), SINN Power (Germany), Swimsol (Austria), SolarinBlue (France), and Sunseap and Sembcorp (Singapore), are actively advancing the research, development, and deployment of offshore floating PV systems.

According to national marine-use policies^[6], offshore PV sites are permitted in four categories of already developed marine areas within provincially managed waters: aquaculture zones, offshore wind farm areas, thermal discharge zones of power plants with confirmed usage rights, and long-idle or abandoned salt pans. Among these, offshore wind farm areas are the primary application selection for offshore floating PV,

enabling Wind-Solar Co-location systems. In China, cumulative grid-connected offshore wind capacity reached 41.27 GW by December 2024^[7], ranking first globally, indicating substantial available sea areas and strong potential for offshore floating PV development.

Shanghai plans to deploy offshore PV projects under the Wind-Solar Co-location system around existing and planned offshore wind farms near the Donghai Bridge, Lingang, Jinshan, and Fengxian, targeting the development of multi-gigawatt offshore PV clusters. Jiangsu Province aims to utilize offshore wind farm areas, aquaculture zones, and thermal discharge areas to build a 10 GW-class offshore PV base by 2027, reaching approximately 10 GW of cumulative grid-

connected capacity, and exceeding 15 GW (striving for 20 GW) by 2030. Shandong Province released an offshore PV construction action plan in 2022^[8], planning two 10 GW-class offshore PV bases around the Bohai Sea and Yellow Sea, with a total planned capacity exceeding 42 GW, and explicitly promoting the integrated Wind-Solar Co-location system alongside the prudent development of floating offshore PV.

From a global perspective, the Global Offshore Floating Solar Atlas published by the Australian National University in 2023^[9], estimates that global offshore floating solar resources amount to approximately 225,000 TWh. The ASEAN region possesses vast offshore solar potential, together with extensive inland water bodies, indicating a substantial future market for China's offshore floating PV technologies and products. However, existing offshore floating PV solutions mainly rely on semi-submersible platforms, with a limited number adopting thin-film technologies (Table 1). These conventional solutions suffer from several limitations: (1) semi-submersible platforms are large and heavy, with complex construction organization, low efficiency, high costs, strong dependence on nearshore fabrication sites and marine engineering production capacity; (2) transport efficiency is low, with only hundreds of kilowatts per shipment (compared to megawatts per shipment for offshore wind); and (3) thin-film solutions rely on non-standard, customized PV modules.

A rapidly deployable foldable offshore floating photovoltaic system, named TK-FFPV, was developed by the Tianjin Research Institute for Water Transport Engineering (TIWTE), as shown in Figure 1. Based on first-principles analysis and the KISS (Keep It Simple and Stupid) design philosophy, TK-FFPV integrates prefabrication, modularization, and foldable structures to transform offshore PV construction from a high-risk, high-cost marine engineering model into a safe, economical, and efficient indoor intelligent manufacturing paradigm for small electromechanical equipment. The approach maximizes supply chain advantages, enables large-scale production for domestic deployment and export, reduces costs, improves efficiency, and accelerates the development of offshore PV.

This paper focuses on recent real-sea wave resistance field tests conducted for the TK-FFPV system.

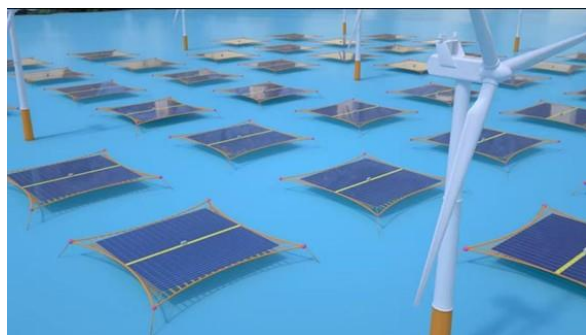


Figure 1. Conceptual application of TK-FFPV in a Wind-Solar Co-location System

II. RESEARCH METHODS

The development of offshore floating PV systems faces critical challenges related to wave resistance, structural safety, and reliable power generation under real sea conditions. From 2022 to 2025 the conceptual design and detailed tests of TK-FFPV have been completed. The study follows a two-stage experimental strategy: (1) laboratory experiments of hydrodynamic tests to validate structural concepts and wave-response behavior, and (2) offshore field tests to assess system performance under actual marine environmental loads.

2.1 Laboratory Experiment

First, a 1:1 full-scale foldable FFPV prototype was tested in the largest wave flume at TIWTE, which is 450-m long, 8-m wide, and 5-m deep. This experiment focused on validating folding-unfolding functionality, structural integrity, and wave-following behavior, providing direct proof of concept for the full-scale design (Figure 2). Subsequently, a 1:8 model scale photovoltaic array model was tested in a large wave basin, which is 50-m long, 30-m wide, 1.8-m deep. The objective was to evaluate hydrodynamic responses, motion characteristics, and wave-structure interaction under irregular waves representative of offshore conditions (Figure 3). These laboratory results established a reliable experimental basis for proceeding to offshore field validation.

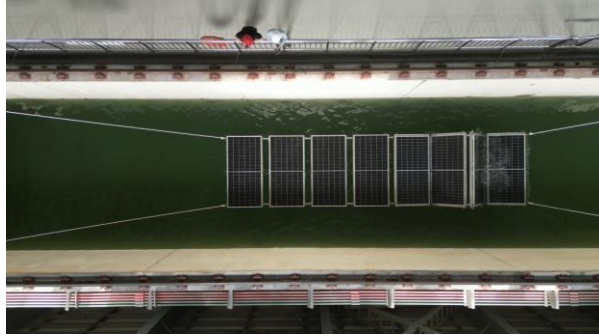


Figure 2. Folding and deployment performance tests of the 1:1 scale TK-FFPV in large wave flume

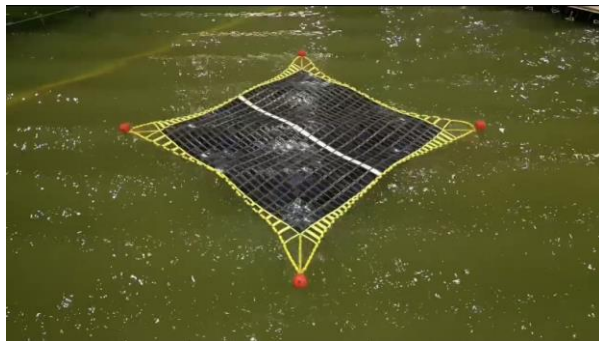


Figure 3. Hydrodynamic performance tests of the 1:8 scale TK-FFPV photovoltaic array in wave basin

2.2 Offshore Field Experiments

To verify the performance of TK-FFPV under real ocean conditions, a 10 kW-class offshore field test was conducted to assess structural safety, environmental durability, and power generation performance in an actual marine environment. The test site comprised a 16 kW full-scale TK-FFPV array, consisting of 4 rows and 7 columns of 580 W PV modules, a 1:8 scale 350 kW-equivalent model with 18 rows and 33 columns of PV modules, and a GNSS wave buoy for real-time wave monitoring. The layout of the offshore test site is shown in Figure 4.

During the test period, a cold air system affected the Yellow Sea from the night of September 16 to September 17, 2025, generating moderate to large waves with significant wave heights of 2.0–3.2 m. A blue-level nearshore wave warning was issued,

and observed wave heights at the test site reached, as recorded by the GNSS wave buoy (Figures 5 and 6). The naturally occurring wave event provided a valuable opportunity to evaluate the wave resistance and operational stability of TK-FFPV under realistic offshore conditions.

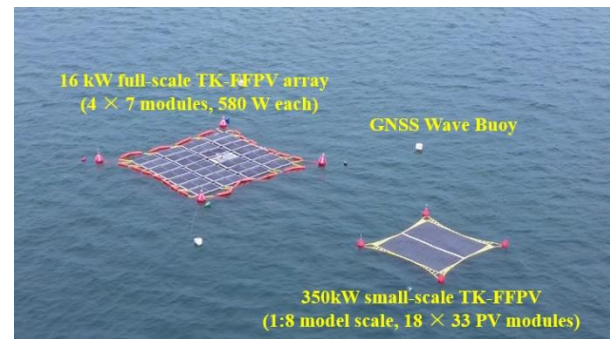


Figure 4. Layout of the TK-FFPV offshore field test site

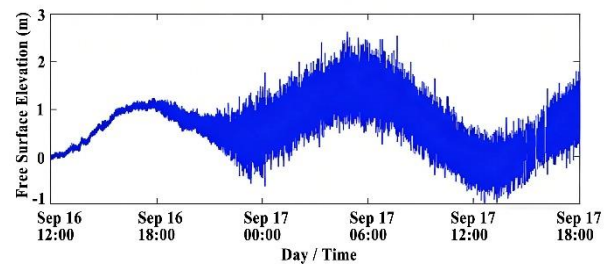


Figure 5. Time series of free surface elevation recorded by the GNSS wave buoy at the test site (From 12:00 PM, Sep 16th to 6:00 PM, Sep 17th)

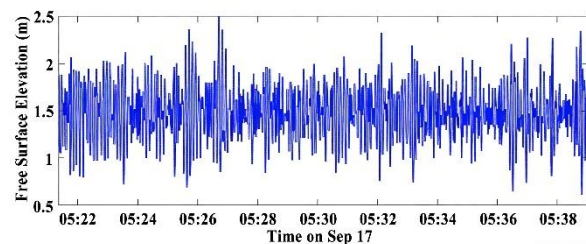


Figure 6. Time series of free surface elevation recorded by the GNSS wave buoy at the test site (From 5:21:22 AM to 5:39:02 AM on Sep 17th)

III. RESULTS AND DISCUSSION

3.1 Experimental Results

Figures 8 and 9 present distant and close-up views of the test site during the large-wave event from Sep 16 to Sep 18, 2025, demonstrating that both the full-scale TK-FFPV array and the 1:8 scale model remained structurally stable and operational under moderate to large wave conditions. No structural damage, excessive deformation, or loss of functionality was observed, confirming the wave-following capability and mechanical robustness of the foldable floating system under realistic offshore sea states. Tests on the 1:8 scale model verified that TK-FFPV's wave resistance exceeds 8 m, demonstrating its ability to withstand typical medium-to-high offshore sea states, a key factor for ensuring overall system safety.



Figure 7. Distant view of large waves in test area



Figure 8. Close-up view of large waves in test area

Figures 10 and 13 summarize the power generation performance of $2 \times 580\text{W}$ PV modules connected in parallel, including instantaneous power, DC current I , DC voltage U , and cumulative power output P . The offshore PV system consistently exhibited equal or higher power output compared with the land-based reference system under identical meteorological conditions. In particular,

the offshore system showed improved stability during peak irradiance periods, indicating favorable thermal and environmental operating conditions in ocean. For comparison, the land-based reference system consisted of $2 \times 580\text{W}$ PV modules installed on the nearest shoreline, approximately 1.5 nautical miles from the offshore test site. The use of the same module model ensured a fair comparison. The measured results show that the offshore PV array provided stable power, current, voltage, and energy output throughout the test period. In the data visualization, blue represents the offshore system and red represents the land-based system, clearly indicating that the offshore PV outperformed the onshore counterpart.

Overall, the experimental results confirm that TK-FFPV can withstand representative offshore wave loads while maintaining stable and efficient power generation, validating both its structural design and functional performance.

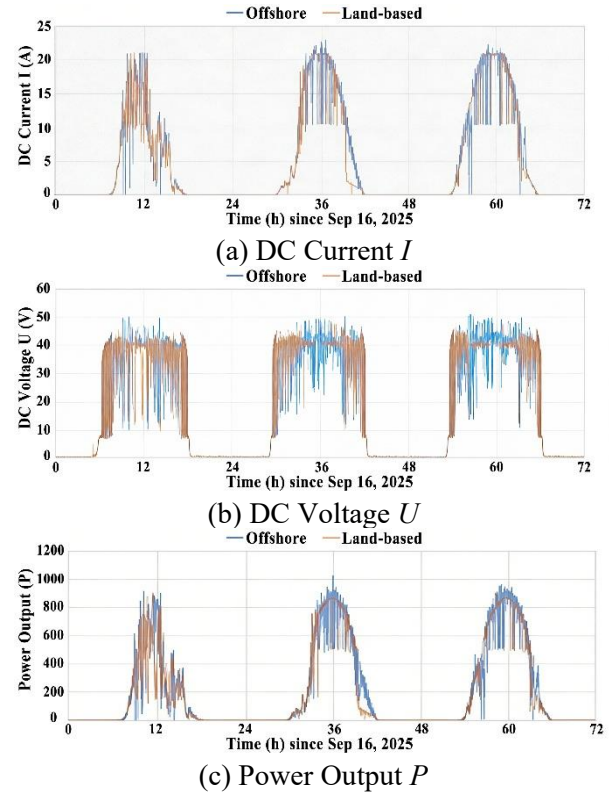


Figure 9. Power generation performance of $2 \times 580\text{W}$ PV modules in the offshore TK-FFPV system (blue) and land-based reference system (red), Sep 16–18, 2025.

3.2 Advantages of the TK-FFPV System

The experimental findings highlight several key advantages of the TK-FFPV concept:

(1) High efficiency:

The integrated floating structure and PV module system is foldable and deployable, achieving a folding ratio of up to 1:10. For example, a pre-assembled and pre-wired floating PV unit measuring 5.0 m × 2.4 m × 1.2 m in folded form can be rapidly deployed into a PV string measuring 50.0 m × 2.4 m × 0.12 m. The design enables efficient road and waterway transportation, rapid offshore deployment, better improved utilization of short marine operation windows, and significant cost reduction.

(2) Ecological compatibility:

Gaps of several tens of centimeters are reserved between PV module units, reducing shading impacts on the marine environment, including planktonic and benthic ecosystems.

(3) Economic performance:

The full life-cycle cost of the floating structure can be reduced to below 0.43 USD/W, in consideration of the recycling and reuse of high-value structural materials at decommissioning. The structural design is well-suited for large-scale automated manufacturing, similar to advanced automotive body-in-white welding processes. The electrical system adopts mature commercial solutions, and the total life-cycle cost is expected to reach approximately 1 USD/W.

(4) International scalability:

The TK-FFPV modular, plug-and-play design, allows for containerized transport and export, unlike semi-submersible offshore platforms that are unsuitable for long-distance maritime shipping. TK-FFPV can meet clean energy demands in emerging economies along the Belt and Road Initiative, such as Southeast Asia and the Middle East, supporting global carbon neutrality and climate change mitigation efforts.

IV. CONCLUSIONS

Based on first-principles analysis and the KISS design philosophy, a rapidly deployable foldable offshore floating photovoltaic system TK-FFPV was developed. By integrating prefabrication, modularization, and foldable structures, this system transforms the traditional offshore construction paradigm of large, high-risk, and costly marine engineering equipment into a safe, economical, and efficient indoor intelligent manufacturing model. Laboratory and field tests were conducted to examine the wave resistance of the TK-FFPV system. Test results demonstrate that both the full-scale array and the 1:8 scale model successfully withstood wave heights of approximately 2 m, while achieving higher power generation than comparable land-based PV systems. TK-FFPV exhibits strong potential as a game-changing technology in the offshore floating PV sector.

The proposed system can be applied in various scenarios, including Wind-Solar Co-location offshore wind farms, enclosed but undeveloped coastal areas near ports, thermal discharge zones of nuclear power plants, seawater desalination, hydrogen-ammonia-methanol production from seawater, and off-grid energy supply for islands and reefs. TK-FFPV thus offers a promising solution to advance a green, low-carbon, and circular energy transition.

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