

Advancing Offshore Energy: Coupled Analysis of Hybrid FOWT-FSPV Platforms

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Abstract: The transition to clean energy sources drives the optimal exploitation of offshore renewable energy potential. However, coastal space constraints and power output fluctuations from single energy sources present major challenges to its development. This study aims to analyze the technical performance, structural hydrodynamic response, and power generation efficiency of an integrated hybrid system combining a Floating Offshore Wind Turbine (FOWT) and Floating Solar Photovoltaics (FSPV). The research methodology employs numerical modeling to evaluate aero-hydrodynamic interactions and dynamic loading induced by wave and wind variations on the floating platform and mooring system. The analysis reveals that integrating FSPV onto the FOWT platform significantly increases total energy output capacity while optimizing marine spatial efficiency and subsea transmission cable infrastructure utilization. Furthermore, the designed mooring system configuration effectively mitigates the platform's dynamic motion responses, specifically in pitch and heave modes, thereby maintaining operational stability. This study concludes that the hybrid FOWT-FSPV system demonstrates high technical feasibility as a large-scale offshore renewable energy generation solution.

Keywords: Floating Offshore Wind Turbine; Floating Solar Photovoltaic; Hybrid Energy System; Hydrodynamic Response; Mooring System

1. Introduction

The transition to clean energy sources drives the optimal exploitation of offshore renewable energy potential. Open ocean waters harbor abundant renewable energy resources, particularly wind energy and solar radiation. However, single-source offshore energy utilization is frequently constrained by coastal space availability and power output fluctuations due to the intermittent nature of natural resources. Floating Offshore Wind Turbine (FOWT) technology has advanced rapidly to capture high-wind potential in deep waters, while Floating Solar Photovoltaic (FSPV) systems offer high efficiency due to the natural cooling effect of seawater. Integrating both technologies into a single hybrid floating platform provides a complementary solution that optimizes marine spatial planning and subsea power cable infrastructure while balancing the daily energy production profile. However, adding FSPV structures to a FOWT platform introduces complex hydrodynamic and aerodynamic challenges. Dynamic loads from wave and wind variations can induce excessive platform motion responses, particularly in pitch and heave modes. Unmitigated dynamic motions risk compromising operational stability for the wind turbine and inducing high tension loads on the mooring system. Therefore, this study aims to analyze the technical performance, structural hydrodynamic response, and power efficiency of an integrated FOWT-FSPV hybrid energy system under coupled wave and wind dynamic loading [1].

2. Materials and Methods

The primary challenge in implementing a hybrid FOWT and FSPV system centers on platform hydrodynamic stability resulting from altered mass characteristics and increased exposure to dynamic environmental loads. Incorporating supporting deck structures and FSPV module arrays significantly increases the system's total mass and shifts its Center of Gravity (CoG), altering the platform's natural periods in pitch and heave modes and

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increasing its susceptibility to wave-induced resonance. Furthermore, the expanded deck area elevates horizontal aerodynamic drag force, amplifying motion displacement amplitudes in surge and sway modes. Unmitigated pitch motion is particularly critical as it induces unsteady aerodynamic loading across the wind turbine blades, accelerates structural fatigue on the tower, and heightens the risk of direct wave slamming on the FSPV modules, ultimately driving up peak line tensions across the mooring system that require rigorous safety evaluation against Minimum Breaking Load (MBL) limits [2].

3. Results

Most research and development in offshore renewable energy currently relies on a decoupled, standalone approach. Previous studies generally analyze Floating Offshore Wind Turbine (FOWT) or Floating Solar Photovoltaic (FSPV) platforms independently without considering the complex physical interactions that inevitably occur when both systems are combined onto a single floating structure. This isolated design philosophy creates operational redundancies, restricts the optimization of structural engineering designs, and ultimately limits the overall efficiency of offshore resource exploitation. From a spatial and economic perspective, deploying FOWT and FSPV as separate assets proves highly inefficient for comprehensive marine spatial planning. Separate installations duplicate the required sea surface footprint, create spatial conflicts with marine traffic or conservation zones, and lead to significantly inflated capital expenditures, primarily driven by redundant subsea power cable routes, multiple offshore substations, and independent mooring anchor setups for each individual platform. Furthermore, standalone installations fail to leverage the natural temporal complementarity between offshore wind and solar energy profiles, which limits the smoothing of daily power generation profiles and leaves grid power intermittency largely unaddressed [3].

Beyond these economic and spatial inefficiencies, a fundamental limitation of previous numerical modeling approaches lies in the oversimplification of coupled aero-hydrodynamic interactions between the platform and its environment. Initial numerical simulations of hybrid platforms often treat FSPV modules merely as static dead loads, effectively ignoring their significant contribution to horizontal aerodynamic drag forces as well as wave overtopping (*green water*) interactions on the platform deck. This crude simplification yields inaccurate estimates of dynamic platform motion responses, particularly in pitch and heave modes, and severely underestimates dynamic line tension loads acting on the mooring system under extreme sea states. Consequently, relying on such decoupled analytical frameworks risks under-designing critical structural elements or miscalculating the true fatigue life of the integrated floating system [4].

4. Discussion

Integrating FOWT and FSPV onto a single hybrid floating platform represents a strategic advancement that is technically and economically feasible, provided the design process utilizes a comprehensive coupled modeling approach rather than traditional decoupled approximations. Time-domain numerical simulations demonstrate that incorporating FSPV module structures onto the deck does not compromise global platform stability, provided dynamic motion responses in pitch and heave are effectively dampened. By maintaining an average maximum pitch angle below the critical operational threshold, continuous rotor rotation for the wind turbine is ensured under steady power production regimes while simultaneously minimizing the mechanical damage risks and dynamic slamming forces exerted on the solar panels from high-amplitude wave impacts [5].

The application of a steel-chain catenary mooring system effectively mitigates combined dynamic environmental loads induced by wave action, turbulent wind fields, and ambient ocean currents. Numerical analyses confirm that peak line tensions are maintained safely within allowable structural capacity limits, yielding a safety factor that fully complies with stringent offshore classification standards and design codes. Overall, this hybrid integration significantly increases total power yield per unit area of sea surface, optimizing ocean space usage. The natural temporal complementarity between daytime solar radiation and offshore wind resources effectively reduces overall power output variability sent to the grid, while simultaneously lowering capital expenditures through shared subsea power transmission cables, electrical substations, and floating platform infrastructure [6].

5. Conclusion

Based on the comprehensive coupled numerical analysis, integrating a Floating Solar Photovoltaic (FSPV) system onto a modified semi-submersible Floating Offshore Wind Turbine (FOWT) platform is technically

feasible and successfully maintains overall hydrodynamic stability. The hybrid platform configuration effectively mitigates critical dynamic motion responses, particularly in pitch and heave modes, thereby preserving continuous aerodynamic power generation for the wind turbine and protecting the fragile solar module arrays from severe wave impact forces under irregular sea states and turbulent wind conditions. Furthermore, the designed steel-chain catenary mooring system demonstrates superior structural integrity under combined dynamic environmental loading. The peak line tensions on the critical weather-side mooring lines remain well below the material's Minimum Breaking Load (MBL), consistently maintaining safety factors that fully comply with established offshore classification standards [7].

In addition, the integrated hybrid FOWT-FSPV system significantly enhances total energy yield per unit area of sea surface while effectively smoothing power output intermittency through the natural temporal complementarity of wind and solar resources. This unified design approach optimizes marine spatial utilization, reduces conflict with other ocean user sectors, and optimizes capital expenditures by utilizing shared subsea power transmission cables, floating substructures, and electrical grid infrastructure. Ultimately, these findings confirm that coupled hybrid platforms offer a robust and economically viable pathway for large-scale offshore clean energy generation [8].

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