Wind Shadowing and Load Response in Floating Solar Photovoltaic (FPV) Systems

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Abstract - Floating solar photovoltaic (FPV) systems have emerged as a promising solution to the dual challenges of land scarcity and the increasing demand for renewable energy sources. By deploying solar arrays on water bodies, FPV systems offer several advantages, including reduced land use competition, enhanced energy production due to the cooling effects of water, and potential synergy with existing water infrastructures. However, the dynamic nature of aquatic environments introduces unique challenges, particularly concerning lift, drag, and wave forces acting on the solar panels and support structures. This white paper explores these challenges, with a focus on understanding the influence of shadowing on the load responses of FPV systems. Through a detailed analysis using OrcaFlex® software, the study examines linear arrays of FPV modules under varying wind velocity and shadowing profiles. The results reveal the significant impact of shadowing on mitigating lift and drag forces, as well as the importance of addressing these forces to ensure system stability, efficiency, and longevity. The paper proposes potential solutions, including optimized panel design, advanced mooring systems, and site selection, to optimize FPV system performance in the face of dynamic hydrodynamic forces.

1. Introduction

As the global shift towards renewable energy sources accelerates, solar power stands out for its abundance and scalability. Land-based solar installations, while beneficial, grapple with issues of land scarcity, environmental footprints, and conflicting land needs. Floating solar photovoltaic (FPV) systems present a compelling solution to these challenges by deploying solar arrays on water bodies like reservoirs, lakes, and ponds.

The benefits of FPV systems include:

1. Optimized Land Use: Leveraging underutilized aquatic surfaces reduces the conflict with agricultural or urban development.
2. Enhanced Energy Production: The cooling effect of water on solar panels boosts their efficiency and output.
3. Reduced Environmental Impact: FPVs help curb water evaporation, impede algae proliferation, and shield water from excess sunlight, potentially enhancing water quality.
4. Synergy with Water Infrastructures: These systems can complement existing water-related facilities, such as hydropower plants or treatment systems, for improved land-use effectiveness.

Despite these benefits, FPV systems face unique challenges due to the dynamic nature of aquatic environments (see figure 1). Hydrodynamic forces, such as lift and drag from wind, waves, and currents, become complex when acting upon solar panels, which are often oriented southward regardless of varying environmental forces. Understanding these interactions is crucial for predicting system behavior and optimizing performance.

One particular challenge is understanding the "shadowing effect," where one panel obstructs airflow to those behind it, altering the forces they encounter. This effect is especially significant in large solar arrays with closely spaced panels. This white paper presents a short sensitivity study to understand the effect shadowing has on load reduction and the importance for quantifying the wind blockage to allow for optimization of FPV systems for the marine environment.

Fig 1*: Failure of a FPV system (https://solaredition.com/destruction-of-floating-pv-plant-by-typhoon-at-yamakura-dam-wind-resistance-in-spotlight)*

2. Methodology

The primary aim of this investigation was to better understand the shadowing effect on the load response of floating photovoltaic (FPV) systems. For this analysis, linear arrays of FPV modules were analyzed, focusing solely on the wind reduction as a function of array length.

This setup allowed for the examination of various shadow profiles under uniform load conditions, thereby streamlining both the analysis and interpretation of data.

For our analysis, we utilized OrcaFlex®, a prominent ocean engineering software extensively used in offshore industries, especially in the oil and gas sector. A detailed description of the model and its numerical framework can be found in the comprehensive documentation, reference materials, and validation reports available at www.orcina.com.

The moored solar arrays were modeled with distinct shadowing profiles, each subjected to comparable hydrodynamic forces, including waves and currents. As illustrated in Figure 1, the models comprised 32 FPV panels supported by 16 flotation modules linked longitudinally. The terminal ends were secured using a mooring buoy made from a 1-meter diameter pipe, while anchorage was provided by a 25 mm stud link chain. These simulations were conducted in a water depth of 20 meters.

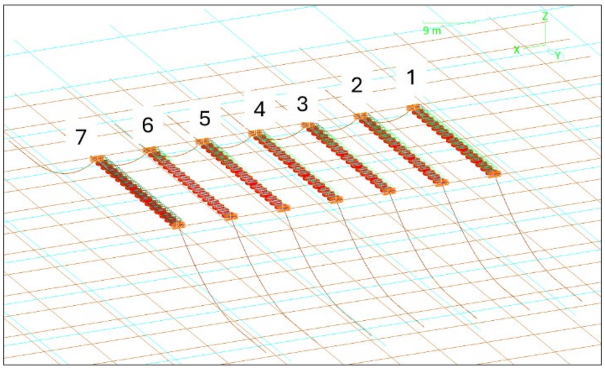

***Fig. 2**: Linear Section of FPV Arrays in Orcaflex®.*

Each module was subjected to wind, as seen in Figure 2, that contributed to drag and lift forces acting on all the FPV panels. We analyzed seven distinct shadowing profiles, with the impact on downstream modules depicted in Figure 3. Here, flow reduction was represented as a percentage reduction in the drag coefficient to simulate wind speed reduction. For instance, in the third string of the solar array, the foremost module faced the full wind force, whereas the drag coefficient for the 17th module was reduced to just 40% of its initial value to represent the reduced wind speed. It is important to note that these percentages are hypothetical and were chosen to evaluate the shadow effect on the FPV systems' response.

Tables 1 and 2 detail the geometric and material properties of the FPV modules and mooring systems, alongside the environmental conditions applied to the models. We used irregular waves characterized by a JONSWAP spectrum to emulate the sea state, with the significant wave height (H_s) and dominant period (T_p) describing the wave conditions. The significant wave height is defined as the mean height of the highest third of the waves, with the maximum wave height within a wave group likely being approximately 1.67 times the significant wave height. A linearly decreasing current profile with depth was assumed, with full velocity at the surface and a specified reduction near the seabed. Wind forces were estimated using the 1/7-power wind profile, which accounts for wind speed attenuation closer to the water's surface, with all wind speeds measured at a standard height of 10 meters above the surface. All wind and wave forces were presumed to be co-linear, acting in the same direction. Drag and lift force coefficients were referenced from the study by Caplan & Gardner (2005), with the estimated to be 1.2 and 1.4 for drag and lift, respectively.

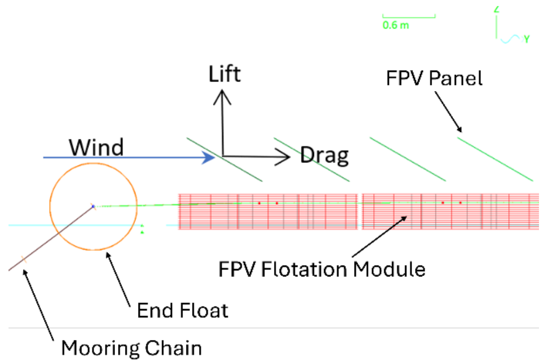

Fig. 3: A side view of the forces being applied to the model.

Shadowing Effect On Drag/Lift (%)

Solar Array String	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	100	90	80	70	60	50	40	30	20	20	20	20	20	20	20	20
2	100	100	90	90	80	80	70	70	60	60	50	50	40	40	30	30
3	100	90	80	70	60	50	40	40	40	40	40	40	40	40	40	40
4	100	100	90	90	80	80	70	70	60	60	50	50	40	40	40	40
5	100	90	80	70	60	60	60	60	60	60	60	60	60	60	60	60
6	100	100	90	90	80	80	70	70	60	60	60	60	60	60	60	60
7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Solar Array String	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
2	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
3	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
4	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
5	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
6	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
7	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

***Fig. 4**: Shadowing Effect on Drang and Lift.*

***Table 1**: Model material and geometric properties*

Parameter	Metric	Value
Solar Arrays	Size	2m x 1 m
	Single Array Weight	35 kg
	Arrays per Float	2
Flotation Module	Size	2.1 m x 2.1 m
	Module Weight	30 kg
Solar Float Assembly	# floats in each string	16
	# solar arrays in each string	32
	Spacing (center to center)	2.2 m
	Total length	35 m
Mooring	End Float	1m dia HDPE pipe
	Mooring legs	40 m of 25 mm stud link chain

***Table 2**: Simulated Environmental Conditions*

Enviromental Conidtion Summary						
	Enviromental Coditions #					
	1	2	3	4	5	6
Wind Speed (m/s)	25	30	35	25	30	35
Wave Height (m)	0.25	0.25	0.25	0.5	0.5	0.5
Wave Period (s)	3.5	3.5	3.5	4.5	4.5	4.5
Current Velocty (m/s)	0.51	0.51	0.51	0.51	0.51	0.51

3. Results

The results of the analysis are presented in Tables 3 and 4, which detail the mean structural loads and their standard deviations for the FPV systems, with the data obtained at the connection of the FPV modules and the lead float. Key observations from the study are as follows:

- Systems with the least shadowing, specifically arrays 6 and 7, exhibited the highest mean loads and standard deviations. This outcome was expected as these scenarios did not account for wind blockage by upstream panels.
- Load cases 3 and 6 were associated with the heaviest loads. These cases featured the most extreme wind conditions and wave heights, leading to increased load impacts.
- Shadowing had a significant effect on load mitigation. For example, the load difference between the un-shadowed solar array 7 and the heavily shadowed array 1 showed a reduction of 177%. Even with conservative shadowing estimates, a noticeable load decrease of around 35% was observed.

Table 4 provides information on instances where solar modules lifted off the water surface during simulations. Notably, arrays 1 and 3 maintained full contact with the water in all load cases. In contrast, array 7, which had no shadowing effect, experienced module lift-off in every load case. It is important to note that during load cases 3 and 6, module lift-off was prevalent across various arrays. A reduction in the drag coefficient due to shadowing of 20-30% appears to limit the lift-off phenomenon. Additionally, the system's leading edge consistently remained submerged, with lift-off primarily occurring in the central section of the array. A critical finding was the rapidity of lift, with significant elevation (over 1 meter) occurring within a brief 3-second interval. This suggests that gust speed is a more accurate indicator of peak wind conditions leading to lift. These insights will inform potential mitigation strategies, which will be further explored based on precise shadowing data.

***Table 3**: Support Structure Mean Loads*

Structure Mean Loads (N)							
		Enviromental Coditions #					
		1	2	3	4	5	6
Solar Array String	1	3478	4298	5461	3497	4313	5479
	2	3911	5116	7014	3937	5148	7013
	3	4015	5219	6941	4065	5270	6970
	4	4303	5761	8275	4346	5816	8384
	5	4724	6561	9923	4788	6591	9884
	6	4865	6858	10281	4934	6915	9197
	7	7366	10776	15242	7273	10771	15220

***Table 4**: Support Structure Std. Dev. Loads*

Structure Std. Dev. Loads (N)							
		Enviromental Coditions #					
		1	2	3	4	5	6
Solar Array String	1	800	907	1096	829	944	1126
	2	842	1028	1428	880	1067	1533
	3	870	1064	1410	904	1118	1457
	4	902	1154	1729	945	1207	1800
	5	963	1320	2287	1016	1368	2294
	6	981	1384	2366	1042	1436	3909
	7	3348	2401	3609	4389	2439	3614

***Table 5:** FPV Array Lift Off Check*

Solar Array Lift Off							
		Enviromental Coditions #					
		1	2	3	4	5	6
Solar Array String	1	✖	✖	✖	✖	✖	✖
	2	✖	✖	✔	✖	✖	✔
	3	✖	✖	✖	✖	✖	✖
	4	✖	✖	✔	✖	✖	✔
	5*	✖	✖	✔	✖	✖	✔
	6	✖	✖	✔	✖	✖	✔
	7	✔	✔	✔	✔	✔	✔

4. Challenges and Solutions

Addressing lift and drag challenges in floating solar systems requires a multidisciplinary approach, encompassing hydrodynamics, materials science, and system design. Several strategies can be employed to mitigate these challenges and optimize system performance:

- Optimized Panel Design: Designing solar panels with aerodynamic profiles and low drag coefficients can minimize lift and drag forces, improving stability and efficiency.
- Advanced Mooring Systems: Implementing robust mooring systems, such as catenary or taut mooring, capable of withstanding fluctuating forces and adapting to changing water conditions is essential for ensuring system stability.
- Additional Support Systems: Integrating an inverse wing (spoiler) to sections of the array can help mitigate lift issues, although this may increase the drag component of the loads acting through the system.
- Ballast Systems: Increasing the mass of the support structure of the solar arrays is a straightforward method to decrease the chances of the system being negatively affected by lift forces.
- Dynamic Positioning Systems: Integrating sensors and actuators for dynamic panel positioning can mitigate the effects of lift and drag, maximizing energy capture and system longevity. However, this adds to the cost, complexity, and reliability of the system.
- Site Selection and Planning: Conducting thorough site assessments to identify optimal locations with minimal exposure to strong currents, waves, and wind can reduce the impact of hydrodynamic forces on floating solar installations.

By combining these strategies, a more resilient and efficient floating solar system can be developed, capable of withstanding the dynamic forces encountered in aquatic environments.

5. Conclusion

Floating solar photovoltaic (FPV) systems have emerged as a promising solution for expanding renewable energy capacity, addressing land scarcity and environmental concerns. By deploying solar arrays on water bodies such as reservoirs, lakes, and ponds, FPV systems offer a unique opportunity to optimize land use and enhance energy production. However, the dynamic nature of water and wind introduces challenges related to lift, drag, and wave forces that must be carefully addressed to ensure the stability, efficiency, and longevity of these systems.

Our study focused on understanding the shadowing effect on the load responses of FPV systems. By employing OrcaFlex®, we analyzed linear arrays of FPV modules under varying shadow profiles and uniform load conditions. The results revealed that systems with the least shadowing experienced the highest mean loads, while the implementation of shadowing profiles significantly mitigated these loads. Additionally, we observed instances of solar modules lifting off the water surface during simulations, highlighting the importance of addressing lift forces in system design.

Addressing the challenges of lift, drag, and wave forces requires a multidisciplinary approach that encompasses hydrodynamics, materials science, and system design. By implementing strategies such as optimized panel design, advanced mooring systems, additional support structures, ballast systems, dynamic positioning systems, and careful site selection, we can enhance the resilience and efficiency of FPV installations.

In conclusion, floating solar photovoltaic systems hold great potential as a sustainable energy solution. By understanding the underlying mechanisms of lift, drag, and waves on FPV systems and implementing appropriate mitigation strategies, we can realize the full potential of floating solar installations, contributing to the global shift towards renewable energy sources while addressing land scarcity and environmental concerns.

6. References

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7. Author/Speaker Biographies

Dr. Judson DeCew is president of Ultrasea and has been a noteworthy leader in the ocean engineering space for over 25 years, working on projects that ranged from offshore aquaculture to marine renewable energy to maritime security systems. His thought-leading work has resulted in over 35 peer-reviewed journal publications and conference proceedings and 9 patents.

Michael Osienski, co-founder and driving force at Ultrasea, boasts an extensive background in ocean engineering and marine systems design. He has led pivotal projects, including the design and deployment of state-of-the-art marine gates and barrier systems, and groundbreaking research into the characteristic properties of chain-link copper alloy nets in marine conditions.