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ENERGY FLUCTUATION OF FLOATING PHOTOVOLTAIC SOLAR PANEL DUE TO WAVE-INDUCED MOTIONS

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ABSTRACT

Solar photovoltaic is predicted to be the most widely used energy method in the future. However, the expansion of solar panels is currently limited by scarce land and lake spaces. To meet the world's future clean energy target, floating solar panels are expected to be deployed on abundant ocean space, but floating solar panels on the ocean will be subject to loads and motions induced by waves. In particular, a continuous rotation can cause the solar panel surface to constantly change its sunlight intake angle, which could lead to a loss of energy. To investigate this phenomenon, a novel interdisciplinary experimental facility has been established, where a solar simulator was installed on top of a wave tank. A floating solar unit is placed in high-concentration light beams and subject to wave-induced motions. Its motions are measured and related to the power output. It was found that the average power output oscillates due to the motions, and an evident power loss was shown by the rotational motion. For all the tested wave conditions, the highest pitch amplitude of 6.7° corresponds to a significant level of 12.7% average power loss. Overall, the work presents a novel experimental approach and results that can estimate power output for floating solar projects in wave environments. The results also highlight the importance of considering wave attenuation technologies to avoid direct wave interaction with floating solar units.

Keywords: Floating solar, wave-induced motions, pitch, power loss, solar simulator, wave tank.

1. INTRODUCTION

Photovoltaic (PV), also known as solar panels, is predicted to become the most deployed energy method in the world, as shown in Figure 1. It is the cheapest renewable energy technology in history, as shown in Figure 2, and it will likely become cheaper over time [1]. It is also fully scalable; different numbers of panels can be used for solar farms at different scales, ranging from small residential rooftops to industrial-scale power plants [2].

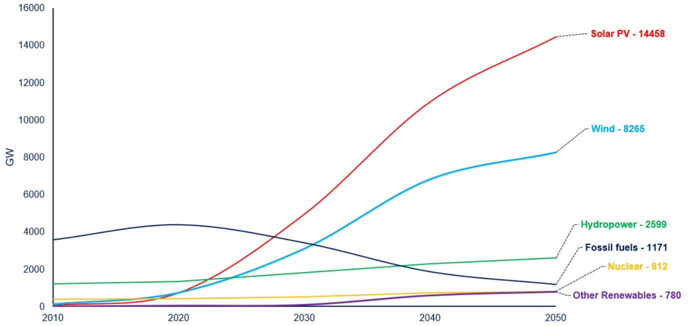

FIGURE 1: World electricity by sources and over time [3]

Although over 14,000 GW PV is planned to be installed globally by 2050 [3], it remains a question where those power plants can be deployed. Whilst many countries around the world have deployed solar panels on rooftops, empty lands, and lakes, there is only 240 GW of PV installed in 2022 [4]. Additional deployment of PV in such space will potentially conflict with human activities and natural resources [5].

In this context, there has been a strong interest in deploying Floating Photovoltaic (FPV) on seas [6]. However, operating FPV in oceanic environments faces significant challenges from waves, which is very different from a calm-water condition (e.g. lakes) [7, 8]. For example, continuous wave motions will induce floating solar panels to move accordingly [9, 10]. This changes the surface angle of solar panels, which decreases the efficiency of converting solar energy, called the mismatch effect [11].

While the mismatch phenomenon is known to exist, there has been a lack of scientific analysis on how the wave-induced motions of FPV are linked with energy efficiency. This motivated the present work to develop a new experimental facility to measure and analyse the motions as well as power performance of a floating solar unit in various wave conditions.

2. EXPERIMENTAL SETUP

2.1 New solar+wave experimental facility

To measure the motion and energy performance of a floating solar structure in waves, a new experimental facility was estab-

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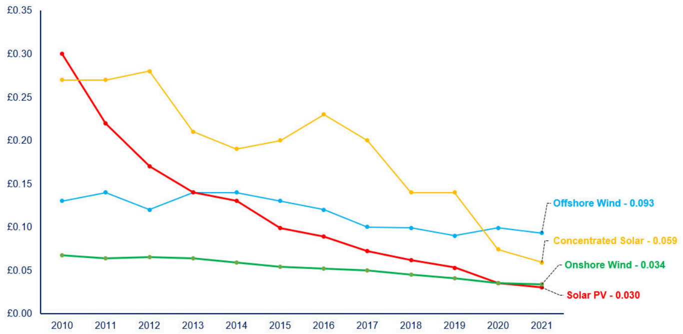

FIGURE 2: Cost of renewable technologies over time (per kWh) [1]

FIGURE 3: Combined solar simulator and wave tank facility at Cranfield University

lished at Cranfield University. Specifically, the novelty is to install a solar simulator on top of a wave tank, as shown in Figure 3. The solar simulator is used to generate light beams, from which, an underneath floating solar unit may generate electricity. The solar simulator was assembled by 21 units of Eterna Lighting's CTH500SL 500W halogen floodlights, arranged as a 7x3 matrix to cover the area where the solar panel is placed.

This electric output can be read when the solar unit is moving in waves and thus the motion and energy results can be linked. The wave tank is 30 m long, 1.5 m wide, and filled with freshwater to a depth of 1.5 m. The drawings and detailed dimensions of this solar+wave experimental facility are given in Figures 4, 5 and 6. The floating solar unit is moored by a four-pointing mooring approach to restrain its horizontal translation.

2.2 Floating solar unit

The floating solar unit consists of a solar panel and a catamaran floating structure to lift the solar panel above the water surface. The PV panel is a common commercial type, made by TDG Holding Co., Ltd and the model number is T050M365. It applies the cell technology of Monocrystalline, with a maximum power output of 50W.

The floating applied a catamaran shape, which is newly designed in this work as an alternative to the contemporary cuboid shape used in industry, which can help save materials. Moreover, benefiting from its hydrodynamically superior shape, the catamaran floater also takes less wave/current loads than a counterpart cuboid floater, corresponding to less movement and transferring less loading to moorings. The detailed design of the catamaran is given in Figures 7, 8, 9 and 10. Contemporary floaters are normally made of hollow composite, which accounts for a significant part of the cost of the FPV system; by contrast, We have used a novel and cheap Extruded Polystyrene (XPS) material to make the catamaran, which offers appropriate strength and buoyancy. The XPS has a density of 38.44 kg/m^3 and a compressive strength of 64.6 psi.

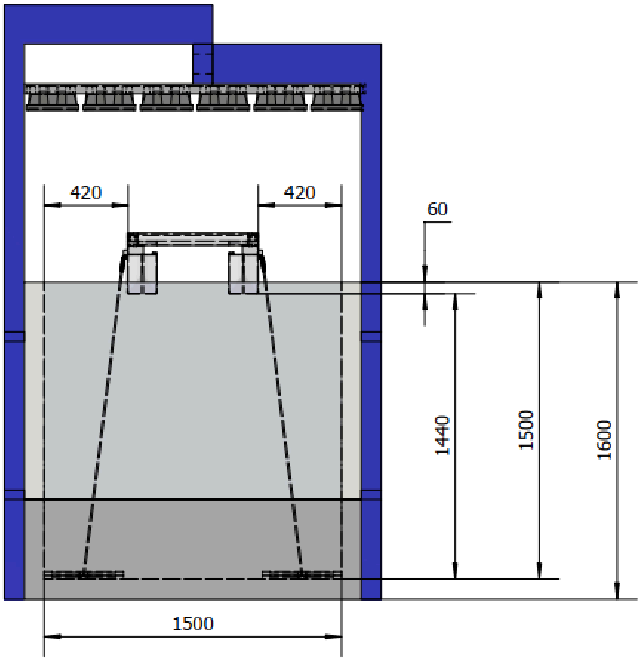

FIGURE 4: Section view of the solar+wave experimental facility; dimensions in mm

2.3 Wave conditions and measurements

The wave tank uses a physical flapper on one end to produce waves which propagate along the wave tank. On the other end, a physical beach is installed to avoid reflection [12], as shown in Figure 6. In this study, different types of regular waves are tested, aiming to link the wave conditions to structural motions as well as the energy output. Ten wave conditions were tested, consisting of five frequencies: 0.8 Hz, 0.85 Hz, 0.9 Hz, 0.95 Hz and 1 Hz, and two wave amplitudes: 0.025 m and 0.05 m.

With the waves continuously being generated and propagating towards the floating solar unit in its heading direction. The floating structure conducts periodic motions with continuous incoming waves, which indicates the experiment has entered its steady state and valid data were taken only after the periodic motions began. The wave-induced movement was decomposed into heave and pitch motions for analysis, while other motion components were neglected in this case. The heave and pitch motions

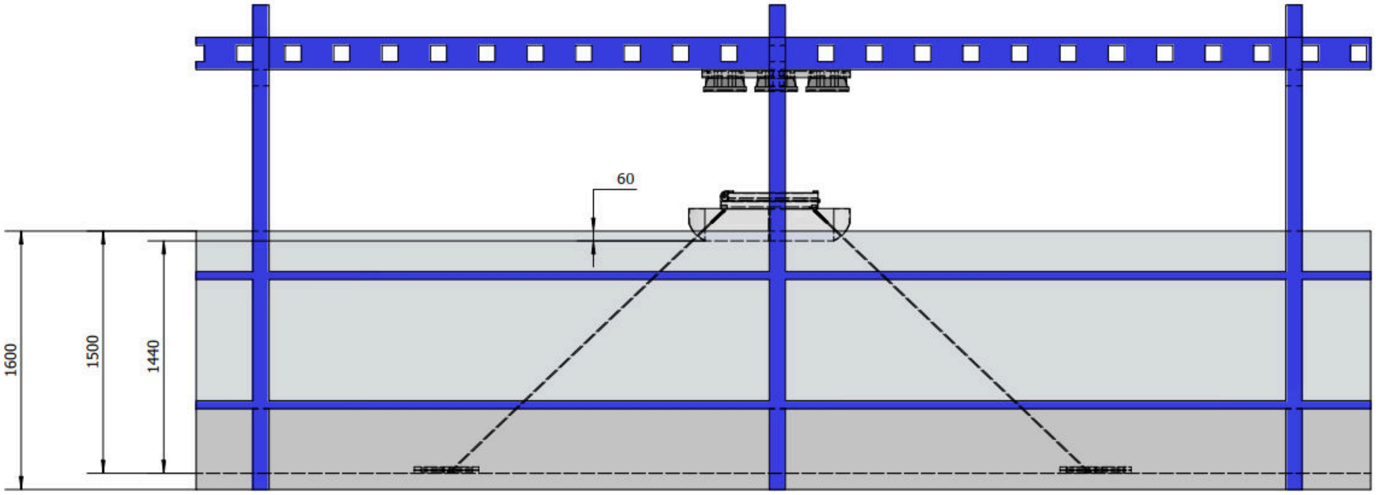

FIGURE 5: Profile view of the solar+wave experimental facility; dimensions in mm

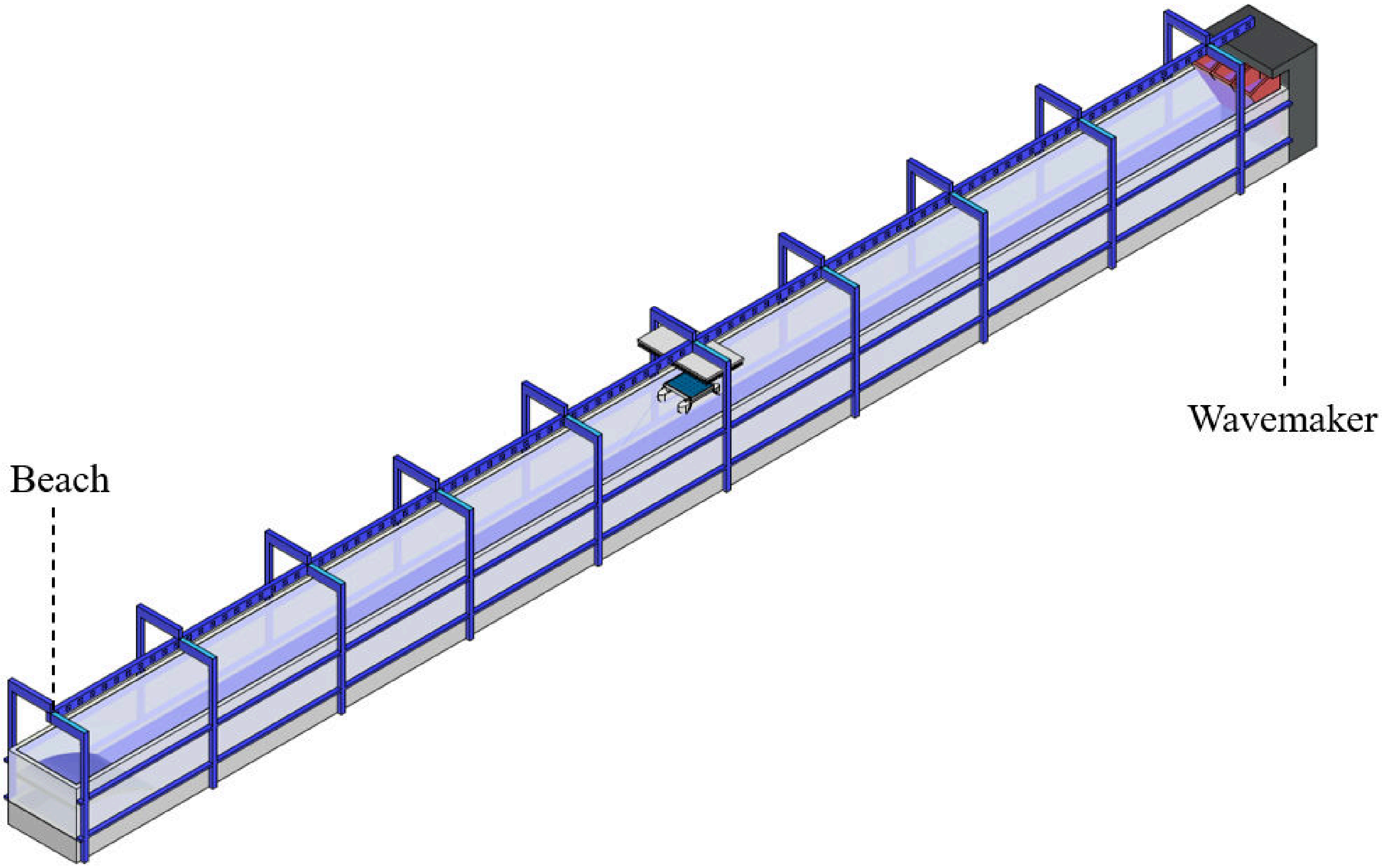

FIGURE 6: Overall drawing of the solar+wave experimental facility

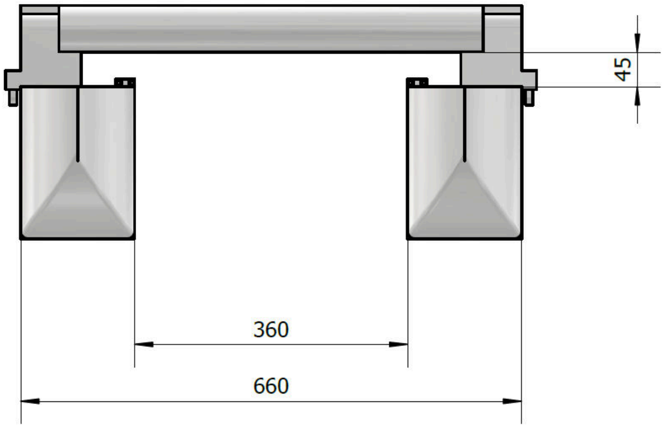

FIGURE 7: Section view of the catamaran floating structure; dimensions in mm

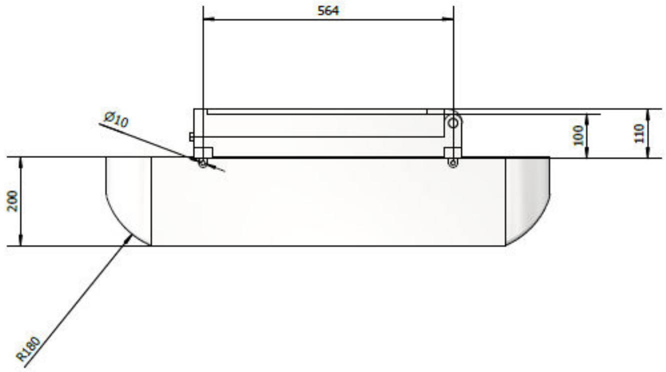

FIGURE 8: Profile view of the catamaran floating structure; dimensions in mm

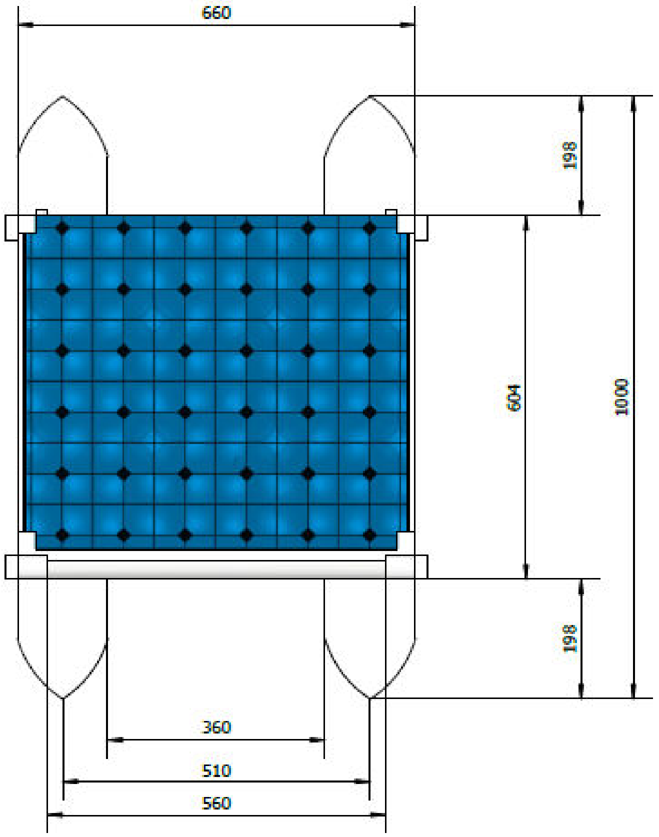

FIGURE 9: Plan view of the catamaran floating structure; dimensions in mm

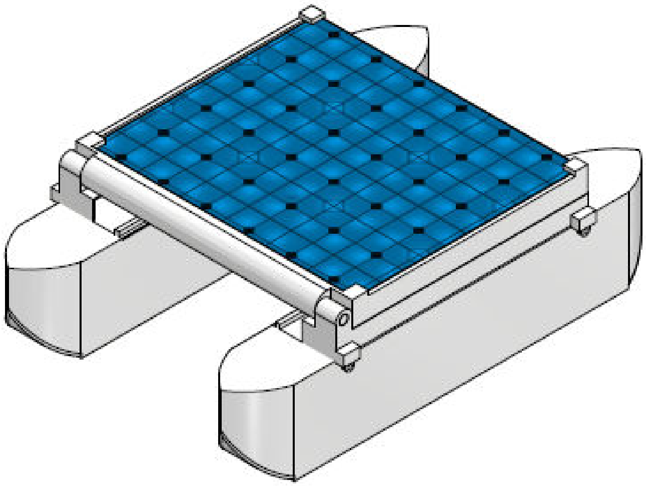

FIGURE 10: Overall drawing of the catamaran floating structure

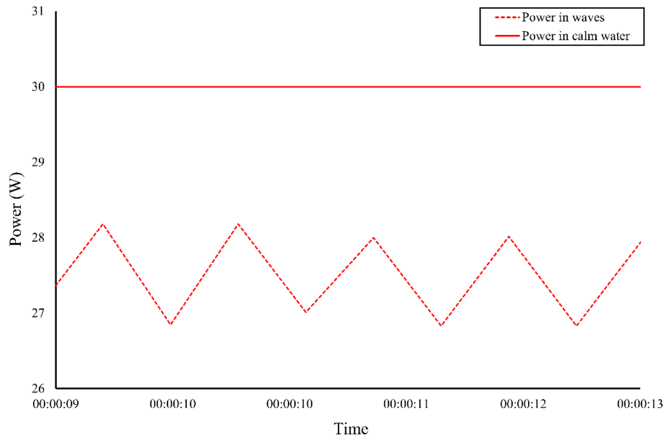

FIGURE 11: Example of FPV power on calm water and in waves (wave amplitude = 0.05 m and wave frequency = 1 Hz)

of the floating solar unit were recorded using accelerometer and inclinometer respectively. The power output of the solar panel was directly read through an external power cable. For the experiment under each wave condition, five wave periods of data were collected and the average of the five is taken as the result of the case. The experiment under each wave condition was repeated three times and it was found that there was no notable difference between the results of the repetitive tests, which means the experiment has minimal uncertainty.

3. RESULTS AND DISCUSSION

An example of the FPV power in waves, in comparison with its calm-water counterpart, is shown in 11. It can be seen that the power varies following wave motions and repeats for each wave cycle. The heave and pitch amplitudes of all tested cases are shown in Figures 12 and 13. It can be seen that the heave motion increases with decreasing wave frequency. This is because lower wave frequency corresponds to higher wavelength, and thus less wave scattering by the structure [13, 14]. A structure cannot be excited by sufficiently short waves due to the scattering effect, and when the dominating wave is long enough the structure will contour with the waves (heave amplitude approximates wave amplitude). The pitch amplitude shows a peak value, which is likely the case where the wavelength is similar to the structure length. A floating structure should exhibit minimal rotation in either too-short or too-long waves. For both heave and pitch, a larger wave amplitude corresponds to large motions.

The power output of the solar unit in waves is plotted in Figures 14 and 15; whilst the structure undergoes oscillating motions in waves, the power output also exhibits upper and lower limits in a wave circle, which is also presented in the figures. The black-dash reference line shows the solar power output when the structure is not moving with waves. Correlating to Figures 12 and 13, it can be seen that the oscillation of the power output increases with the increase of heave motion, while the average power output decreases with the increase of pitch motion. The oscillation can be attributed to the distance between the solar panel and the solar simulator, as the heave motion constantly brings the panel closer and farther from the light source, thus the light strength alters.

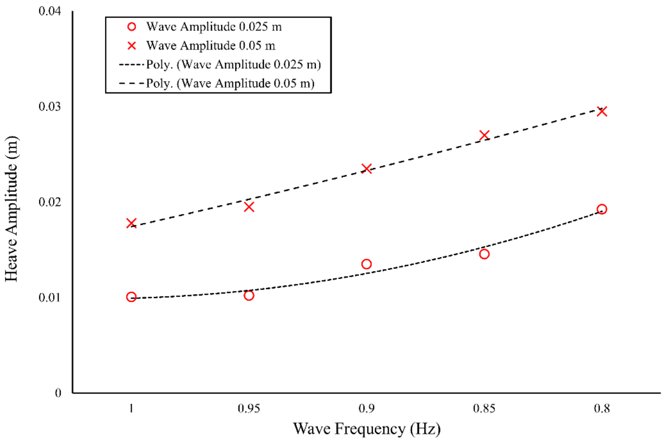

FIGURE 12: Heave amplitude of the structure in waves

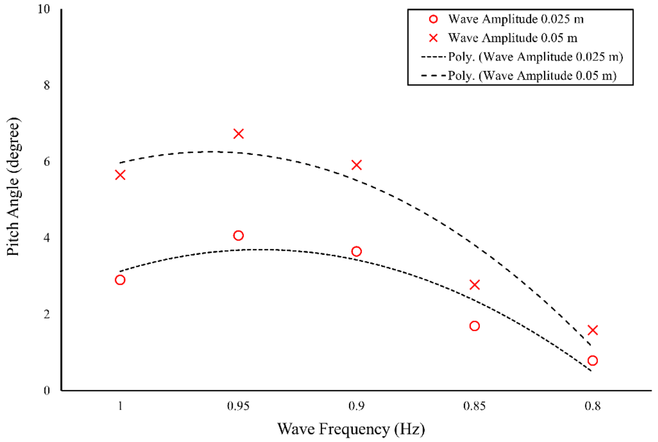

FIGURE 13: Pitch amplitude of the structure in waves

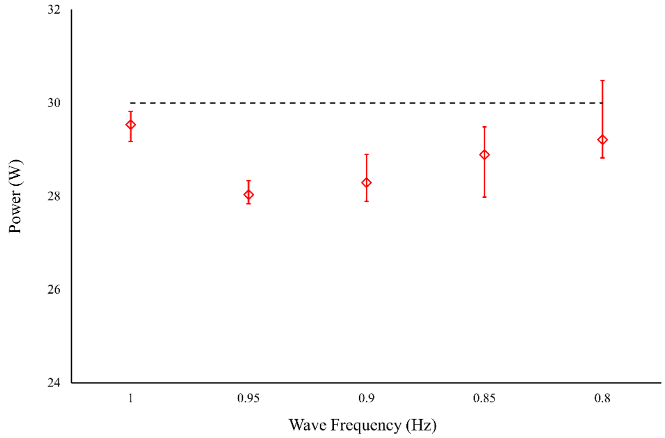

FIGURE 14: Power magnitude of the solar unit moving with wave amplitude 0.025 m; dash line shows reference level of no motion

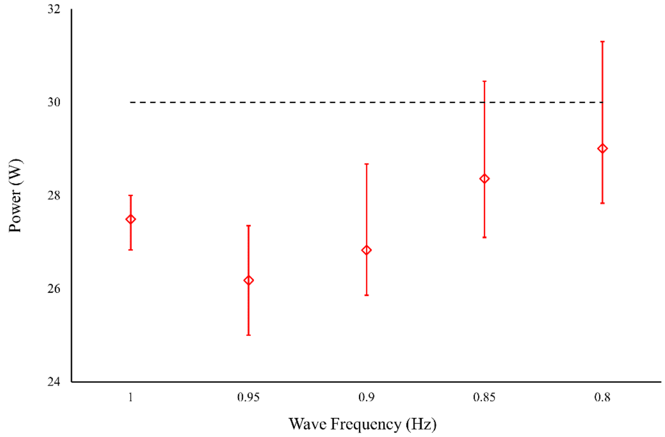

FIGURE 15: Power magnitude of the solar unit moving with wave amplitude 0.05 m; dash line shows reference level of no motion

In reality, since the distance between a solar panel and the sun is infinite, the influence of heave may be negligible. The average power output changes are related to the pitch motion that causes a misalignment between the solar panel and the light. This is particularly relevant for solar panels deployed on seas. It is evident that wave-induced motions will cause lower solar power harnessed than that of a still-water counterpart.

The data of pitch amplitude and power loss in each wave condition is outlined in Table 1. The highest pitch amplitude in all the measured wave conditions is 6.7°, and this corresponds to a significant level of 12.7% average power loss. To mitigate such power loss for ocean-based solar applications, a wave attenuation technology, e.g. breakwater [15], could be applied on the edge of a floating solar farm to avoid direct wave interaction with solar units. This will also support a holistic coastal management plan [16].

To enable the prediction of FPV power performance in wave environments, an accurate empirical equation would be particularly valuable. Based on the analysis of sunlight mismatch due to the rotational motion, a hypothesis appears that the average power loss of an FPV in waves may be predicted using a sine function $powerLoss = sin(pitchAmplitude)$. The accuracy level of such an equation is analysed in Figure 16, and it can be seen that the equation is fairly accurate and obvious inaccuracy only occurs for one case where the measured power loss was very low. In this context, this equation can be potentially very useful for coastal and offshore FPV projects, as it provides the ability of swift power prediction.

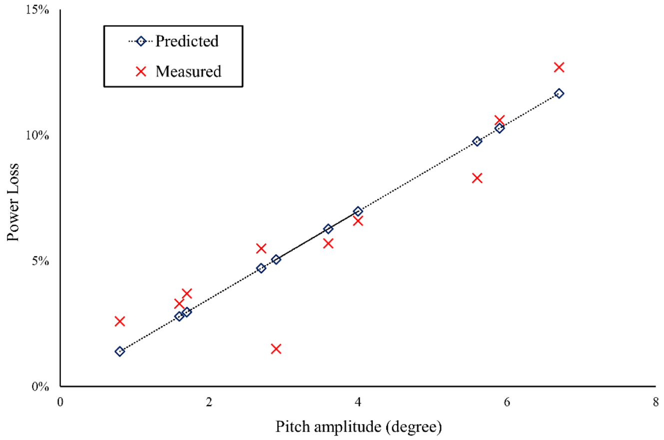

FIGURE 16: Power loss of FPV in waves: measured in the present experiments *versus* predicted by Equation $powerLoss = sin(pitchAmplitude)$

4. CONCLUSIONS

In order to study the power output of a floating solar panel influenced by wave-induced motions. A novel experimental facility was established combining a solar simulator and a wave tank. A floating solar unit was designed and assembled for tests of its power output in different wave conditions. Wave-induced motions of the solar unit and the corresponding power results were measured and analysed.

It was found that the pitch motion of a floating solar unit in waves can cause significant power loss compared to a calm-water scenario, which is due to the light misalignment from panel rotations. A pitch amplitude of 6.7°, can cause a significant level of 12.7% average power loss, highlighting the importance of implementing wave attenuation technologies in future floating solar projects on the ocean.

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DATA AVAILABILITY

All data underlying the results are available as part of the article and no additional source data are required.

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TABLE 1: Data of pitch amplitude and power loss

Wave amplitude (m)	Wave frequency (Hz)	Pitch amplitude (°)	Power loss
0.025	1	2.9	1.5%
0.025	0.95	4	6.6%
0.025	0.9	3.6	5.7%
0.025	0.85	1.7	3.7%
0.025	0.8	0.8	2.6%
0.05	1	5.6	8.3%
0.05	0.95	6.7	12.7%
0.05	0.9	5.9	10.6%
0.05	0.85	2.7	5.5%
0.05	0.8	1.6	3.3%

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