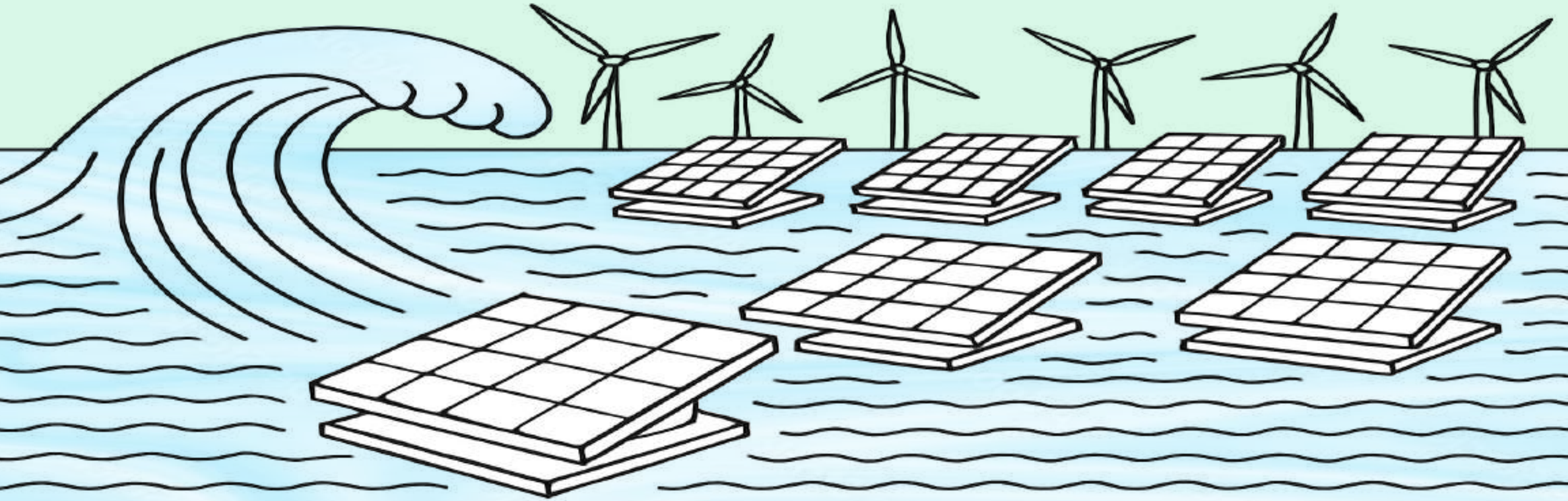
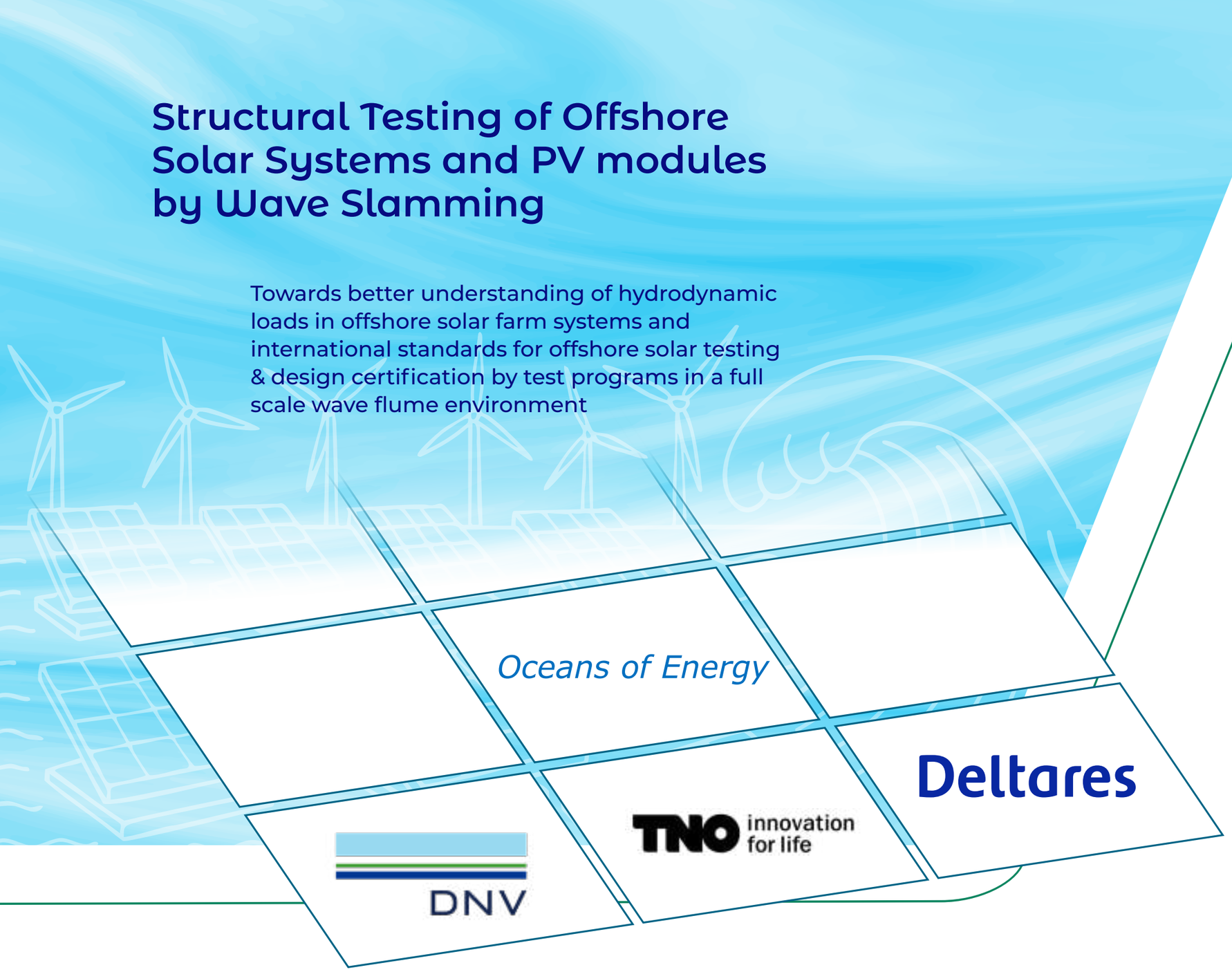
WHITEPAPER

Structural Testing of Offshore Solar Systems and PV Modules by Wave Slamming



Structural Testing of Offshore Solar Systems and PV modules by Wave Slamming

Towards better understanding of hydrodynamic loads in offshore solar farm systems and international standards for offshore solar testing & design certification by test programs in a full scale wave flume environment



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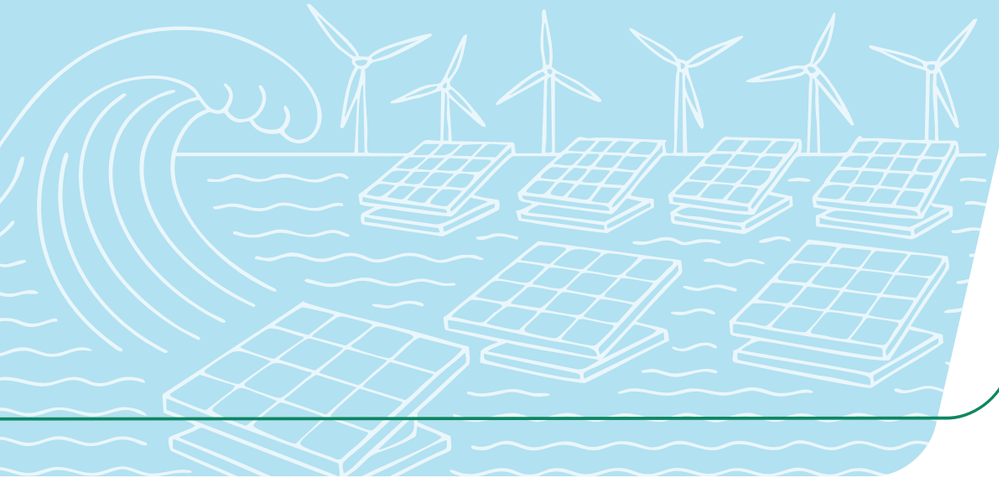
Executive Summary

The Structural Testing of Offshore Solar Systems and PV modules under wave slamming at the Deltares Delta Flume is a first-of-a-kind testing activity. The results of these tests will contribute to establishing a solid scientific basis for standardized testing protocols which is of great importance in the path towards certification of offshore solar systems.



Offshore solar holds immense potential to support the global energy transition. Unlike traditional solar technologies and inland floating solar, offshore solar systems are specifically engineered for harsh marine environments to withstand severe conditions. Despite the growing importance of offshore solar, there is a lack of established standardized test protocols, design standards and certification schemes for this novel technology. This lack impacts the risk profile of offshore solar projects and thereby affect the industry's rollout.

Offshore solar has already showcased reliability in the offshore environment. The Oceans of Energy offshore solar system has been tested offshore for four years through their North Sea Two (NS2) demonstrator, facing extreme environmental conditions. Next to the offshore pilot, the NS2 project also hosted an experimental testing campaign in the Deltares Delta Flume (recognized as the largest flume in the world) focusing on:

1. full-scale hydrodynamic tests of an Oceans of Energy's offshore solar platform array and
2. wave slamming tests of fixed PV-mounting and PV modules. The objective of these tests was to understand specific farm behaviour and performance in a controlled environment. DNV has been involved in the project to witness the test and to share its insights on the development of certification frameworks. In the introduction of the paper DNV provides a broader perspective on the outcomes of the NS2 project.

The hydrodynamic test revealed a relation between the system's response to varying wavelength and floater length. The wave-slamming test aimed to investigate potential performance degradation of PV modules but revealed no sign of degradation. It underlined the importance of proper mounting and support of the PV modules on the floater. This was confirmed by power performance and electro-luminescence measurements performed by TNO, despite significant wave forces up to 25.kN.

The tests have validated the system's performance and provided critical data to refine and validate predictive numerical models for larger-scale deployment. Moving forward, it is critical that starting from a sound scientific basis, research institute and technology developers collaborate to gain detailed insights into the system's behaviour and performance. However, the involvement of certification bodies in this process is equally important to establish widely adopted standard tests, design standards, and certification schemes, to give credibility and all stakeholders assurance that the product is safe and can survive 25 years at sea. The Structural Testing of Offshore Solar Systems and PV modules by wave slamming is an important step in this direction.

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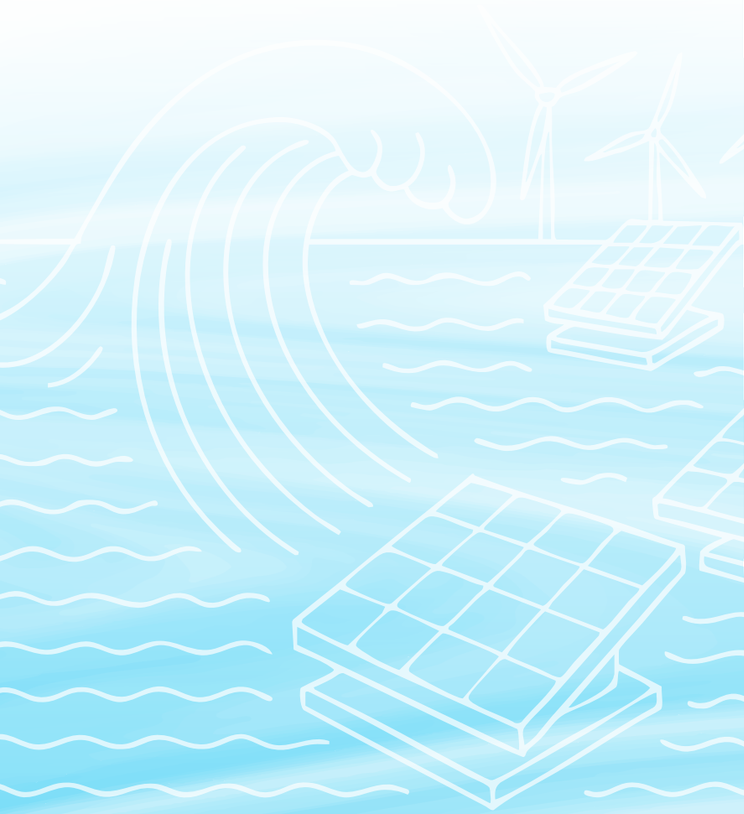

1 Introduction

In the Netherlands, several companies and organizations are working on the development of Offshore Solar. Offshore solar systems consist of floating platforms equipped with photovoltaic (PV) modules that can be flexibly linked together to from scalable energy farms on the ocean's surface. As the push for renewable energy accelerates, offshore solar is emerging as a promising solution against pressing challenges for renewables on land. Additionally, integrating solar with offshore wind farms allows for the efficient use of existing infrastructure (as of the complementary energy generation profiles) and the improved utilization of the wind farm site space.

Despite its potential, large-scale offshore solar is still in its early stages and there are currently no standardized testing or certification processes in place. These standards are essential to ensure that offshore solar farms can be deployed safely, cost-effectively, and with long-term resilience. Offshore wind energy has already established such frameworks, setting a clear and proven precedent for offshore solar to follow.

To bridge this gap, research and innovation projects are playing a key role in gathering the knowledge needed to develop offshore solar testing standards and certification. Oceans of Energy has outlined a roadmap of research initiatives aimed at addressing these challenges. Different methods are applied in these initiatives: numerical modelling, small-scale experimental testing, full-scale experimental testing, and offshore demonstration projects. Each method has its own characteristics, which is why it's important to use them in a complementary way.

One such research initiative is the NS2 project, which includes Oceans of Energy, Deltares, and TNO as collaborative partners in the project consortium. In 2022, the consortium conducted full-scale experimental tests in a wave flume, studying the impact of wave slamming on several floating platforms of Oceans of Energy. Understanding these forces is crucial to determining the structural resilience required for offshore solar farms to withstand the harsh marine environment. Full-scale experimental testing was the preferred method for wave slamming as wave slamming is difficult to scale. On top of that, the experimental setting allows for full controllability of the forcing conditions, which allow establishing a clear relation between the forcing conditions and measured loads.

This white paper serves three key purposes:

1. To provide an overview of the current state of the Offshore Solar developments in the North Sea.
2. To present the methodology and findings of the experimental testing conducted within the NS2 project.
3. To offer recommendations for the next steps toward certification, informed by the NS2 project results.

DNV has been invited to share its insights on the process of developing certification. They share their view on the outcomes of the NS2 project in the Introduction to highlight a broader perspective on the results of the research project.

DNV is currently developing two standards: one for anchoring and mooring and another for photovoltaic floats. These standards are the outcome of two joint industry projects in which Oceans of Energy is participating. These envisaged standards are still in the initial phase, so broader industry collaboration is needed to establish comprehensive standards that support the certification of offshore solar systems. Ultimately, this provides all stakeholders and clients with confidence that the product is safe and capable of withstanding 25 years at sea.

Memo to:
Oceans Of Energy

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Prep. By: MAGJOH / MDMRAH

Approved by:

Background

DNV has been invited to the Deltares Delta Flume to observe a full-scale laboratory test of part of the Oceans of Energy solar farm system. The test is called the NS2OSP testing program, a collaboration between TNO, Deltares, and Oceans of Energy. The aim of DNV's participation in the testing was to: 1) increase DNV's understanding of the structural and mechanical requirements of offshore solar systems; 2) develop a further understanding of how testing activities can support the development of offshore solar certification; and 3) disseminate our shared learnings from the project.

The results of the testing program are discussed in a paper titled "Whitepaper: Structural Testing of Offshore Solar Systems and PV modules by Wave Slamming." DNV is issuing this memo regarding the paper.

Model test

The full-scale testing conducted at the Deltares Delta Flume was witnessed by two DNV experts in the field of offshore solar. The testing program was a pioneering effort to evaluate the performance of offshore solar systems. This testing, aimed to simulate offshore environments, providing important information on how these systems respond to varying operating wave conditions in relation to floater length.

By testing the system in operating conditions, valuable insights were gathered on the local forces and interactions that the system will endure once operational. The test program also included several variations of wave lengths for each of the tested wave heights, which is crucial to establish understanding of the floater's response to the environment. With full-scale response data and knowledge about a variety of wave conditions, it enables the calibration of numerical simulation models.

Ensuring the durability and performance of PV modules under wave slamming conditions is vital for the overall reliability and performance of offshore solar farms. The knowledge gained from the test should be used to optimize system components, improve durability, and ensure reliable performance in diverse marine environments.

Way Forward

It is crucial to use the data obtained from these tests to enhance the design and reliability of offshore solar systems. While full-scale tests offer critical real-world data, they must be complemented by robust numerical models. These models can simulate a wider range of conditions and scenarios that are impractical to test physically. By expanding and refining these models, the system behavior can be predicted under extreme conditions and designs can be optimized accordingly.

The most effective strategy involves a combination of well-executed model (full-scale or scaled) tests and validated numerical models. This dual approach ensures that the physical tests validate the simulation models, which can be applied to provide a broader understanding of potential system responses. This synergy enhances the reliability and accuracy of performance predictions.

The currently available numerical software for simulating floater motions and wave interactions is not suited for the complexities of breaking water wave slamming on PV modules. This limitation highlights the urgent need for developing a new tool specifically designed to address this issue. Such tools should be capable of simulating the dynamic interactions between braking waves and PV modules, ensuring that the systems can withstand the harsh marine environment. Integrating data from both physical tests and numerical models will be essential to provide comprehensive design and analysis capabilities.

The industry needs to continue collaborating to establish widely accepted design standards and procedures to build trust in offshore solar systems.

2 Commentaries

Deltares, Roderik Hoekstra

Senior Project Manager Offshore Engineering

“The acceleration of the energy transition is one of Deltares’ focus areas in our corporate R&D agenda. We are eager to implement our expertise as well as our experimental and numerical facilities to develop knowledge that contributes to the acceleration of the energy transition. Offshore solar is an emerging form of renewable energy generation at sea and has the potential to be a complimentary source to the ongoing installation of offshore wind.

We are therefore excited that we have been able to test the Oceans of Energy offshore concept in the Delta Flume in partnership with a.o. Oceans of Energy and TNO in the North Sea 2 Offshore Solar Project. The Delta Flume is a unique testing facility where we can test prototype concepts and generate the largest artificial waves of the world. Next to numerical modelling, scale testing and offshore demonstration, we consider prototype testing in a controlled testing environment like the Delta Flume a key element in developing a standardization and certification procedure of offshore solar.

The Delta Flume tests have provided useful insight into the behavior of the floating system and individual components under severe wave loads. Understanding the relation between offshore conditions and actual loads on the floating system and PV modules can help simplify future testing protocols and feed design guidelines. As this was also one of the first floating infrastructure applications that we accommodated in the Delta Flume, we have also learned a lot about the testing procedure itself. This experience helps in improving the design and planning of future experimental testing campaigns of floating infrastructure.”

The Delta Flume tests have provided useful insight into the behavior of the floating system and individual components under severe wave loads.

TNO, Jan Kroon

Programme manager Floating Solar

“Offshore solar is an application area with great potential. Before large-scale deployment of offshore solar becomes reality, it is of great importance to address the R&D challenges in the field of performance, reliability, costs, and ecology at an early stage to derisk and develop a solid knowledge base. TNO therefore brings in all its competences in the field of Solar, Offshore Wind and Naval Offshore Structures to support innovations such as those of Oceans of Energy to help them further in their ambition to make offshore solar a commercial success.

In the NS2 project, Oceans of Energy, Deltares and TNO collaborated in a unique experiment in the Deltares Delta Flume in which the floating system of Oceans of Energy and the PV modules were exposed to a train of impacting waves on a realistic scale and controlled manner. The results of this experiment enabled the project team to validate hydrodynamic models for the design of offshore solar farms, and to quantify the mechanical impact of slamming waves on the PV modules and measure their effect on the power performance. This will subsequently ensure growth of offshore solar towards a mature and widely accepted PV application with a major impact on the energy transition.”

Offshore solar is an application area with great potential

Oceans of Energy, Fabian Koppes

Head of Product

“The NS2 Delta Flume tests have greatly increased our understanding of how our offshore solar systems surpass the high waves in the offshore North Sea environment. We were able to test our system under similar wave events as we witness at offshore sites, but now in a laboratory set up. This experimental setting allowed us to single out specific waves and measure their impact on our system in a more accurate way.

The results enable our team to further increase the reliability for lifetime performance predictions and improve the validation of our hydrodynamic models for designing large offshore solar farms. In addition, the monitoring setup used is further integrated into our Asset Integrity Monitoring system, which is a critical asset management tool during the 25-years of our offshore solar farm operations.

This collaboration together with Deltares, TNO, and DNV is of large importance in making progress towards certification of offshore solar. Lab experiments are a key step towards standardization and standardized testing in the field of wave load analysis on floating platforms and on impacts of wave slamming on PV modules. Finally, we also see these tests as an invitation: solar systems work in offshore conditions, let’s collaborate towards establishing a thriving industry capable of realizing large scale renewable energy generation.”

The NS2 Delta Flume tests have greatly increased our understanding of how our offshore solar systems surpass the high waves in the offshore North Sea environment.

3 Offshore solar and gaps towards certification

Offshore Solar: The Next Frontier

Offshore solar has the potential to increase renewable energy generation by expanding production beyond land-based solar farms. Where land and grid availability pose constraints for further roll-out of wind and solar, the vast seas and ocean space provide ample opportunities. Offshore solar can potentially generate 5 times more energy than offshore wind in the same surface area. Alternatively, according to the OOE-OSI model, Offshore solar can provide an additional 20% to 50% energy output of an offshore wind site by using less than 5% of the site's space, while using the same offshore grid connection[1]. Figure 3 presents a concept of the approximate offshore solar capacity for different farm sizes.

In the Netherlands, the Ministry of Climate and Green Growth (KGG) considers offshore solar as an important opportunity to contribute to an affordable renewable energy system [2]. Therefore, the Netherlands is exploring the potential to integrate 3 GW of offshore solar by 2030, as outlined in the National Energy & Climate Plan.

Offshore solar is a rapidly developing industry. It consists of floating platforms with a mounted solar PV-system, that are kept stationary by a mooring system and supply power via a dynamic export cable to a grid connection point or an offshore wind turbine. Each of the system components and the installation & operations procedures are specifically designed for the harsh offshore conditions and therefore are completely different than floating solar systems for calm and inshore water bodies.

So far, two product classes have been tested in offshore conditions: the Flat Pontoon concept, consisting of floating interconnected pontoons close to the sea surface that use the sea for carrying the systems (tested in pilots for over 4-years since 2019), and Elevated Truss concept, consisting of truss structures that carry the solar systems above the sea surface (tested in trials for several months) [3] [4]. In coming years, this technology is implemented within offshore wind farms, incl. 0.5 MW in Hollandse Kust Noord in 2025 [5], 5 MW in Hollandse Kust West in 202 [6], and 50 MW in IJmuiden Ver in 2029 [7], developed by major international project developers Shell, Eneco, RWE, Total Energies, Vattenfall, and Copenhagen Infrastructure Partners investing in first projects as early adopters.

North Sea Two Offshore Solar Project

Oceans of Energy (OOE) envisions a standardized offshore solar system of 1000mx1000m with an installed PV-capacity of 200 MWp that fits in the space between four offshore wind turbines. The 1km2 scale allows for numerous cost benefits including strong reductions in hardware and installation campaigns for mooring lines, anchors, and power export cables. Furthermore, scaling results in a protected inner-array field (the perimeter is more heavily exposed to the offshore environment) which allows for optimized floaters.

According to Oceans of Energy design philosophy (the Flat Pontoon concept), the most promising way of establishing large scale offshore solar is to use the sea surface for carrying the offshore solar system, floating like a water lily. This design offers additional benefits, which are the self-cleaning effect of the PV modules as waves pass over the floaters, and the enhanced systems' resilience by the reduction of wind loads due to its proximity to the sea surface.

1 Variance is caused by differences between low-solar regions with high wind resources (such as Northern Europe) and high-solar regions with less wind resources (such as Mediterranean-Europe).

Figure 1 NS1 floaters being washed by waves in stormy conditions North Sea 2019

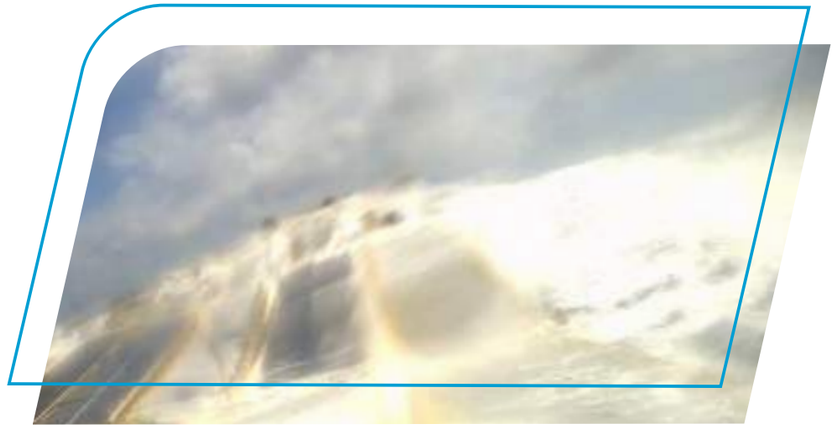


Figure 2 - North Sea 2 floaters in waves > 5 meters, 12km offshore in the North Sea

The Oceans of Energy offshore solar technology was first tested in offshore pilots in the period since 2019-Q4, as part of the North Sea One (NS1) project in collaboration with MARIN and TNO. NS1 successfully addressed several challenges of developing an expandable floating system directly on the sea surface that could withstand offshore conditions, and proved that industry standard PV modules could survive in offshore conditions (“Proof of Concept”).

The system consisted of standardized light-weight rigid floaters that can be integrated into offshore solar arrays by an ‘interconnector’ component. The concept of having rigid structures and a flexible part in between is inspired by the spine, that allows humans to bend our backs, just as it allows the floaters to bend with the waves. For the structural integration of the PV modules, a specific mounting solution was developed that enabled the PV modules to withstand the slamming waves from breaking the PV module glass.

In 2021, Oceans of Energy, together with Deltares, TNO, Twentsche Kabelfabriek (TKF), Het Koninklijk Nederlands Instituut voor Onderzoek der Zee (NIOZ), Wageningen Marine Research, and Utrecht University,started the follow-up project North Sea Two (NS2). The main objective was to increase understanding of offshore solar[2] and to prepare scaling to larger systems. To feed and improve design tools for large scale offshore solar farms of 1km^2, the North Sea Two (NS2) offshore solar farm has been built, installed and operated (with an off-grid set up) at the Offshore Test Site (operated by the North Sea Farmers) 12 km off the coast from The Hague. The system has been in the water for four years, ranging in size from several floaters to a maximum size of 64 floaters

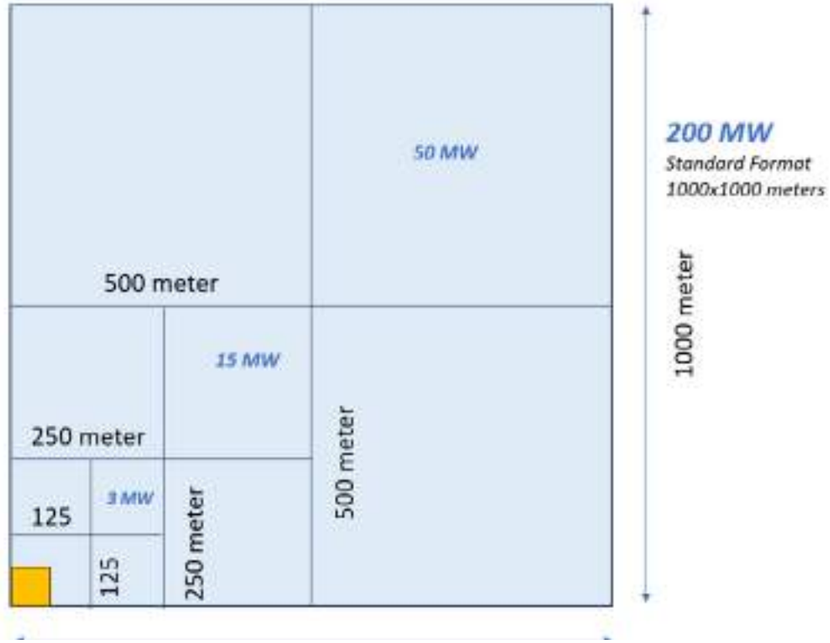


Figure 3 Oceans of Energy's roadmap towards 1km2 square offshore solar system with in yellow (bottom-left) as reference NS2 size

2 addition to the technological / engineering understanding that is highlighted in this paper, the NS2 project has focused extensively on topics incl. site permitting, environmental research, and energy system research; For questions on these topics, please send a request to offshore.solar@oceansofenergy.blue

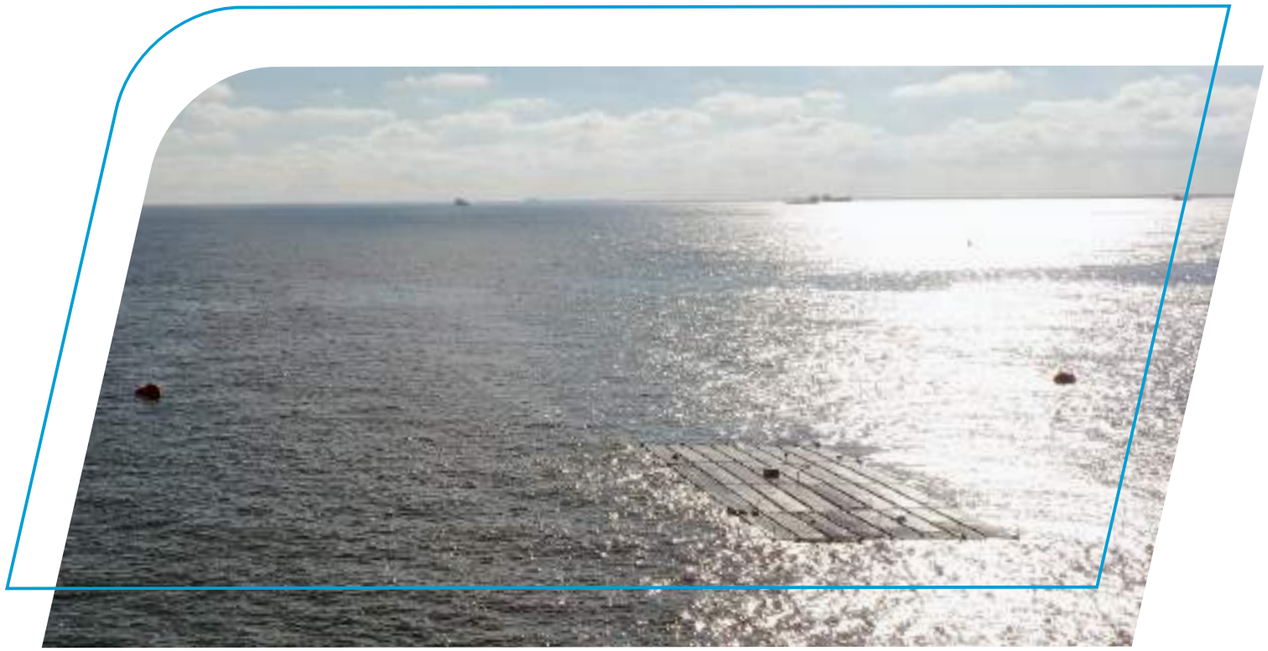


Figure 4- Oceans of Energy NS2 Offshore Solar Farm System, 12km offshore from the Hague

(0.5 MW-scale), and faced major environmental conditions including 10+ ‘named’ storms.

Next to the NS2 offshore solar farm pilot, the NS2 project also hosted an experimental testing campaign at prototype scale in the Deltares Delta Flume. The advantage of a testing campaign in the Delta Flume is the ability to have full control over tested environmental conditions and to directly link observed behaviour with measured forces, which is not possible in uncontrolled offshore environments. Furthermore, it allows to test design aspects which can only be realistically tested at full scale, such as e.g. the interconnected behaviour between the floaters, as opposed to scale model testing.

Delta Flume tests are therefore complementary to small scale testing in other basin testing facilities and pilots offshore.

The learnings from the Delta Flume tests have been used for further development of Oceans of Energy’s 1km2 scale standardized system and the implementation of the first of a kind offshore wind integrated offshore solar project at Hollandse Kust Noord (“HKN1”, Summer-2025). In addition, these tests are also of great importance in the pathway towards certification of offshore solar systems as they help define standardized testing protocols and certification requirements.

Certification & Standard testing of Offshore Solar

Qualifying a novel technology is of great importance, as there often are not any existing performance standards or certification schemes specific to the topic. That is the case for offshore solar, since it places existing technology in a new environment that is not contemplated in solar or offshore standards. To address this topic, Oceans of Energy has participated in two joint industry projects (JIPs) organized by DNV. Their objective was to produce guidelines on how best to ensure the safety and reliability of floating solar mooring, anchoring, and floaters throughout their lifespan.

To certify the technology, a combination of offshore standards can be proposed, which are typically for marine energy converters (MEC), offshore floating wind turbines, and generalized offshore structures, with PV installation standards. However, that is not always sufficient to prove the technology's reliability, as there may be areas not covered by both standard types.

To adequately cover existing gaps, it is necessary to conduct additional calculations, simulations, and testing campaigns in laboratory and field conditions. The NS2 consortium has identified several topics that require testing to ensure that a reliable, high-performing product will be offered, including:

Farm behavior

The Oceans of Energy system design consists of rigid floaters, which have PV modules on top, flexibly interconnected to one another. The floaters are installed at water level and the farm moves with the waves. This

unique combination of flexible and rigid components is not captured by existing offshore standards.

Interconnection loads

Measuring loads at interconnection points provide insights on how mooring loads are distributed throughout the entire farm crucial for the fatigue analysis and lifetime estimation of the components. These measurements can be validated with data from offshore demonstrators.

Mechanical loads on PV modules:

The design with PV modules close to the water surface results in exposure to breaking waves that can slam on the PV modules. These wave impacts are specific to certain offshore solar concepts, and particularly the flat pontoon concept (for elevated truss platform wind impact is more of a concern), and not yet captured in standards and test protocols. These wave loads can potentially lead to cracking of the module enclosures and/or damage on the PV-cell level, which may reduce lifetime power performance.

For the sake of reliable and reproduceable results in an uncharted technology domain such as offshore solar, the partners in the NS2 project joined forces to ensure quality in the test plans, analysis of results, and eventually help the industry move forward.

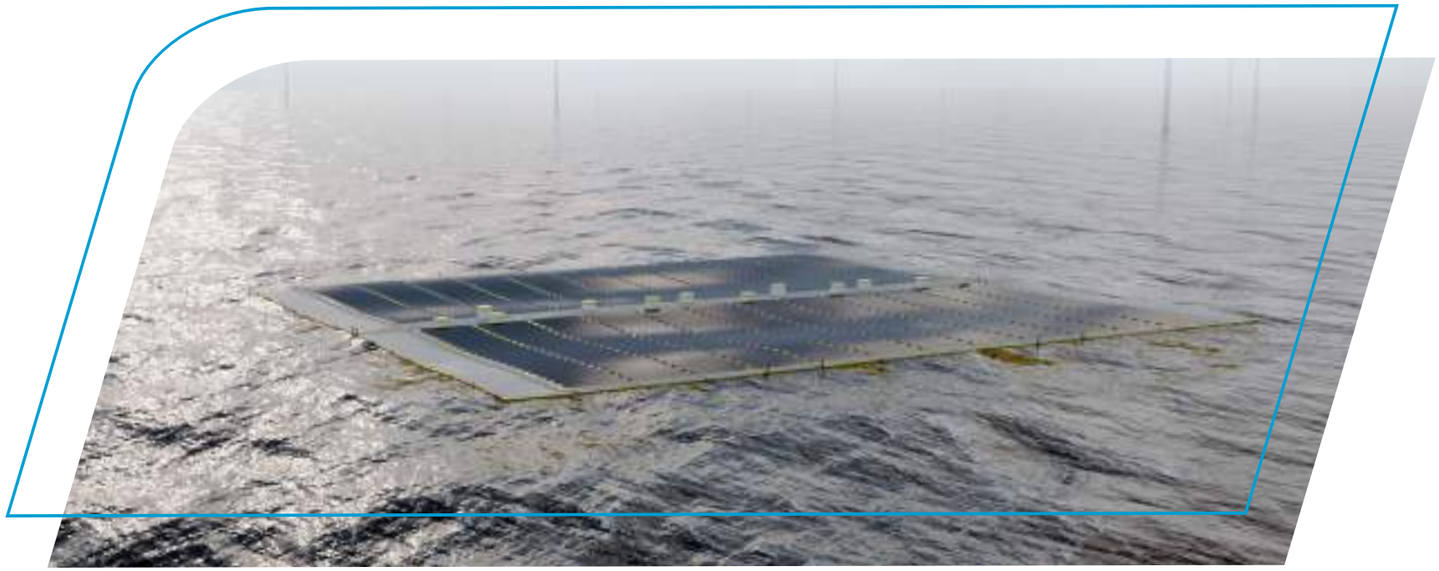


Figure 5 Render of the Oceans of Energy Offshore Solar platform in the windfarm Hollandse Kust Noord (HKN).

Testing scope

The NS2 experimental testing scope in Sep-Oct 2022 consisted of two test series and have been conducted in the Deltares Delta Flume, capable of generating representative North Sea waves (see Appendix I for more information on the Delta Flume):

Full-scale hydrodynamic tests of offshore solar array (Chapter 4)

Four full scale Oceans of Energy interconnected floaters were positioned inside the flume to measure the behavior and impacts of the breaking waves on the floaters and the PV modules, including the impact-reductions from wave dampening at more inner platforms. The mooring and interconnection loads were measured, as well as the acceleration and gyration of the floating platforms.

Wave slamming testing of fixed PV-mounting and PV module (Chapter 5)

A glass-glass PV and a dummy module were mounted on a fixed partial platform, which was positioned in different orientations with respect to the incoming waves to quantify mechanical stresses caused by direct wave impacts on the PV module cells, glass and frames and measure potential performance degradation.

4 Full-scale hydrodynamic tests of offshore solar array

Figure 6 Tests of an array of four floaters in the Delta Flume

Test objectives / relevance

The series tested a one row array of four floaters with PV modules (see Figure 6). The test series was performed to investigate the interaction of the array of floaters in a realistic wave field. These results can also be used to improve and/or validate numerical models to understand wave-structure interactions for moored systems.

The full-scale tests give insight in non-scalable effects, such as stiffness of interconnectors and loads on the PV modules.

Methodology

The array consisted of four separate OOE floaters. Interconnectors were used to join the floaters. A mooring system of fiber ropes and chains kept the floating array in position. The mooring system was bolted to the bottom of the Delta Flume. The floaters were equipped with load cells measuring mooring line loads, strain gauges on the platforms, pressure sensors, and inertial measurement units to record acceleration and gyration of the platforms. These sensors were connected to an on-board acquisition system, that was coupled with the Delta Flume data acquisition system. Next to that the wave height was measured at several locations in the Delta Flume. Camera equipment was also installed to monitor and record the behavior of the floating array during different wave conditions.

The wave heights tested in the Delta Flume ranged from 0.25 m up to 2.50 m, with wave periods varied between 2 to 16 s. This provided significant loading conditions on the floating platforms, corresponding to waves that may occur several times per year in the North Sea. The tests did not

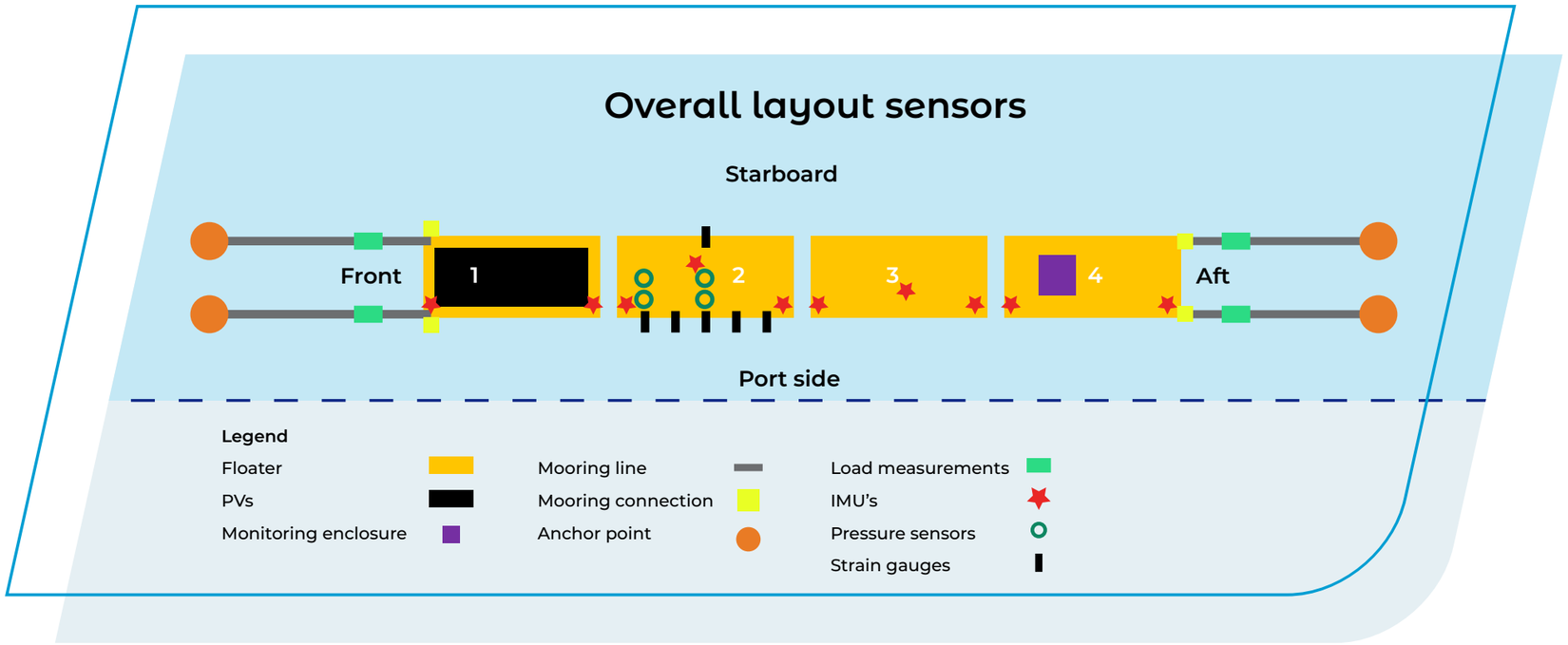


Figure 7 Measurement equipment set up on the four floating platforms.

include the most extreme North Sea wave conditions with return periods in the order of 1/10 to 1/50 years owing to limitations in the facilities. Furthermore, the water depth in the flume (6.5 m) is lower than at realistic North Sea deployment areas with water depths typically around 20-30m, resulting in typically steeper waves and therefore increase in aggressiveness in terms of wave slamming. Regardless, testing at full scale provided realistic platform and PV module responses under severe wave loading. Such accurate load data is nearly impossible to measure at tests in other basins / flumes, where systems often need to be scaled down with factors of 1 : 10 up to 1 : 30. The outcomes of the Delta Flume tests are used to validate numerical models that can subsequently be used to compute loads under more extreme design conditions.

Key Results

During the testing program no faults & fault mechanisms have been witnessed in the system configuration. The experiments revealed five key findings:

1. The system's response to varying wave conditions; an important relation was observed between wavelength and floater length [8] . Compared to the floater's length, longer waves propagate under the floater farm with minimal attenuation. Shorter waves, however, are attenuated by the floaters. The farm size by itself has little influence on this phenomenon. It is an interesting design consideration if the floating farm can mitigate wave energy, perhaps allowing exploitation of other marine activities in the lee side.
2. Different loading mechanisms were identified: direct wave impact, wave over wash, slamming loads, free span. Better understanding of these mechanisms helps to determine which loading mechanisms are most crucial to consider in the design process.
3. Testing at full scale resulted in reproducing realistic interconnection behavior and platform motions. The measurements of platform accelerations have been used to determine design criteria for the system and its electrical components.
4. The data provides good validation material for dynamic analysis, including measurements of line forces and platform accelerometers, despite limited water depth and wall effects of the facility. Due to the low water depth and the size of the farm, the mooring system is not fully representative of North Sea conditions. The data was used to validate the numerical model for these test conditions with good correlation between tests and numerical results.
5. The wave impact on moving floating structures showed to be lower than on fixed modules. The test results can be used to define which input conditions can be used in the fixed wave slamming tests with varying wave conditions, to represent actual loads in floating conditions.

Wave slamming impacts are expected to be largest on the floaters at the outer edges of a larger offshore floating solar system. The floaters further inside are more protected from waves and will therefore experience less wave slamming impact. The tests performed in this project are representative for the wave slamming impacts on floaters at the outer edges of an offshore solar field and therefore normative for all floaters on a large scale offshore solar farm.

5 Wave slamming testing of fixed PV-mounting and PV modules

Figure 8 Fixed measurement setup.

Test objectives / relevance

Offshore Solar systems are designed for lifetimes of 25 years and during this period performance degradation needs to be avoided by optimizing for offshore conditions a) the PV module design, b) the PV-mounting system, and c) the offshore solar farm system design.

The fixed test aimed to a) investigate the loads on a small-scale floater element under various wave conditions, simulating real-world scenarios for flat pontoon concept offshore solar systems; b) to quantify the effects of repetitive wave slamming on glass-glass based photovoltaic (PV) modules. The measured parameters included PV module deformation, localized module pressures, and subsequent changes in PV performance.

By fixing a small-scale floater element above the slope of the Delta Flume (see Figure. 8), the experiment simulated the impact of direct wave forces on the modules. By varying the angle of the small-scale floater (0-15 degrees) and testing different wave heights and periods, the test will aid in understanding the hydrodynamic loading and the design of PV modules in harsh marine environments.

Methodology

To quantify the mechanical stresses induced by wave impact on PV modules, a PV module was instrumented with strain gauges to measure the resulting deformations, while a dummy module equipped with pressure sensors was used to capture the pressure loading conditions. The analysis focused on the fixed rig tests, where regular wave trains were generated to impact both the PV and dummy modules simultaneously. These wave trains, with controlled wave heights ranging from 0.5 to 2.5 meters and periods from 2.78 to 16 seconds are used to create a simplified, controlled environment for evaluating the mechanical response and pressure distributions on the modules. Both modules were mounted side-by-side on a fixed frame, simulating the floater structure's configuration.

This setup allowed for a controlled environment, eliminating the complexities associated with the motion of floaters and wave reflections off the flume walls. By isolating these variables, a more accurate statistical analysis of the measurement data was possible. The fixed rig tests enabled the collection of repeatable and reliable data, which is vital for understanding

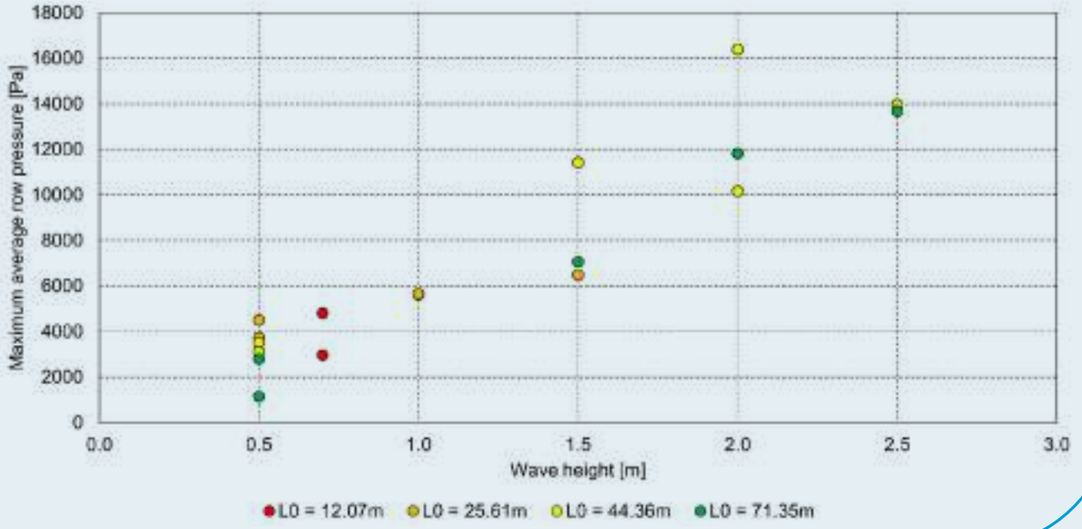


Figure 9 Maximum average row pressures as a function of wave height. Each dot represents data from a regular wave train, with the color indicating the corresponding deep water wave length (L0).

the effects of wave loading on PV modules. Additionally, power performance and electroluminescence measurements were conducted to investigate potential degradation effects on the PV modules used in the experiments.

Key Results

This experimental study addresses the question of whether standard photovoltaic (PV) modules can withstand the harsh conditions of offshore environments, particularly the impact of wave slamming in floating solar systems. The study subjected PV modules to breaking waves with heights of up to 2.5 meters, generating peak loads of 25 kN (equivalent to 2.55 tonnes) on the PV module . Compared to North Sea conditions the lower water depth in the flume (7m instead of a typical 20-40m offshore) led to the generated waves being typically steeper and thereby causing increased slamming. Owing to this, the generated waves are only partially representative for the maximum design sea states for the North Sea, showing the need for validated numerical models to translate the test results to actual design loads.

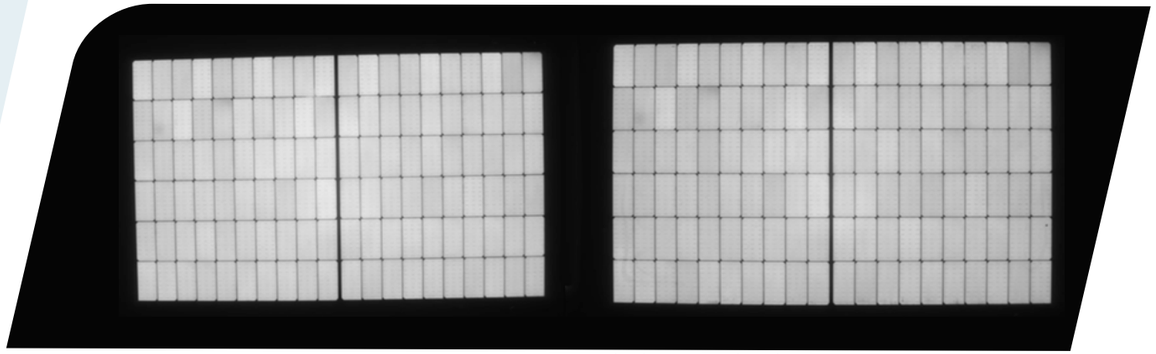


Figure 10 Electroluminescence images of the PV modules taken before (left) and after (right) wave slamming testing indicating that no microcracks are formed

The modules exhibited no signs of performance degradation or cell cracks, as confirmed by power performance (current-voltage) and electro-luminescence (EL) measurements, despite these significant forces. These findings are particularly relevant to flat pontoon floating solar systems, where the support structure behind the entire glass surface of the PV module is crucial in limiting deformation caused by wave slamming. The detailed key findings of the experiments are:

1. Wave height vs. pressure and force: A positive correlation was observed between wave height (up to 2.5 m) and pressure and force , with maximum pressures reaching 16 kPa (Figure 9) and maximum estimated global module loads of 25 kN. These global module loads were derived by multiplying the maximum average pressure by the surface area of the PV panel. To put these values into perspective, the maximum pressure is equivalent to a person standing on two feet, while the maximum load corresponds to approximately 30-35 people standing on a single module.
2. Wave height vs. strain: A positive correlation was found between wave height and measured strains, with maximum strains of approximately 200 µm/m (microstrain). This suggests that higher waves induce greater deformations in the PV module. However, interpretation of these strain results is complicated by the platform specific support conditions of the PV modules during testing, particularly given that the modules were supported in a manner that constrained their motion over the entire surface area. The exact nature of the module's fixation to the underlying structure have influenced the measured strains, making the results system specific to the tested Oceans of Energy platforms.
3. Performance degradation and cell cracks: Despite being subjected to significant wave-induced loads, the tested PV modules showed no signs of performance degradation or cell cracks. This was confirmed through power performance (Current-Voltage) and Electroluminescence (EL) measurements, as shown in Figure 10.

6 Lessons learned and next steps

Witnessing the two experiments and analyzing the results provided several valuable learnings

The Oceans of Energy Offshore Solar systems and standard glass-glass PV modules have been exposed to severe wave conditions generated in a flume at full scale

A test setup of a row of four interconnected Oceans of Energy offshore solar floaters and a fixed test setup for glass-glass based PV modules have been exposed to large waves with a maximum wave height of 2.5m. These waves were generated by the Deltares Delta Flume, capable of producing realistic North Sea waves that are both powerful and steep. There has been no observable damage to the floating system during experimental testing in the Delta Flume after visual inspection. The measurements demonstrated the behavior of the floating system and individual components under severe wave loads and realistic platform motions. No indications were found that under the given circumstances standard Glass-Glass PV modules have encountered performance degradation as of wave slamming in the flat-pontoon offshore solar concept. Results may be used to define more unified design criteria for such systems under even more extreme design conditions.

Different test types are complementary

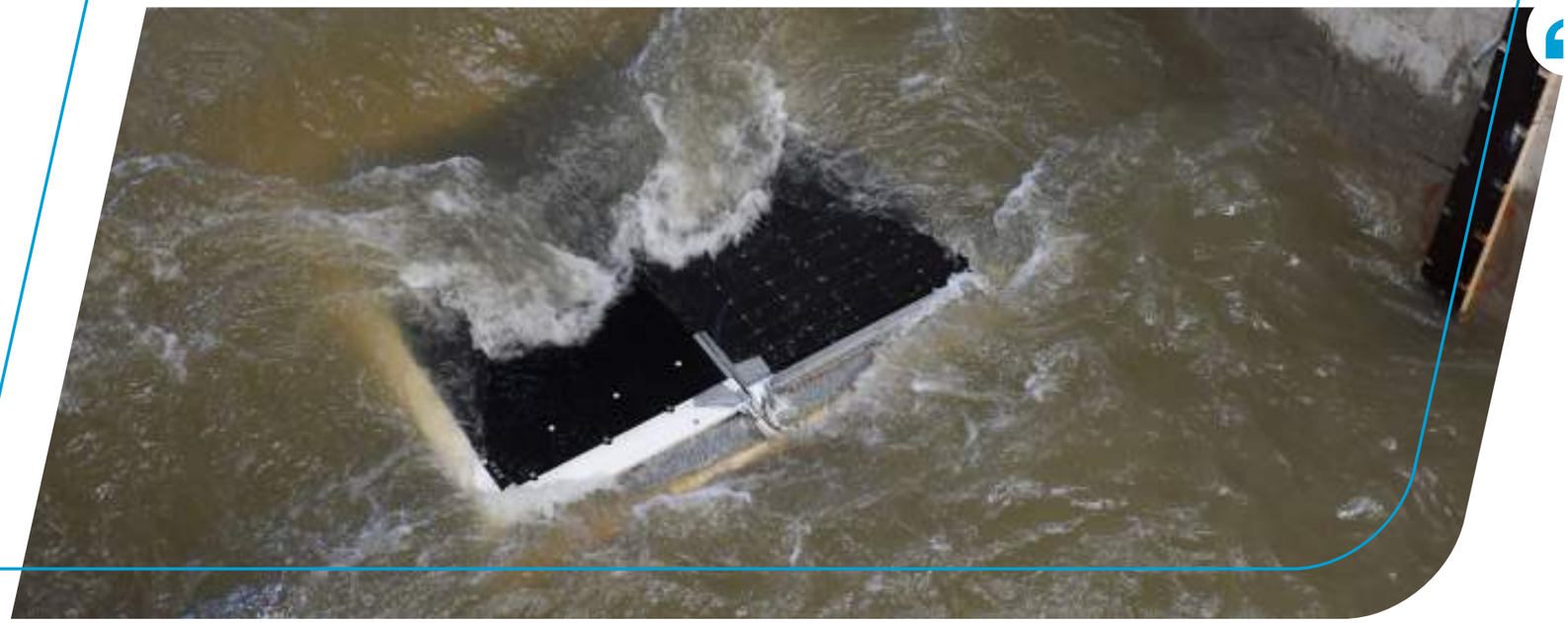
Different test set ups are useful for different objectives. While small-scale tests are useful to obtain understanding in dominant mechanisms that determine farm behavior and impacts on the mooring system, full scale tests such as in the Delta Flume are crucial to understand actual forces on single elements which are also difficult to scale. These results are used to validate numerical models, which proved to be in the right order of magnitude. Offshore solar system pilots will ultimately tell you the truth, although understanding underlying mechanisms is more challenging due to restricted monitoring capabilities and the unpredictable offshore conditions. A combination of approaches (numerical modelling, small-scale, full-scale, offshore pilots) is needed to provide a reliable understanding of the system's performance over time in real-world applications. This is crucial to prevent safety hazards offshore and to save costly offshore testing programs.

Need for database to design standard test protocols for PV modules

The results from the wave-slamming test highlight the need for establishing databases that capture relevant PV module strains in various offshore solar environments and design concepts. By combining this information with potential failure observations, it will be possible to design meaningful accelerated lifetime testing protocols in a laboratory setting. For example, high-frequency vibration tests using a shaker tester at resonance frequencies could be employed to simulate the effects of long-term exposure to wind and wave-induced loads. The development and execution of such test protocols is valuable for the PV-industry so that modules will be built to survive +25 years in offshore conditions. This will decrease risk perception and generate the confidence of investors and financiers.

Advancing test set-up of floating structures in the Delta-flume

It was the first time that the Delta Flume accommodated a floating offshore solar structure at full scale. The insights from these tests contribute to establishing a consistent design methodology for testing floating structures: Which load mechanisms to consider? Which return periods to use as design conditions? How to represent this in a fixed test setup? These standardized test protocols may act as a guideline for certification bodies to verify a product's performance.



> Collaboration between research institutes and technology developers in testing campaigns is crucial to gaining detailed insights into product behavior and performance.

Correlation between loads and wave conditions

The loads measured during this testing campaign show a strong correlation with wavelength and wave steepness. At sea, Oceans of Energy installs the same sensor set ups as used in the Delta flume to further confirm these findings. Gathering data from pilots at sea allows to further validate design updates and numerical models versus costly basin experiments.

Viable means for measuring in real-world applications

Sensor installation and correct measurement of strains, movement, and pressures can be tricky in extreme conditions; the experiments provided insights on robust sensor installation. New sensor installation measures have been applied, and installed in the real offshore environment, providing the best data we can get and lowering the chance of losing costly equipment.

These learnings provide the sector with an opportunity to advance towards standardized test protocols. These protocols need to be developed for all critical components. In parallel to the tests conducted through the NS2 project, Deltares and Oceans of Energy have been developing a testing program specifically focused on the dynamic export cable, including its routing from the floater at the sea surface to the seabed. Prototype-scale tests on a section of dynamic export cable were performed to understand its behavior under various offshore flow and wave conditions, aiming to improve the design of a cable protection system. While analysis is still ongoing, the data gathered represents a unique contribution to the existing state-of-the-art literature, as this experiment was conducted at prototype scale and investigated cable motions under the combined effects of current and waves – an area previously unexplored.

Collaboration between research institutes and technology developers in testing campaigns is crucial to gaining detailed insights into product behavior and performance. However, the involvement of certification bodies in this process is equally important to ensure quality assurance and credibility for consumers, insurers, investors, and regulators. Certification typically applies at all stages, from early concept development to commercial projects, using widely accepted standards. These standards should cover the most comprehensive technical references suited to the system and be applicable to the complete farm and its components.

DNV is currently developing two standards: one for anchoring and mooring and another for photovoltaic floats. These standards are the outcome of two joint industry projects in which Oceans of Energy is participating. These standards are still in the initial phase, so broader industry collaboration is needed to establish comprehensive standards that support the certification of offshore solar systems. Ultimately, this provides all stakeholders and clients with confidence that the product is safe and capable of withstanding 25 years at sea.

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Figure 11 Impression of the Delta Flume at Deltares with a wave that passes over the edge of the flume.

Appendix A

Deltares Delta Flume

The Delta Flume of Deltares is 300 m long, 5 m wide and 9.5 m deep (see Figure 11). In the flume individual waves can be generated up to a height of 4.5 metres. The maximum significant wave height is limited to approximately 1.6<Hs<2.0 metres. The maximum wave achievable height depends, amongst others, on the water depth and the type of structure that is placed in the flume.

The slope at the back of the Delta Flume is made up of sand with a concrete top layer. The concrete thickness is not uniform over the height of the slope. For example, the thickness of the flat part of the slope (i.e., after x=192.2) at z=6.0 m is limited and prone to damage. Damage to the slope would have been detrimental to the experimental plan, so the wave height was limited during calibration and testing.