Drakoo - Energizing the Future with Ocean Waves

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***Abstract*— The ocean provides an abundant source of renewable energy, including wave energy. Established in Singapore Hann-Ocean Energy has been developing its proprietary wave energy conversion technology "Drakoo" ("Dragon King of Ocean" or "Coolest" in Chinese) since 2008. The Drakoo has been tested successfully in full-scale in the Singaporean sea, in the National Renewable Energy Centre (UK) and Hann-Ocean's large-scale wave flumes. The device allows for cost-effective electricity generation from all scales of waves. Having had its first commercial pilot project (16kWp) for Sembcorp Marine in August 2013 and followed by four more years further data collection and product development, the latest 15kWp Drakoo WEC module has been developed and tested extensively to produce affordable and clean electricity from as low as 0.3m sea waves, with a peak efficiency of 46% from waves to electricity.**

In this paper, the Drakoo development milestones are presented and the test results of the 15kWp Drakoo WEC module are discussed. Finally, the potential applications of Drakoo are illustrated.

***Keywords*— Wave energy converter, Drakoo, sea pilot project, ocean renewable energy, wave scatter diagram, wave flume, tank tests.**

I. Introduction

Drakoo is a high-efficient wave energy converter, which uses a water turbine installed between two oscillating water columns together with two groups of one-way flow checkerboard valves to capture the incident wave energy and converts the hydraulic energy to electricity. The Drakoo WEC working principle, as illustrated in Figure 1, and the overall structure is simple. The device is expected to keep stationary on the water surface, and the water turbine's runner is the only rotating part underwater enclosed by the hull structure. This simplicity results in low capacity costs, low costs of electricity produced and ease of maintenance.

With the 15kWp module market-ready, a large range of device capacities from 1kWp up to 50kWp modules can be customised and built for order, since the existing Drakoo module is scalable to produce electricity for any wave site of 0.3m high waves and beyond. Megawatt-scale is achievable by scaling up and creating long arrays. The practical choice of Drakoo-array capacity can be optimised for its life-cycle cost-effectiveness based on the wave statistics and the demand for annual average power of the selected sea site. Drakoo has multiple applications in both fixed and floating modes. It can be deployed in shallow or deep waters to produce electricity from wave power. Drakoo WEC can also be integrated with breakwaters, floating architectures, or O&G offshore platforms, or to provide baseload power to the local grid for clean energy production.

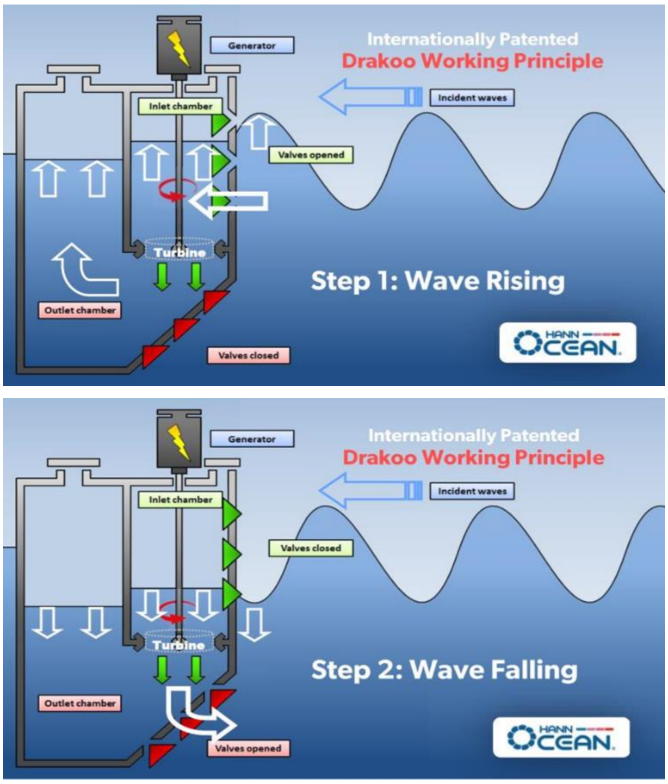

Fig. 1: *Drakoo-B working principle; Step 1 – Inlet Open & wave peak coming in; Step 2 – Outlet open & wave trough coming in.*

II. Development Milestones

Earlier verifications through wave flume tests of small-scale Drakoo has proven the concept and its performance characteristics. Moreover, a two-year operating large-scale test-pilot in Singapore water has given Hann-Ocean the experience in building a WEC that is robust, durable and survivable. Prior to any follow-up massive commercial deployment of Drakoo WEC array in real sea, large-scale wave flume tests for Drakoo prototypes have been performed. It can ensure the accuracy of annual energy generation prediction and minimize the risks to operate at continuous off-design performances in the sea. During these developments, practicalities as complete system assembly and disassembly, as well as maintenance procedures have been verified. Three of the most important milestones are discussed in the following sections.

A. Drakoo 1kWp Wave Flume Test at NAREC

The first key milestone in the development of the Drakoo technology is the 3rd party verification test conducted by National Renewable Energy Centre (NAREC) of UK in June 2011. The main objective was to establish the 1st stage wave energy conversion efficiency (from incident wave energy to hydraulic energy). This efficiency is commonly defined as Capture Width Ratio (CWR). In Drakoo, it is the conversion efficiency from incident wave energy to hydraulic kinetic energy going through the turbine duct installed between the inlet and outlet chamber of the Drakoo. For these tests, at NAREC, the turbine does not contain a runner.

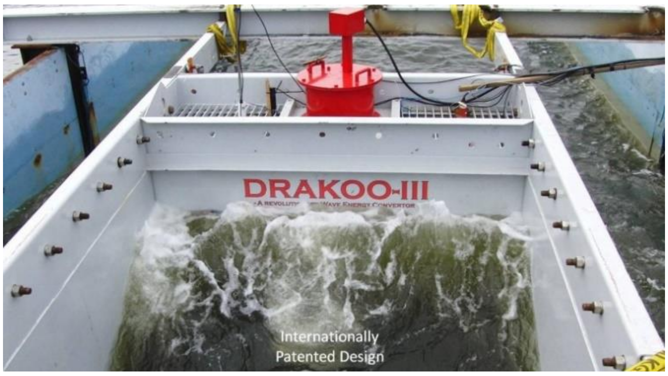

Fig.2: Drakoo-III-B 1kWp WEC operating at NAREC

The NAREC wave flume consists of an 8-paddle Edinburgh Designs' wave maker positioned in one end of the wave flume and a sloping beach at the opposite end. The flume is of dimensions: 56 m in length, 5.2 m in width, 7.2 m in height and with a water depth of 6.5m.

A Drakoo-III (1kWp) prototype was installed in the said wave flume, thanks to a framework of I-beams and side girders as shown in Figure 3. The girders are also used for attachment of guiding plates/side girders to channel the wave towards the Drakoo front. The overall dimension of the 1:2-scale Drakoo is 2.11 x 0.88 x 2.72m (LxBxH) as shown in Figure 4. The front of the Drakoo consists of three inlet windows. On the bottom, three outlet windows are located at 30-degree angle towards the front.

The CWR is expressed as the ratio of kinetic energy (E_K) in the flow through the hydraulic turbine duct to the incident wave energy (E_W):

$$CWR = E_K / E_W \quad [1]$$

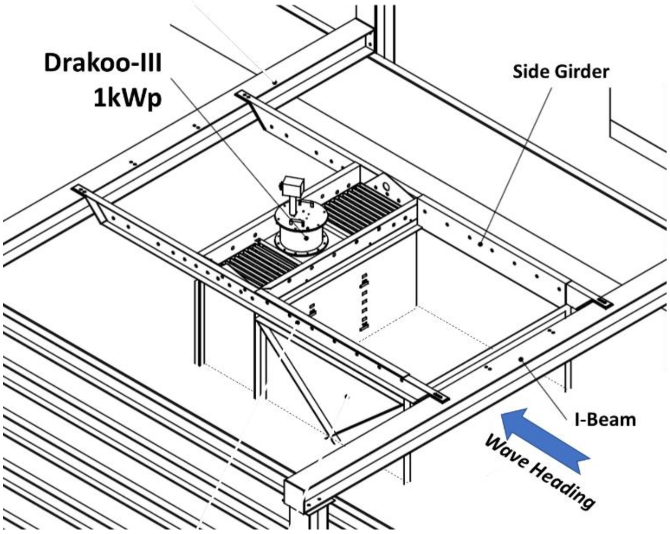

Fig. 3: Drakoo-III-B 1kWp WEC NAREC Test Layout

The incident wave energy for regular wave by linear wave theory is expressed as:

$$E_W = \frac{L\rho g^2 H^2 T^2}{32\pi} \quad [2]$$

The kinetic energy within the turbine duct for regular wave is expressed as:

$$E_K = \frac{1}{2}\rho A v^3 T \quad [3]$$

Where L is the length of the Drakoo module, ρ the water density, H the wave height, T the wave period, A the turbine duct cross-sectional area and v the duct cross-sectional average flow speed in root-mean-square.

In order to obtain the necessary outputs to derive the CWR, four water level sensors (located at 8m from the girder, 5.5m from the girder, inlet chamber of the Drakoo and outlet chamber of the Drakoo) to provide the wave height and period of the wave. The flow speed in the turbine duct is measured by a water flow speed sensor. As a result of the tests under the above-given setup, a peak CWR higher than 80% and 58% on average value for regular waves were derived.

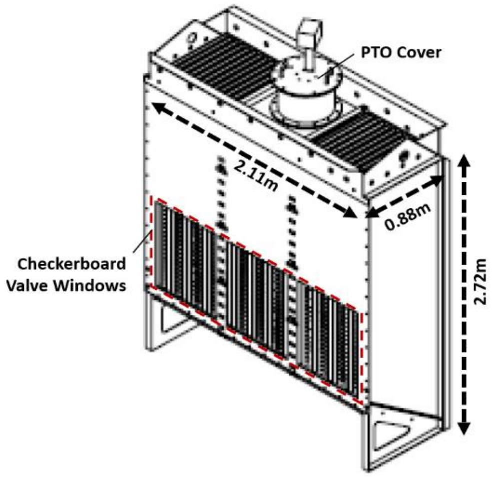

Fig. 4: Drakoo-III 1kWp WEC Layout

B. Drakoo 16 kWp Pilot Project

In February 2012 Hann-Ocean received a grant from SPRING Singapore under CDS (TI) for a research and development project for Singapore's First Wave Energy Converter. Thereafter, Hann-Ocean started the product design and prototyping of a 4kWp module. By the end of November 2012 Hann-Ocean delivered a 16kWp Drakoo 4-in-1 WEC array based on the said 4kWp prototype to the SembCorp Marine shipyard in Singapore as the first commercial Drakoo order.

The final assembly of the pilot project started in June 2013, and in August 2013 the Drakoo array was successfully launched at a pier-end of the shipyard. The relatively ease-of-access and ease-of-recovery to the shore of the module made it possible and necessary to upgrade and optimise the system three times from August 2013 to September 2014. The project timetable is given in Table 1 to describe the test pilot development activities.

The installed Drakoo array comprises four Drakoo-B0004 modules (4kWp each), welded together and connected to two buoyancy bodies using Hann-Ocean's Rigid Pontoon Connectors. A single Drakoo unit consists of 6mm steel-plated hull with a partition dividing the inner space to Inlet Chamber and Outlet Chamber, which contain two oscillating water columns. Furthermore, three checkerboard valve frames and one Power Take-Off (PTO) are placed in each Drakoo module.

TABLE I
LIST OF ACTIVITIES AT SEMBCORP MARINE SHIPYARD

Date	Operation
19 Aug. 2013	1st Launch of the 16kWp Drakoo array.
9 Sep. - 25 Oct. 2013	1st Upgrade: re-enforcement of the pontoon connectors and re-conditioning of the PTO moreover, Checkerboard Valves.
10 Mar. - 9 Jul. 2014	2nd Upgrade: full state and performance investigated, re-conditioning on anti-fouling moreover, replacement of two generators conducted.
5 Aug. – 27 Aug. 2014	3rd Upgrade: An unexpected performance issue and a module submerge event investigated and solved. The Checkerboard Valves re-conditioned.
27 Aug. – 10 Nov. 2014	16kWp Drakoo array in operation for further endurance testing and performance data collection.

Two buoyancy bodies take care of a horizontal balance of the full Drakoo module while the Drakoo is floating in the sea. Water tanks inside these buoyancy bodies are used for ballast, whereby to regulate the balance of the floating body. The buoyancy bodies also function as mooring interfaces. Vertical guidance with rubber fenders applied on the back is used to guide the array along a guide frame for mooring at variable tides as shown in the Figure 5. The vertical attachment allows the floating array to move up and down by the tidal change, while it is kept relatively stationary with reference to the water line. The rubber fender guidance has been studied and optimised in order to suppress the roll of the Drakoo WEC array.

Fig. 5: The 16 kWp Drakoo WEC array in operation mode

The pilot project was of great importance for Hann-Ocean in order to get sea trial experience and performance data. Firstly, an understanding of the WEC real-sea efficiency reduction between design wave and the actual wave was established. The fouling issue of marine growth has been identified to be of significant negative impact on the performance. The issue has been tackled successfully for the tropical waters of Singapore and seas alike, by using a super slippery anti-fouling paint scheme on the vital parts of flexible checkerboard valve rubber leaves and the turbine.

Secondly, the maintenance procedure during the module upgrades has been improved several times; these experiences help to reduce costs for future commercial projects. The survivability of the structure and design margins of the components have been tested in a stormy sea.

Finally, as mentioned before and presented in Table 1, during the multiple upgrades, many performance and durability improvements have been implemented and tested successfully. To sum up, this pilot project not only leads to the advancement of the existing technology, installation and maintenance methods but also demonstrates the economic feasibility of the Drakoo technology.

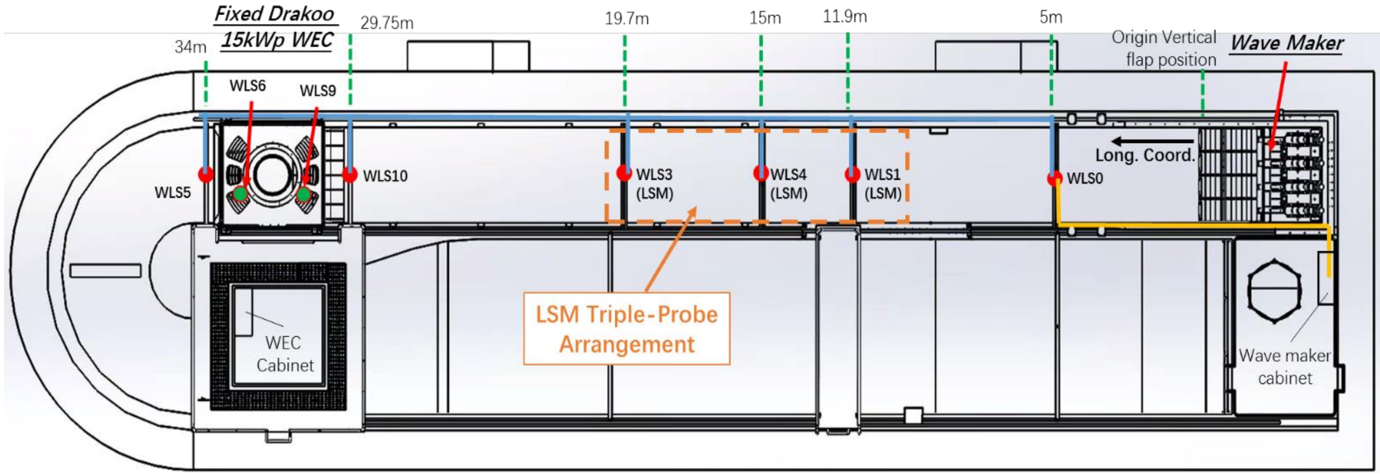

Fig. 6: Top view of wave flume with Drakoo WEC and water level sensor arrangement

C. Drakoo 15kWp WEC Module Performance Tests

Based on the past experiences, including the above-mentioned milestones, a full-scale Drakoo WEC prototype of 15kWp has been designed and built in 2016. The Drakoo WEC module illustrated in Figure 7, has been specifically designed for coastal and near-coastal large array applications. The design process involved an extensive CFD study using stead-state simulations as well as transient simulations using the OpenFOAM VOF solver waveFoam.

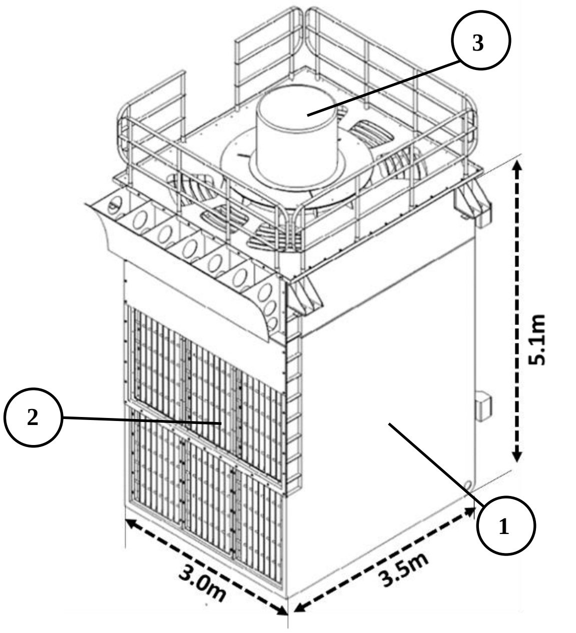

Fig. 7: Drakoo 15kWp WEC Overall Configuration, including 1) Drakoo steel hull, 2) checkerboard valves, 3) power take-off system

The built prototype has been used for characterisation of its power output and for numerous parametric studies with the use of the company-owned twin wave flume in Nantong, China as described in [1]. The overall dimension of the Drakoo 15kWp is 3.0x3.5x5.1m (LxBxH) and has an optimal performance at a zero-crossing wave period of nearly 5 seconds. In the following sections the performance test setup, including the sensor configuration, mechatronics, power control and the performance of the Drakoo module is discussed.

1) Sensor Configuration: A triple probe configuration for the so-called Least-Square Method (LSM) is used to define the incident wave height, the reflective wave height and the wave period. To be able to measure and determine these using the LSM approach, a series of criteria are set for the inter-probe distances described in [2] and [3]. The sensor arrangement within the twin wave flume is given in Figure 6, containing a similar triple sensor arrangement for measurements to be conducted during the fixed WEC tests.

Furthermore, the sensor arrangement within the Drakoo module consists of two water level sensors installed in the Inlet and Outlet Chambers and two pressure sensors installed upstream and downstream from the turbine for direct relative turbine head measurement. The pressure sensors are located at or close to average-pressure locations over the perimeter around the stator or the cross-section of the diffuser lower edge. One flow speed sensor is installed inside the turbine stator at a location with relatively smooth inflow to compute the turbine flow rate. In addition to that and for redundancy the inlet and outlet chamber water level sensors are also used to compute the turbine flow rate history. The turbine flow rate is also seen as the interchanging flow rate between the two water chambers, which is possible to compute using the volume change in the inlet and outlet chambers. An optical sensor is installed at the turbine shaft coupling to measure the rotary speed. As for the power electronics measurements: a total of six current and voltage measurements are conducted to compute electric powers on each of the three operating MPPT controllers. Having this set of sensors, the wave environment can be verified using the LSM sensor arrangement; the hydraulic and mechanical variables are measured as well as the electric power output of generator and MPPT controllers.

2) Mechatronics & Power Control: The Power Take-Off (PTO) consists of a customised hydraulic turbine of 1.1m diameter, which is directly coupled to a Permanent Magnetic Synchronous Generator (PMSG) with a peak power of 15kWp. Mechanical power is efficiently transferred to the 3-phase A/C output of the generator with a voltage output of up to 200VDC (after the 3-phase rectifier) and a peak efficiency of 94%. Counter-torque is to be provided to the PTO by the generator to control the turbine at the optimal speed for most efficient hydro-mechanical conversion. Three Maximum Power Point Tracking (MPPT) controllers are used for this specific task, using their customizable control curve. Since a single MPPT is able to receive the power of 5.0kW and a maximum input voltage of 200VDC, each of the three MPPTs is taking care of a specific power range in series fashion (low, mid and high-power range).

Each MPPT is connected to an isolated battery pack and controls the battery's charging stages. The electric power is either directed to the battery set or electric loads. Relays, controlled by the MPPTs, are triggered to switch power diversion from the battery bank to loads stepwise; the operational power demand of the loads is perfectly matched to the amount of mean power provided, to divert the power most efficiently and most stable. Extensive experience has been gained on the overall power control and diversion, where diversion efficiencies of 98% have been reached in latest tests. The complete electric system has been thoroughly reviewed and upgraded in January 2018, by which the peak capacity of the complete system has increased to 15kWp.

Safety features have been implemented as well, such as an automatic generator brake to avoid over-voltage within the system. The MPPTs contain numerous safety features, such as over-current, ground-fault and arc fault protection.

3) Power Output Characterisation: The electrical powers upstream and downstream each of the MPPTs are measured during the performance tests, till July 2018. Latest results of performance tests of March 2018 are given in the power output scatter diagrams in Figures 8 and 9 for mean and peak values, respectively. These test series are conducted within the wave period range of 2 – 8 seconds and 0.3 to 0.9m wave height only.

		Wave Period, T (sec)												
		2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50	8.00
Wave Height, H (m)	0.3	0	0	9	88	239	320	338	325	247	269	223	221	182
	0.4	0	0	103	318	393	578	699	678	605	542	578	499	462
	0.5	5	9	252	422	672	944	1145	1093	979	956	868	867	842
	0.6	7	53	316	569	999	1419	1639	1589	1358	1286	1209		
	0.7	6	154	466	803	1349	1878	2266	2013	1951				
	0.8	18	233	598	1270	1855	2508	2956	2697					
	0.9	17	299	757	1302	2313	3175	3601						

Results of 23 & 24 March 2018 Tests

Fig. 8: Drakoo 15kWp Generator Mean Power Output Measured

The results prove that the Drakoo has a rather wide efficient operating range between 4.0 to 6.0 seconds in wave period, with an optimum close to 5.0 seconds. Deducted from these results, the wave height of 1.6m is required to meet the peak power of 15kWp at the optimal wave period.

		Wave Period, T (sec)													
		2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.20	5.50	6.00	6.50	7.00	7.50	8.00
Wave Height, H (m)	0.3	0	0	0	260	582	667	799	835	746	569	665	544	514	457
	0.4	0	0	198	631	888	1045	1163	1247	1164	1096	1085	1144	915	904
	0.5	0	0	615	908	1488	1692	1864	1820	1836	1699	1815	1655	1436	1505
	0.6	0	216	729	1308	1798	2061	2421	2469	2318	2306	2184	2058		
	0.7	0	368	1062	1642	2258	2758	3417	3396	2740	3033				
	0.8	73	522	1325	2224	3107	3702	4195	4267	3693					
	0.9	42	627	1440	2659	3569	4688	5088							

Results of 23 & 24 March 2018 Tests

Fig. 9: Drakoo 15kWp Generator Peak Power Output Measured

A crucial limitation to these tests is that secondary wave is not taken into consideration for post-processing, this is a wave when it has travelled three times the distance between wave maker and Drakoo WEC. It limits the number of waves that can be analysed to 1 to 3 waves, depending on the wave period. Therefore, the tests are of a short duration of typically 30 seconds of wave production or lesser. Moreover, the PTO systems' mechanical inertia, which includes a large flywheel, needs a time of typically 1 or 2 matured incoming waves to build up to a stabilised (but naturally fluctuating) rotary speed. Therefore, the power outputs presented in above scatter diagrams are conservative. For the same reason, the mean values are around 60% of the peak values within the design operating range.

Next, to the output power, each energy conversion efficiency within the WEC is determined. A total peak efficiency (from wave power to generator output) is derived to be 46% based on the latest performance tests of March 2018. To reach this performance all energy conversion components within the Drakoo WEC are to be in good states, such as robust and decent sealing checkerboard valve leaves, optimum turbine parameters, optimised MPPT control curves for operating at optimal PTO work-point and a balanced power diversion to battery or loads. These and more optimisations have all been carried out to reach the latest power output record of 11.2kW in peak power output.

Fig. 10: Engineers of DNV GL and CSSRC at the Drakoo 15kWp test site of Hann-Ocean Energy.

On 24th of July 2018 Hann-Ocean Energy has successfully completed the latest performance and wave load test of the 15kWp Drakoo wave energy converter, witnessed by DNV GL (the Norwegian international accredited registrar and classification society) and participated by China Ship

Scientific Research Center (702 Institute). The test protocol was reviewed, settings were verified, and sensors were calibrated by DNV GL engineers. The tests included 228 wave tests and 15 stress measurements over a wave spectrum with wave heights in range of 0.3 - 0.9m and wave period of 2.5 - 8.0 seconds. At the moment of writing the final specifications and testing results are being reviewed. The test report will confirm the power outputs of the Drakoo 15kWp WEC and provide valuable data for its supporting structure design in various wave conditions. The data will also be used to create a comprehensive database for Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) simulations for the Drakoo WEC.

III. Summary

The Drakoo wave energy converter has gone through a holistic and continuous optimisation process in the last decade. Key milestones include the test session conducted by NAREC in 2011, providing the capture width ratio for different wave scenarios. The test results showed a significant CWR over a relatively wide range in wave period and a peak CWR of over 80%. Moreover, the data gathered, and practical experiences gained from the pilot project deployed in the tropical waters at SembCorp Marine Integrated Yard in Singapore (2013), lead to several upgrades of the device, which strongly increased the overall efficiency, robustness and survivability of the Drakoo technology. These upgrades of the array increased Hann-Ocean's experience in operation and maintenance, which will allow driving down costs of future projects. Finally, the continuous wave tank tests allow Hann-Ocean to analyse the Drakoo's behaviour in numerous regular wave conditions, resulting in a latest power output record of 11.2kW in March 2018. It also leads to additional upgrades and tailored solutions of the Drakoo module. These wave tank tests have been of vital importance for preparations of real-sea deployment.

The latest 15kWp Drakoo WEC module, tested and witnessed by DNV GL, is now ready to offer an affordable and sustainable power supply for the offshore industry, coastal developments and remote islands worldwide. As recent proof of that, Hann-Ocean is delighted to announce that it has been engaged by an international engineering consulting company to conduct a detailed design study for the application of the Drakoo technology for wellhead platforms in the Middle East.

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