# Wave Energy Experiment in the Maldives

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***Abstract*— A Wave Energy Converter (WEC) to harness the power of breaking waves was discussed in previous papers (AWTEC2016[1], EWTEC2017[2]). We use a number of small rotating turbines (< 1m diameter) to harness energy from breaking waves on shore. Because the water flow inside the breaking wave is much faster than that in the ocean wave in deep sea area, we may use smaller devices. During the first phase of R&D (FY2014~2017), we have developed two half-scale prototypes which have been installed in Kandooma Island in the Maldives and sending information of power generation to us through internet. The full-scale prototype will be ready and soon tested also from this year. Our WEC devices are suitable for small islands where the electricity costs are high, that are not connected to power grid, and fuel consumption needs to be reduced by development of renewable energy sources. Here we report the current status of the field test at the Maldives.**

***Keywords*— Wave energy converter, WEC, breaking wave, Maldives**

## I. Introduction

We chose on-shore WEC device with small turbine standing on sea floor at shallow water ~1 m depth, where the forward-running water in breaking wave will drive the turbine as shown in CG image of Fig. 1. Key features of our WECs are

(1) Kinetic energy around the breaking wave zone is much higher than the swells at deep sea area. If we utilize the strong forward-running water flow, we may harness enough energy by using small size turbine[1,2].

(2) There are strong vortex flow in the breaking wave, which lower the power conversion efficiency of WEC and might cause damage to the turbine. We have to design WEC hardware to be robust enough or introduce flexible material[5].

(3) Small and simple WEC design will be suitable for the mass-production in industry, thus the production cost will be lower.

(4) Installation and maintenance cost of WEC on-shore will be lower than the off-shore case.

(5) Wave energy potential at shore is lower than that of offshore, while our choice will be economically feasible if we can make WEC device reasonably cheap.

(6) We need to proceed the WEC project with careful consultation on the environmental impact and also impact on fisheries.

(7) Integration of our WECs with seawall will be the best choice. We are also studying on this design.

Fig. 1. Arrays of small WECs will harness electricity from the rapid flow of breaking waves. The design—dark-colored blades on top of white bodies with thin stems—is visually pleasing, and resembles a flock of birds or group of flowers. (Image Credit: Andreja Balon Kral).

We started R&D on OIST Wave Energy Converter in 2014. The milestones are:

1. FY2014-2015: The conceptual design study and proof of principle experiments.
2. FY2016-2018: Phase-I. Small power WEC (open-turbine)
   (1) half-scale turbine (35 cm dia.) with 1.3 kW generator.
   (2) full-scale turbine (70 cm dia.) with 10 kW generator.
   (3) The field test at Kandooma Island of Maldives from May 2108.
3. FY2018-2019: Phase-II. High power WEC (tubular-turbine)
   (1) tubular turbine (80 cm dia.) with 60 kW generator.
   (2) 30 kW power conditioner.

At the time of editing this manuscript (May 2018), we have just installed two half-scale WECs (35 cm dia.) in the Maldives, which are nicely operating until today.

* This work of OIST is supported by Kokyo Tatemono Company Limited (Kokyo), and its experiment shall be performed in collaboration with Ministry of Environment & Energy (MEE) of the Government of the Republic of Maldives under MOU agreed by and among MEE, as well as Holiday Inn Resort Kandooma at South Male Atoll, Maldives.

## II. Wave Condition at Maldives

Figure 2 shows our experimental site at Kandooma Island in the Maldives. The experiment is kindly supported by Holiday Inn Resort Kandooma Maldives. The red arrow in Fig. 2 marks the experimental site, where the stable swells are arriving from the Indian Ocean in a southeasterly direction. There are many other islands in the Maldives, while the wave breaking zone is typically 400~500 m away from the island. Uniquely here it is very close to the shore (<100 m), so that is why we chose Kandooma Island for the first experimental site. We can easily access the installation site on foot directly from the island.

The Maldives consists of 1,200 coral islands on 26 atolls, composed of live coral reefs and sand bars, situated atop a submarine ridge 960 km long that rises abruptly from the depths of the Indian Ocean. The steady ocean swells arrive mostly from the South without losing their energy after propagating over long distances in the deep sea. Therefore, many famous surfing spots are located in the Maldives. The swells are from the South Indian Ocean close to the South Pole, where sea conditions always involve high winds due to low pressure. The generated swells propagate through 3000~5000 km of ocean, heading North to the Maldives. This long-distance travel acts as a frequency filter, i.e., the high frequency components decays fast, and low frequency swells remain with very small loss.

Fig. 2. The Wave Energy project, which is kindly supported by Holiday Inn Resort Kandooma Maldives, will test prototype WEC-units on Kandooma island. The red arrow marks the experimental site, where the stable swells are arriving from the Indian Ocean in a southeasterly direction.
Credit of photo: Holiday Inn Resort Kandooma, Maldives

According to ocean wave theory, the propagating wave power in the deep sea is given as follows [4].

$$P_w = \frac{1}{8}\rho g H^2 v_g \quad \text{[Watt/m]} \tag{1a}$$

$$v_g \approx \frac{1}{2} c = \frac{gT}{4\pi} \tag{1b}$$

where $v_g$ is the group velocity. For example, for period $T$ = 12 sec (a typical swell in the Maldives), and wave height $H$ = 1 m, we have $v_g$ = 10 m/sec, $P_w$ = 12.5 kW/m (power flow across unit distance).

Figure 3 shows wind and wave statistics for one year at Malé Maldives (January 2016 ~ December 2016), for which archived weather data at Windguru[5] is used. Figure 4 shows four days wind and swell data at Male Maldives, April 26~ April 29, 2018. In Maldives, stable swells are arriving from south east direction throughout the year. And the period of the swell is always in the range 8 to 12 sec, which is quite suitable for wave energy usage. The swell height is only ~1 m, thus the wave power potential at Maldives is relatively low compared to other areas, such as west of Portugal, Spain and Ireland. However, no extreme weather conditions are recorded, because there are no typhoons or intense storms in the Maldives. This is due to zero Coriolis force near equator. The high heat flux from the sun creates strong ascending air current, but it can not build up to the cyclone, typhoon or hurricane because of lack of triggering spinning force. This is an important information for the ocean energy community. Performing start-up projects should be much easier in the Maldives than other places.

The availability for wind power is 48% assuming a cut-in speed of 6 m/sec, while for wave power it is 68% by assuming a cut-in wave height of 1 m. This is fairly high, so the investment recovery period should be shorter.

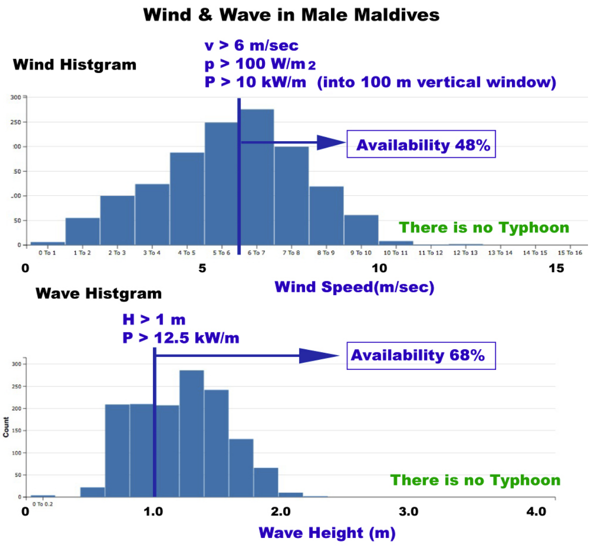


Fig. 3. Wind and wave power statistics for one year at Male Maldives (January 2016 ~ December 2016).

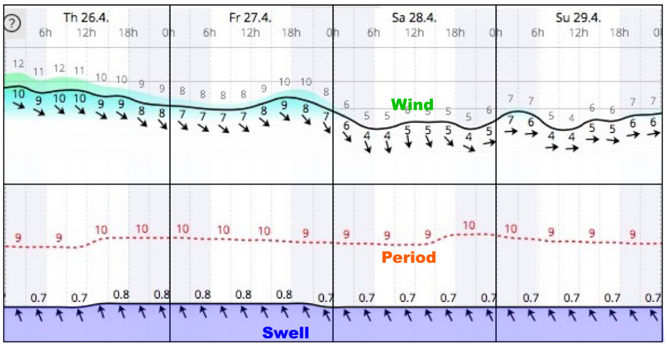


Fig. 4. Four days wind and swell data on Windguru (April 26 ~ April 29, 2018) at Male Maldives

By comparing wind and wave statistics, we find an interesting feature here. The power flow of wind at 6 m/sec becomes almost the same as 1 m height of the wave, i.e. ~10 kW/m. Here we assume vertical window height for wind power is 100 m, which is the height we can easily reach in todays wind power technology. In nature, all waves are created by wind (except the earthquake and tsunami). Both the wind speed of 6 m/sec and the wave height of 1 m are in the same moderate weather condition. The question arises; which is better to harness the energy from the wind or the wave. The better choice depends on the total cost per unit energy production, i.e., how much cost do you need to construct machines, operate them and demount them at the end of lifetime divided by the whole electricity production. This will be an interesting subject to study in future.

## III. Experimental Site at Kandooma Island

From 2018, we start the first experiment at Kandooma Island (Fig. 2). Two half-scale WEC units, followed by two full-scale WEC units will be tested, and generated power will be monitored from Japan through internet.

Figure 5 shows the aerial view of test site taken by a drone and beach view from the seawall. The installation site is very shallow (~1 m) thus there are no living corals. And also, there are no divers or swimmers in this area. The sea floor is fairly flat, made by coral limestone. Presumably, repeating breaking waves have been scraping the top of the corals and created the flat floor, thus this place is fairly suitable for WEC installation. We find many rocks (coral lime stone fragments) on the shore side, which are evidence of breaking wave activity.

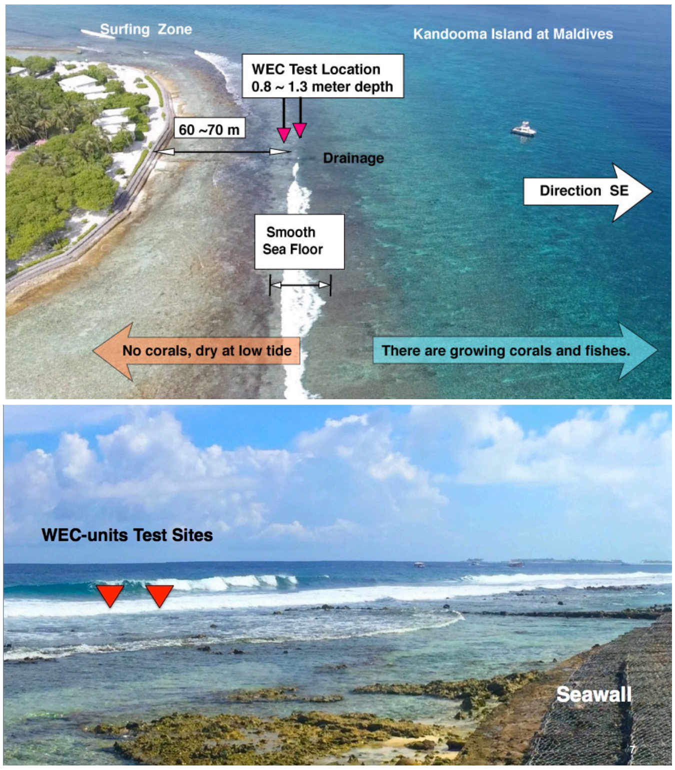


Fig. 5. Test site is at south east side of Kandooma island. Test site is 50~60 m away from the seawall, and very shallow, thus there is no living corals. We can also access to the test site directly from the island on foot.

As shown in Fig. 7, we will install WECs at points 47 m and 57 m from the seawall. Waves are breaking at 60~80 m from the seawall, thus there is a high degree of vortex flow mixing at WEC installation points, and the total energy conversion efficiency will be low. To gain higher power with better efficiency, we should install WEC at 80 m from the seawall, where the waves keep surf-wave, and right before the breaking. However, it is known that the rip part of surf-wave has much higher velocity flow (>10 m/sec), and there is a certain risk of damaged on turbines due to high speed rip. In this first phase of experiment, in order to perform experiment safely, we decided to install WECs at shallower locations.

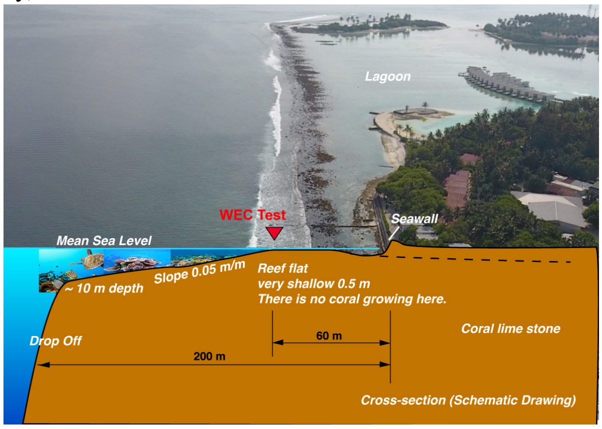


Fig. 6. Cross-section (schematic drawing) of the installation site. The drop-off is 200 m away from the island. The wave breaking zone is 50~80 m away from the island, where the water depth is 0.5 ~ 2 m. We chose test point at 50~60 m from the seawall.

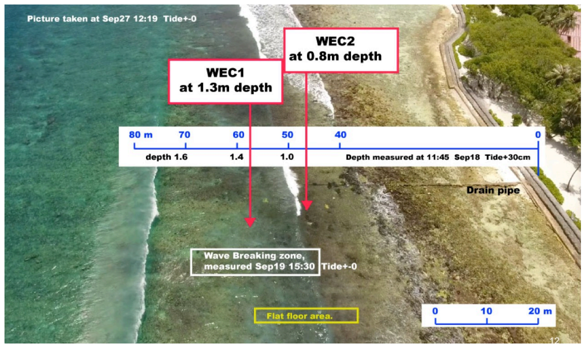


Fig. 7. We will install two half-scale WECs at water depth 0.8 m and 1.3 m.

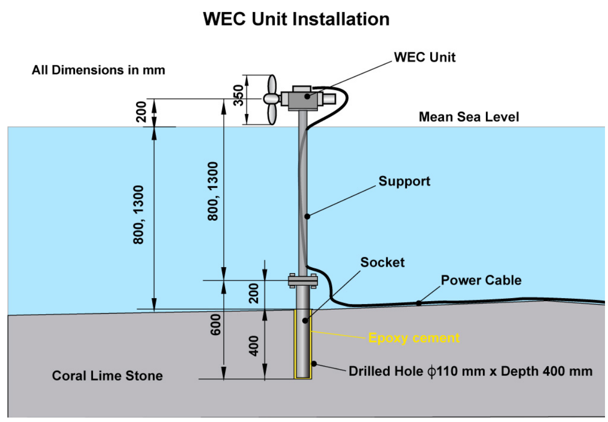


Fig. 8. We mount the WEC unit by support socket, which is epoxy cemented to the vertical hole of 110 mm diameter made by core drill.

Figure 8 shows how to mount the WEC unit on the sea floor made of coral lime stone. Using core drill, we make vertical hole of 110 mm diameter and 400 mm depth, followed by cementing the socket with epoxy glue. To minimize the fluid pressure on the supporting rod by the breaking wave, we made its cross-section as elliptical shape. Installation is not straightforward, because we have to work under the breaking waves. We have to avoid installation during the Monsoon season because of high swells, May-October in the Maldives.

In the near future, when we move to the Phase-II R&D, we will develop a new WEC system using tubular-turbine, and also improve the installation method. The new WEC will be installed at the point near 80 m from the seawall, and harness the energy from the surf-wave directly. The power conversion efficiency will be much higher.


Fig. 9. We measure the generated power by the monitoring system located right next to the existing power house on Kandooma[3].

## IV. TURBINE & GENERATOR R&D

Table–I summarizes the WEC generator R&D strategy. There are several technical issues to be solved in creating a serviceable WEC. Most of the issues are related to the high energy density of breaking waves. Also, the safe installation of WECs into the breaking wave zone should be investigated carefully. To mitigate these challenges, we decided to start R&D on a half-scale device.

The turbine of the scaled-down model (half-scale) was machined from a block of aluminum alloy (A7075) using a digitally controlled milling machine (Fig. 10). One of the most difficult technical challenges in our WEC design is we decided to immerse the expensive electric generator into the salty sea water. The permanent magnet (NeFeB magnet) and the silicon steel used in the magnetic circuit are very weak against moisture.

In order to perfectly seal the generator body from the sea water, we fabricated the generator housing based on the vacuum chamber design. After assembling the generator, we performed Helium gas-leak test as shown Fig. 11. Leak rate was lower than $1 \times 10^{-10} \mathrm{Pa} \cdot \mathrm{m}^3/\mathrm{sec}$, which is much lower than our requirement $3 \times 10^{-8} \mathrm{Pa} \cdot \mathrm{m}^3/\mathrm{sec}$ (total 100 cc Helium gas-leak during 10 years operation at atmospheric pressure). When the shaft rotates, Helium start to leak much faster through the mechanical seal. After filling silicon oil, the oil leakage is designed to be lower 100 cc for 10 years operation through the mechanical seal.

The silicon oil is for lubrication of the mechanical-seal. The oil inside the housing is applied positive pressure +0.1 MPa by means of the mechanical diaphragm. The static pressure will keep silicon oil filling into nanometer-gap between two SiC rings inside the mechanical seal.

Cooling is one of the most important issues in high power generator design. Roughly speaking, 10% of energy is dissipated inside the generator, i.e., mainly Joule loss in the winding coils on the stator core. We remove the heat from the windings through the stator core, the aluminum housing and finally into sea water by the forced convection flow of the breaking wave.

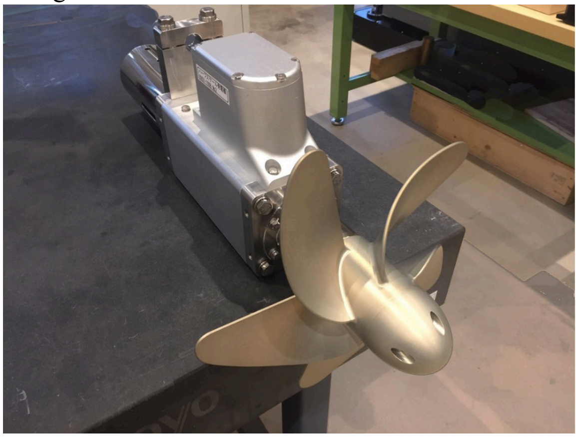

Fig. 10. Half-scale WEC unit, having 5-blade turbine of 35 cm diameter, permanent magnet generator in waterproof housing and 3-phase power cable. Detail description can be found in ref. [2,3].

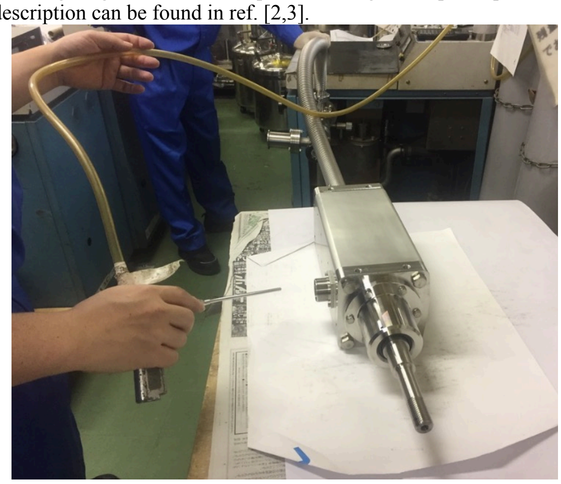

Fig. 11. After assembling the generator, we performed Helium gas-leak test to confirm vacuum seal performance.

Figure12 shows the full-scale prototype generator under development at ICHINOMIYA DENKI CO., LTD. The size of the generator is roughly twice larger than the half-scale, while the volume is eight times larger, and thus its weight is now180 kg. The generator housing is made by aluminum casting in order to lower the fabrication cost. However, we found a large number of small pits (~0.1 mm) inside the casted aluminum body, which might become a source of small water leaks. To reduce voids and improve reliability, we will use aluminum die casting method in the next generator.

The power connector (feedthrough) sometimes limits the maximum capable power, and also may cause troubles under high humidity of salty water and/or repeating mechanical shocks propagating through the cable due to the wave. We are currently developing a robust hermetic feed-through based on our custom design at OIST.


Fig. 12. Full-scale prototype generator under development at ICHINOMIYA DENKI CO., LTD. Engineer is connecting feedthrough at the bottom of the generator, through which the generated power is sent out to three phase sub-sea cable.

TABLE I
WEC GENERATOR R&D STRATEGY

| **Model Name** | **Half-scale Prototype** | **Full-scale Prototype** | **Mass Production** |
|---|---|---|---|
| Peak Power | 1.3 kW | 10 kW | 60 kW |
| Continuous Power | 600W @330rpm | 5 kW @330rpm | 30 kW @1800rpm |
| Housing | Aluminum Machined | Aluminum Casted | Aluminum Die casted |
| Turbine | 35 cm, Open 5 blade | 70 cm, Open 5 blade | 70cm, Tubular 6 blade |
| Turbine Material | Aluminum Alloy Machined | SUS304 Casted | SUS304 Casted |
| Generator | Direct Couple PM | Direct Couple PM | Gear Couple IPM |
| Grid Connection | No Standalone | No Standalone | Yes 3x10kW Power Conv. |
| Field Test | May 2018 - | Oct 2018 - | April 2019 - |
| Period | FY2016-2017 | FY2017-2018 | FY2018-2019 |
| R&Ds | Phase-I R&D | | Phase-II R&D |

The full-scale turbine (five blades, 70 cm diameter) will be fabricated by the casted stainless steel.

The electrical performance of the generator was verified on a test bench, where we confirmed 5 kW output power, and efficiency 92% at 550 rpm rotation speed. Five full-scale generators are under fabrication, where two of them will be tested at Maldives, and other two will be tested at Seragaki marine-station of OIST Okinawa, where we test WECs under extreme weather condition of frequently visiting Typhoon. The remaining one generator will be tested with the power conditioner unit planned for the mass production model.

## V. POWER CONDITIONER

We are still in conceptual design phase. Among various renewable energies, the solar power and the wind power have been widely spread and their technologies are well established. When we design the power conditioner in our wave energy system, it will be useful to learn from these leading technologies. By comparing the solar and the wind power, the solar power system is closer to our wave energy system, because of their output power rating. A large number of solar systems are in the range of a few kW to 10~50 kW. We follow this design.

## VI. SUMMARY

We started R&D on OIST Wave Energy Converter in 2014. During the first phase of R&D, we have developed two half-scale prototypes which have been installed in Kandooma Island in Maldives and sending information of power generation to us through internet. The full-scale prototype will be ready and soon tested also from this year.

In the next phase of R&D, we will develop high-power WEC technology using tubular turbines. In the near future, we hope to connect our WECs to the power grid and try to supply power to Holiday-Inn Resort Kandooma.

## ACKNOWLEDGMENT

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