

# Wind Power Generation

## – Development status of Offshore Wind Turbines –



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*Wind power generation is one of the most widely-accepted renewable energy technologies in the world. In Europe, offshore wind power is in the spotlight because lands appropriate for constructing wind farms have been limited. The North Sea nations plan to develop large-scale offshore wind farms. Japan has also been accelerating the introduction of wind power generation since the Great East Japan Earthquake, which caused electrical power shortages. The prompt commercialization of offshore wind power is expected. Because compared with onshore wind power, Japan has many more offshore sites available and the higher potential for the growth of local industries. Mitsubishi Heavy Industries, Ltd. (MHI) takes advantage against other domestic companies in the development of large offshore wind turbines with a rating of 5MW and above for overseas customers. This report describes an overview of the development status the large offshore wind turbine as well as the operational status of the MHI's 2.4MW offshore wind turbine, which was installed off the coast of Choshi, Chiba prefecture under the Japan's first national offshore demonstration project.*

### 1. Introduction

Wind power generation started to be deployed in the late 1990s. Denmark was the leader, and Germany and Spain followed in deploying wind power, resulting in widely spread into the countries across Europe. Some nations who introduced wind power in early days shifted to explore offshore wind power, because there were few lands remaining that were suitable for wind turbines. Offshore option offers a stronger average wind velocity, a wider selection of locations and fewer problems with noise and landscape than onshore option. Other benefits of offshore wind power include the higher potential of growth of local industries and of increasing job opportunities. Since these benefits became more apparent, the North Sea nations have developed large offshore wind farm plans one after another. It is predicted that more than half of the future wind power in the EU will be offshore.

Japan, on the other hand, faces a lack of electricity due to the Great East Japan Earthquake, and the country is now intensively promoting wind power generation to obtain electricity from its own renewable sources that do not emit CO<sub>2</sub>. In addition to small land area, Japan is one of the most populous nations; there are few lands available for onshore wind power. As a result, Japan started to accelerate deploying not only onshore wind power, but also offshore wind power, as it makes a greater contribution to local industries and is more appropriate for large-scale deployment.

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## 2. Development status of offshore wind turbines

We began wind turbine development in 1980, and have delivered more than 4,000 turbines, mainly for domestic and U.S. customers. We have been part of an offshore wind power demonstration and research project conducted by the New Energy and Industrial Technology Development Organization (NEDO) since 2008, which was the beginning of the full-scale development of offshore wind power. This project calls for the construction of demonstration units off the coast of Choshi and northern Kyusyu, operating them and collecting demonstration data for commercialization. We are responsible for designing and constructing a 2.4 MW demonstration unit off Choshi and for studying the operation and maintenance (O&M) techniques under offshore conditions, in cooperation with Tokyo Electric Power Co., Inc. O&M research commenced in March 2013. We have also joined other offshore wind power projects in the UK, Round 3, and began to develop a 7MW-class offshore wind turbine in 2010. We acquired UK based Artemis Intelligent Power, Ltd. and used its proprietary digital control technology as the core to integrate the world's first Digital Displacement Transmission (DDT) hydraulic drive train into the 7MW model. In June 2013 we completed assembling the nacelle, which is now being tested at MHI's Yokohama Dockyard & Machinery Works.

## 3. Demonstration status of the 2.4 MW offshore wind turbine

### 3.1 Development of 2.4 MW offshore wind turbines

#### 3.1.1 Design aspect

We selected the MWT92/2.4 model (50 Hz, IEC Class I) as the basis for the 2.4 MW offshore demonstration unit and upgraded the MWT92/2.4 model for the site off Choshi. The MWT92/2.4 model is one of the most reliable 2.4 MW models with ample operational performance, and more than 500 units have been operated on land. The main upgrade points are as follows: (1) Higher anti-corrosive characteristics to endure offshore conditions, (2) enhanced remote-monitoring and -controlling systems to compensate for poorer accessibility than onshore sites, and (3) enabling measurements and tests, including lightning strikes and blade erosion specific for offshore conditions.

#### 3.1.2 Specifications of the wind turbine

##### (1) Countermeasures for corrosive offshore conditions

For onshore wind turbines, the nacelle intakes outer air to cool the lubricant cooler of gearbox and the generator cooler, as well as the heat generating components such as motors, electric control panels and transformers. But it is not acceptable to intake salty outer-air under offshore conditions, because it corrodes the components. As a result, the nacelle of the offshore demonstration unit is highly air-tight to minimize the inflow of corrosive outer-air. The nacelle also has weatherboard louvers and salty particle removal filters in the air inlets to remove corrosive materials from outer air. The air taken in the nacelle goes out from an exhaust vent at the rear of the nacelle, where an exhaust fan is equipped to enhance the ventilation capability. The gearbox coolers have been changed to be made of higher corrosive-resistant material than the original models, enabling direct cooling with the outer corrosive air to reduce intake air flow rate. The lubricant oil of gearbox is first cooled with the coolant water and the warmed coolant water is then cooled by outer air at the coolant water/air coolers to avoid lubricant oil leakage from the cooler outside the nacelle even if the coolers are damaged or the pipe fitting fails. **Figure 1** shows the items upgraded from the onshore model. The coating grade of offshore demonstration unit is selected one class higher than that used on onshore models in accordance with the IEC61400-3 offshore wind turbine standards. The surface of the tower is covered with a fluorine coating agent, which is the first application to the tower of offshore wind turbine.

##### (2) Advanced remote-monitoring and -controlling systems

The nacelle is equipped with a Condition Monitoring System (CMS) consisting of 10 vibration sensors and a revolution meter, enabling the operation conditions of main components to be continuously and remotely monitored. The sensors are at the main bearings, the gearbox and the generator; and the meter is at the generator shaft. The nacelle

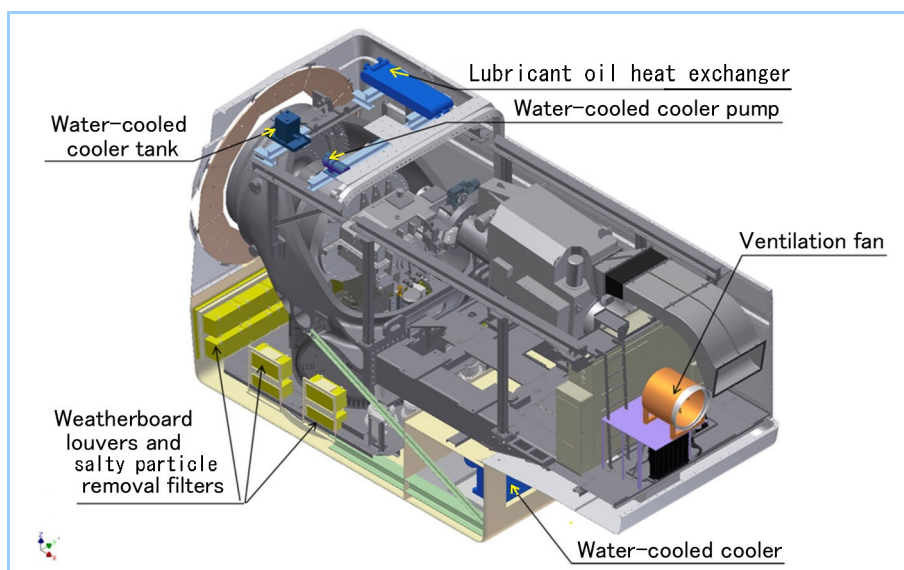
also has two types of cameras inside, enabling the vicinity of the rotating high speed coupling to be monitored and providing an overall view inside the nacelle.

Operators check the conditions on a monitor in the operation room on land. The met mast built about 300 m from the demonstration unit has a web camera, enabling the external conditions of the demonstration unit to be remotely monitored for abnormalities.

Following special control capability has been added to the demonstration unit: (i) The trip events will be remotely reset, (ii) the trip alarms will be remotely turned off in order not to lower the capacity factor, and (iii) the demonstration unit will be automatically restarted if the trip event is due to transient phenomena detected in the converter control panel. (iv) the function check system of the pitch control and auxiliary motors (health check system) is newly installed and the yaw rotation becomes controllable remotely.

### (3) Measurements and tests specific for the demonstration unit

The demonstration unit has Atmospheric Corrosion Monitoring (ACM) sensors<sup>1</sup>, thermometers and hygrometers inside and outside the nacelle. The ACM sensors continuously measure air salinity, helping to determine the quantitative anti-corrosion effects. The data are remotely monitored. The demonstration unit has a Rogowskii coil near the bottom of the tower, which continuously measures lightning current. Three types of anti-erosion coatings are applied to each of the blade tips to understand the degradation under offshore conditions



**Figure 1 Configuration of the 2.4 MW offshore wind turbine**

This drawing shows the points changed from the original onshore turbine.

## 3.2 Operational status of the 2.4 MW offshore wind turbine

The nacelle was assembled at MHI's Yokohama Dockyard & Machinery Works, the blades were manufactured at MHI's Nagasaki Shipyard & Machinery Works and the tower was made by another manufacturer abroad. After completion, all of the components were gathered in Yokohama, loaded on two Self-Elevating Platform (SEP) vessels (the Kuroshio and the Aso) and then towed to the installation site off Choshi. The components were installed on the foundation (conical gravity bed type) with large cranes. **Figure 2** shows the components towed by the SEP vessels, and **Figure 3** shows the installed demonstration unit.

The continuous operation research started in March 2013, and the demonstration project will continue until the end of the 2014 fiscal year. **Table 1** shows the operational performance of the demonstration unit to date: the capacity factors were 39.4% in March, 33.7% in April and 37.0% in May. If the halt period for the research activities and maintenance is excluded, the factors were 45.3% in March, 53.2% in April and 37.0% in May. The values are nearly twice those of typical onshore wind turbines (20% to 30%) in Japan, showing excellent wind conditions at the offshore site.

The first maintenance work was conducted in March 2013 after 500 hours of the beginning of operation. The main purposes of the maintenance were to check the various bolts including

tower connecting bolts, to retighten them, to check the lubrication at the moving portions and to conduct other initial check-ups. It was inappropriate time for maintenance works because sea conditions were likely to be rough with continued high waves for many days and it was difficult to access the foundation by ship in such sea conditions. Actually, we were only able to check them on cumulative nine days, less than half of the 20 days maintenance period originally planned. The maintenance work was sometimes interrupted by the abrupt weather change. We reluctantly carried over most of the low-priority check items to the next maintenance. This fact shows the difficulty of maintenance under offshore conditions, providing many lessons for further improvement.



**Figure 2** Nacelle, hub and blades transported to the offshore construction site by ship



**Figure 3** Completed offshore wind turbine (photo center) and met-mast (photo right)

**Table 1** Operational records of the 2.4 MW offshore wind turbine

2013	Capacity factor (CF)		Planned outage periods	Reasons
	Calendar-day basis	Operation-day basis		
March	39.4 %	45.3 %	4 days	Research activities
April	33.7 %	53.2 %	11 days	Research activities and planned maintenance
May	37.0 %	37.0 %	0 days	--

[Calendar-day basis] CF = monthly output / (rated power x calendar days x 24)

[Operation-day basis] CF = monthly output / (rated power x operation days x 24)

## 4. Development status of 7 MW offshore wind turbine

### 4.1 Selection of key factors of the turbine

We started the development of our first offshore wind turbine in 2010 in order to join Round 3, offshore wind power projects in the UK. The main challenges of developing offshore wind turbines are to reduce the capital cost per kWh and to reduce malfunctions of the components such as gearbox and power converters. We reduced the capital cost per kWh by enlarging the wind turbine, by increasing the rated output and the rotor diameter. We also reduced the malfunction potential by using highly-reliable components. Round 3 has a long lead-time (5 years or longer) before the construction start date, and there are many new entrants as well as familiar existing firms in the market. As a result, we selected the most competitive model at the time of commercialization. It has a much higher rated output and longer rotor diameter (7 MW, 167 m) than the largest model (5 MW, 126 m) in service at the time when the development started. The swept area per kW ( $\text{m}^2/\text{kW}$ ), which is the index of power production capability, is increased from 2.49 to 3.13, more than 20% higher than the existing 5MW model. To enhance the reliability, we compared various drive train based on our expertise on the proven gearbox system and the direct drive permanent magnet synchronous generator system. We finally decided to develop a hydraulic drive train based on the Digital Displacement Transmission (DDT) hydraulic drive train of a UK venture company, Artemis Intelligent Power, Ltd. (see Chapter 4.3). It was the world's first attempt to use a DDT hydraulic drive train for a wind turbine. The hydraulic drive train is expected to realize both low capital cost and high reliability. It was also advantageous for us to apply our self-developed hydraulic technology to the DDT hydraulic drive train. To reduce the transportation cost, we decided to develop the long blades (over 80 m) with an EU manufacturer to produce them in the EU. **Table 2** lists the design features for the 7 MW offshore model.



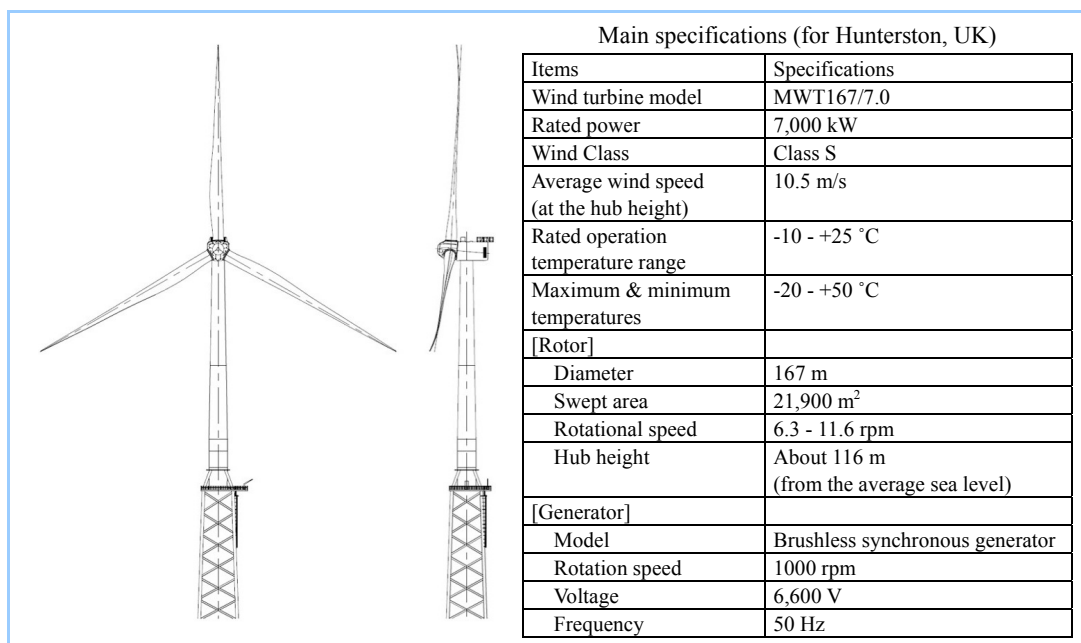
**Table 2 Design features for the 7 MW offshore wind turbine**

	Items	Contents
(1)	High annual energy production	The wind turbine shows very high capacity factor (> 55 %) with high rated power output (7 MW).
(2)	High quality of electricity and grid compatibility	Using versatile brushless synchronous generators at a constant rotational speed enables good power controllability that meets grid requirements.
(3)	High reliability and capacity factor	Using a hydraulic drive train enables high reliability and robustness. (The hydraulic drive train is an alternative to conventional gearboxes with poorer reliability. The hydraulic drive train does not need a power converter and other devices with high failure rates.) The redundancy of cylinders enables high availability to be maintained if some cylinders fail. Total replacement is not required. The hydraulic components are partially exchangeable. (Conventional direct drive trains and gearboxes require complete replacement after failure.)
(4)	Low maintenance cost	The design enables the equipment inside the nacelle to be easily replaced. (The devices are carried up and down inside the tower without interference from the weather.)
(5)	Low capital cost	The wind turbines use versatile hydraulic devices and materials and inexpensive synchronous generators. (Using no rare earth materials decreases material sourcing risks.)
(6)	Easy scale-up	Using modular design of the hydraulic drive train enables easier scale-up (in shorter time and at lower development costs).

Capacity Factor (CF) = Yearly output / (7 MW x 365 days x 24 hours)

## 4.2 Overview of the 7 MW offshore wind turbine

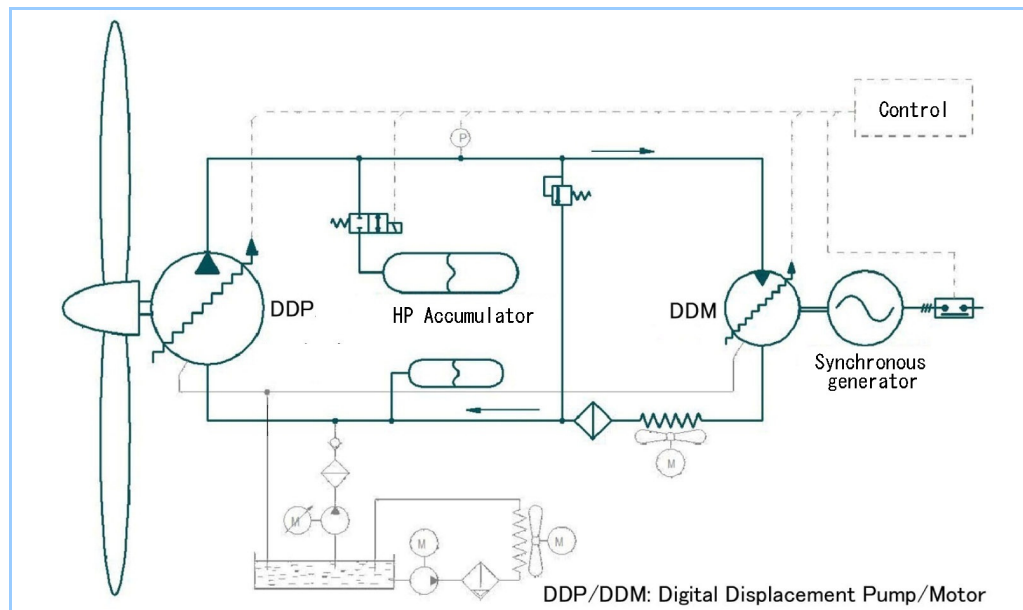
**Figure 4** is an outline and the main specifications of the 7 MW offshore model. The hub height was decided based on the capability of the available cranes and the wind-shear effects, and the design average wind-speed and temperature range were determined based on the wind conditions and weather in the North Sea. The 7 MW offshore model has an air-tight nacelle, which has louvers and salty particle removal filters at the intake vent to reduce corrosion damage induced by salt. The nacelle also has a small regenerative-dehumidifier to control the humidity inside the nacelle. Each of the electric control panels has an independent water-cooled cooler to indirectly cool the panels with the outer air, completely preventing salt damage. The nacelle has a winch at its ceiling that helps to carry components through the tower during regular maintenance, which makes the maintenance easier even in heavy weather. The 7MW offshore model has two generators with 50% capacity each to increase the partial load efficiencies. In the case of a generator failure, the other generator will continue to operate at the partial load. The nacelle has a landing platform for emergency use at its top. The tower has an oil sump at its top to store the operating oil from devices including the DDT hydraulic drive train if it leaks. Specifically, the nacelle cover acts as an oil pan to prevent sea pollution.



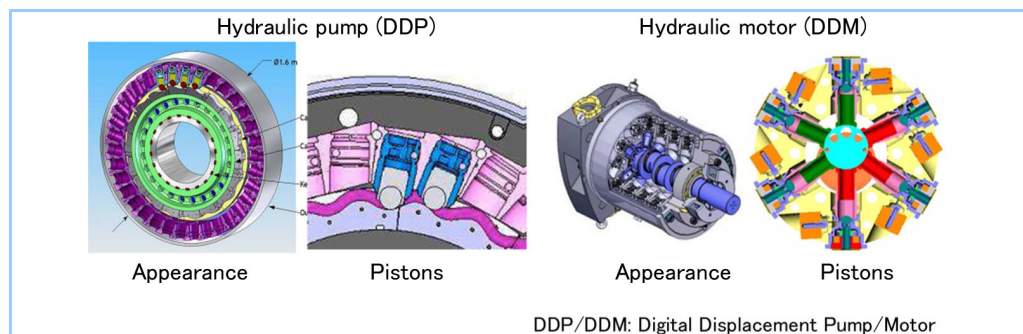
**Figure 4 Basic specifications of the 7 MW offshore wind turbine**

### 4. 3 Development of hydraulic drive train<sup>2</sup>

**Figure 5** shows the basic configuration of the DDT hydraulic drive train. The hydraulic drive train consists of auxiliary machinery including a hydraulic pump, a hydraulic motor, pipes, an accumulator and coolers. The rotational power of the rotor drives the hydraulic pump to generate high hydraulic pressure. The pressure travels through the pipes to rotate the motor at a constant speed. The motor rotation drives the power generators to produce electricity. The accumulator absorbs any hydraulic pressure fluctuations. The hydraulic pump is a ring-cam type multistage piston pump, and the hydraulic motor is a crank type piston motor. **Figure 6** shows the basic configurations of the pump and the motor. The 7 MW offshore model has two 3.5 MW motors with 50% capacity each. With 3 motors, the output would increase to 10 MW. Increasing the number of pump stages would also increase the output easily.



**Figure 5 Basic configuration of the DDT hydraulic drive train**



**Figure 6 Hydraulic pump and hydraulic motor**

**Figure 7** shows the development steps of the DDT hydraulic drive train. The first step is assembling a closed circuit consisting of an existing 1.6 MW hydraulic pump and a hydraulic motor. Next, the circuit is used to simulate the hydraulic drive train to measure the energy transmission efficiency and to check the compatibility of the hydraulic drive train with the drive train of wind turbine. The development steps include elemental tests for components such as the hydraulic piston, valves, cams and rollers. The existing 2.4 MW demonstration wind turbine is used to verify the operation of the DDT hydraulic drive train at Yokohama Dockyard & Machinery Works. The hydraulic drive train was downsized from 7 MW to 1.5 MW, and underwent a response test and a load test by simulating wind turbine input to the hydraulic pump at the Machinery Works. After the tests, the 1.5 MW hydraulic drive train was installed in the 2.4 MW demonstration wind turbine. The world's first wind turbine with a DDT hydraulic drive train started operation in January 2013. A nacelle with a 7 MW hydraulic drive train was also assembled and underwent an operational test and a load test using simulated input. The nacelle will soon be shipped to the 7 MW model construction site in the UK.

Development of DDT		2011			2012				2013		
		4	7	10	1	4	7	10	1	4	
1	DDP/DDM Combination test		1.6 MW model								
2	Element Test (Component Endurance Test)		Sliding members								
3	Shop Full Load Test						1.5MW model			7MW model	
4	Reliability Verification Test									2.4MW demonstration wind turbine at Yokohama Dockyard & Machinery Works	

Figure 7 Development steps of the DDT hydraulic drive train

#### 4. 4 Blade development<sup>2</sup>

A blade of the 7 MW offshore model is 81.6 m in length. One blade, which is for a load test, has already been completed, and the other blades for the 7 MW offshore model are currently being manufactured. To reduce the blade weight, the spars (a structural component) that support most of the wind load are made of carbon fiber, which is electrically conductive. The lightning protection system common in the conventional full glass-fiber blades is not applicable for these carbon-fiber blades. The shape and location of the receptor for the blade were optimized, and lightning tests showed that the receptor has a 100% lightning capture rate. The tests also showed that there was no degradation in the strength of the carbon fiber due to lightning strikes. Figure 8 shows the lightning test being carried out. There are no noise regulations at offshore sites, so the tip speed of the 7 MW offshore model was made higher than onshore models. The blades were made more slender to reduce their weight. This design tends to lead to erosion at the leading edges of the blades. To determine the most appropriate coating agent and the maximum allowable tip speed, acceleration tests were conducted.



Figure 8 Appearance of the lightning test for the blades

## 5. Conclusions

Nowadays, offshore wind power generation is in the spotlight and expected to see early commercialization in many countries including Japan. This paper describes the development status of MHI's offshore wind turbines. We developed the 7 MW offshore model, which is planned to be built in Hunterston, UK, and commence a full-scale operation test. We will also deliver the 7 MW offshore model for the national floating-type offshore demonstration project in 2014, which will be the first Japanese floating-type offshore wind turbine with 5 MW and above. We wish to thank NEDO and the Department for Business, Innovation & Skills (BIS) in the UK for their support in developing the 2.4 MW and the 7 MW offshore models. We also appreciate our customers and related parties for their valuable advice and support. We will deliver our 7 MW offshore model to promote domestic and overseas offshore wind power generation, and we will continue our efforts to help solve energy-security problems for mankind by promoting CO<sub>2</sub>-free, inexhaustible renewable energy.

## References

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2. Umaya et al., Proceedings of Japan Wind Energy Symposium Vol. 34 (November 2012) pp. 150-174