Corrosion in the Marine Renewable Energy: A Review

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ABSTRACT

Marine renewable energy has potential to play a significant role in the world’s future energy system. Marine renewable energy has attracted many developers and researchers around the world aiming reducing carbon emission and enhancing blue economy. To promote the development of successful marine energy devices, it needs to achieve the reliable conditions for facing aggressive and corrosive marine environment. Corrosion is an important issue in marine environment. Corrosion can cause structural deterioration and product loss in the main component structure of marine energy devices, such as turbine. Corrosion has been studied for many years, and this paper focuses to review about the most possible types of corrosion occur in marine renewable energy device, factor affecting corrosion, method of corrosion identification, and corrosion that occurred in marine renewable energy device. Study work in corrosion of the marine energy is recommended in order to assess failure and increase the lifetime of marine energy device itself.

KEY WORDS: Marine renewable energy, marine energy device, corrosion

NOMENCLATURE

<table>
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<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>DNV</td>
<td>Det Norske Veritas</td>
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<tr>
<td>EIS</td>
<td>Electrochemical Impedance Spectroscopy</td>
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<tr>
<td>ISO</td>
<td>International Organization of Standardization</td>
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<tr>
<td>OTEC</td>
<td>Ocean Thermal Energy Conversion</td>
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1.0 INTRODUCTION

Renewable energy is generally defined as sources of energy which are naturally replenished, and is typically regarded as an abundant, inexhaustible and non-polluting resource \cite{1,2}. Because of the global energy crisis and environmental pollution issue, renewable energy receives more attentions and much of this development is going on out at sea \cite{2,3}. Renewable energy resources can be categorised as illustrated in Figure 1. Renewable ocean energy (referred hereafter as ocean energy) is a part of marine renewable energy, and marine renewable energy is included of renewable energy \cite{4}. Marine renewable energy can be defined as renewable energy generation that utilise marine resources or marine space. In general terms, marine renewable energy devices use marine space, and they are installed, deployed, commissioned, operated, maintained and decommissioned at the sea. Marine renewable energy devices are also connected to the electricity grid and distribution systems \cite{4}. Ocean energy is also defined as an ability to do works from converting one energy form of the sea to another form of energy (electricity) which can be harnessed by human-kind \cite{5}. Types of marine renewable energy can be categorised into tidal energy, wave energy, ocean thermal gradient, salinity gradient, offshore wind, and biomass energy \cite{6}. There are three main forms of marine renewable energy which are being predominantly developed, these are offshore wind, tidal energy, and wave energy \cite{2}.
From all marine renewable energy devices, offshore wind farms have been experiencing the fastest development [2]. Offshore wind turbines harness the energy of the moving air over the oceans and convert it to electricity [6,7]. Many offshore wind farms have been developed since 1991 (Vindeby, Denmark and the United Kingdom (Blyth Harbour, 2003) in European Atlantic and North Sea coast countries. Currently the largest offshore wind energy farm is Horns Rev off the north coast of Denmark (80 x 2 MW) [8].

Electricity also can be generated by ocean tides energy. Two types of tidal movement energy: the first is the potential energy from the rise and fall tides and the second is the kinetic energy from tidal current movements [7]. The potential energy from the difference in head between high and low tides of the sea is harnessed by using tidal barrages. Tidal barrage structures are built and enclosed a tidal estuary to capture energy created from the rising and falling tide. When the tide goes in and out, the water flows through turbines in the barrage and generates electricity [6,9]. Sihwa Tidal Power Plant in Korea and La Rance Tidal Barrage in France are the examples of tidal energy.

Tidal currents devices use the kinetic energy from the moving water to drive a turbine, much like wind turbines but fully submerged and can be placed directly in-stream to generate power from the flow of water [3,4,6,7,10]. Marine current energy is a new renewable energy and although its technology can be derived from wind turbines, it needs further research and developments [11]. Tidal current turbine devices have two basic types: axial flow and vertical axis crossflow [12]. Compared to wind and wave energy which are intermittent and variable, tidal current energy has the advantages of high predictability and regularity, which makes the utilisation of tidal current energy more interesting [3]. Examples of tidal current energy are Marine Current Turbines’ SeaFlow and SeaGen, Clean Current Power Systems (Canada), Hammerfest Strom (Norway), OpenHydro’s Open-Centre Turbine, Enermar’s Kobold Turbine. The worldwide theoretical power of tidal energy (including tidal currents) has been estimated at around 1,200 TW/year [13] and the theoretical resources of tidal power in Indonesia itself around 287 GW [14]. Therefore, the potential tidal energy development into rapid growth and progress in industry and academia during the last decade [3,15,16].

Wave energy is derived, ultimately, from the wind [17]. Wave energy is difficult to predict among marine energy resources because waves are caused by highly variable winds blowing over the surface of oceans [18]. Wave energy is captured by stationary or move up and down devices through a hydro turbine to generate electricity [19]. To date, more than one hundred wave energy concepts are being tested with many still at the R&D stage [4], so it is relatively immature than the other types of marine renewable energy technologies [20]. Some examples of wave energy prototype plants such as the Pico OWC plant in the Azores, the Japanese Mighty Whale floating offshore device, Pelamis, Wave Dragon (overtopping device), etc. The other types of marine renewable energy that remained early at R&D stage are salinity gradient, Ocean Thermal Energy Conversion (OTEC), and marine biomass, but they are not discussed here.

While marine renewable energy technologies come in many forms, there are challenges that are common to all. The nature of marine renewable energy technologies mean that the greatest challenge is operation in the marine environment itself [21]. Marine renewable energy devices are exposed to highly dynamic, harsh marine environments, and complex stresses, including the following: corrosive stresses, mechanical stresses, and biological stresses. Corrosive stresses include: atmospheric marine exposure, seawater exposure, wet-dry cycles, temperature variations, complex design (joints, bolts, welds), and materials pairings. Mechanical stresses include mechanical impact, wave and current exposure. And, biological stresses include basically fouling [22]. Marine renewable energy devices exposed to the seawater environment are at higher risk of corrosion moreover after many years [23]. They are susceptible to corrosion attacks due to the harsh marine environment and this may lead to damage the devices, then it can reduce service life [24].

Because of corrosion is a major cause of structural deterioration in marine and offshore structures, it becomes a major concern to all offshore constructions [25,26]. Marine growth and corrosion must be accounted for and controlled. Corrosion can lead to structural material degradation, facilitate fatigue cracks, brittle fracture and unstable failure [27], and the integrity of the entire structure can be affected considerably [23]. Economic losses resulting from corrosion amount to billions of dollars per year worldwide and the total annual estimated direct cost of corrosion in the U.S. is a staggering $276 billion—approximately 3.1% of the nation’s Gross Domestic Product (GDP) [28]. Therefore, the chances of success for marine renewable energy depend on the ability to minimize operational risks and prolong service periods without costly maintenance stops [29], although there are fluctuative hydrodynamic loads which can cause structural damage due to vibration caused by the turbine which is working continuously in the ocean environment [30]. The idea of corrosion is not new, however detailed discussion and studies about corrosion of the marine renewable energy are limited. In this paper, the corrosion in the marine environment will be firstly review and discuss, including types of corrosion, factor affecting corrosion, and methods of corrosion identification. Followed by the corrosion in the marine renewable energy devices. Then, the challenges in marine renewable energy devices against corrosion damage are also given. At last in the author’s opinion, the key of corrosion in marine renewable energy that to be researched or developed will be concluded.

2.0 CORROSION IN THE MARINE ENVIRONMENT

By definition, “corrosion is the physico-chemical interaction between metal and its environment, which results in changes in the metal properties and which may often lead to impairment of the function of the metal, the environment, or the technical system of which these form a part” (ISO 8044-1986). Corrosion also can be defined as the damage to metal caused by reaction
with its environment [31].

Metal is mentioned in the definition of corrosion, because corrosion is a natural process for metal that causes them to react with their environment to form more stable compounds with economic, environmental, and technical consequences [31,32]. Metals, whether they are attacked uniformly or pit or crack in corrosion, are all corroded by the same basic mechanisms, which are quite different from those of other materials. It is known, metals and alloys are the backbone of industrial and engineering structures because of their high strength and ductility. However, metals are thermodynamically unstable and undergo corrosion in most of the aggressive marine environments [33]. Corrosion cannot be avoided but delayed and controlled by applying various techniques such as the heat and rate reduction, removal of oxygen or oxidizing materials and changing the concentration of the working environment [34].

It is known that the surfaces of marine renewable energy devices are exposed to corrosive environments as an aggressive environment for steel-based constructions [35,36]. Offshore-long term exposure to humidity with high salinity, wave action and the presence of a splash zone area, and high corrosive stress give rise to very fast corrosion and damaged areas [37]. The splash zone of offshore structures is the most vulnerable to corrosion. Examples for steel corrosion (metal loss) criteria are provided in Table 1. To control corrosion, corrosion protection such as anti-fouling coating systems and cathodic protection can be applied to marine structures. In the case of marine propellers or rudders, the high-flow velocity and low pressure distribution around the propeller can cause strong cavitations. Strong cavitation can stimulate erosion on the marine rudders as results in damages on the rudders’ surfaces [35]. Then, erosion can enhance corrosion rate in few ways: mechanically stripping the protective layer on metal, either if it is an organic coating, a passive film or corrosion products, creating fresh reactive sites [38].

<table>
<thead>
<tr>
<th>Zone</th>
<th>Corrosion rate of unprotected steel in mm/year</th>
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<tr>
<td>Atmospheric</td>
<td>50 to 75</td>
</tr>
<tr>
<td>Splash zone</td>
<td>230 to 400</td>
</tr>
<tr>
<td>Tidal zone</td>
<td>50 to 230</td>
</tr>
<tr>
<td>Immersed (seawater)</td>
<td>130 to 200</td>
</tr>
<tr>
<td>Seagrond (soil)</td>
<td>60 to 130</td>
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2.1 Mechanisms

In maritime engineering, Det Norske Veritas (DNV) [40] suggested corrosion can be divided into several types [23]:

2.1.1. Uniform Corrosion

Uniform corrosion is the degradation of a metal over all areas exposed to the environment [41]. The continuous contact between steel surfaces and iron ore particles may lead to differential aeration zones and the formation of distinct anodic and cathodic regions and then leads to the relatively uniform loss of metal at the exposed surface [23]. Uniform corrosion is generally more predictable because the corrosion occurs over the entire area, so it is easier to measure and predict. Materials, such as carbon steel, that do not form a natural passivation layer are more susceptible to uniform corrosion. Protective coatings are often used to combat uniform corrosion. This coating method can successfully protect assets from uniform corrosion, however, any break in the protective coating can increase the localized corrosion like pitting, leading to unexpected catastrophic failure of the components [41].

2.1.2. Pitting Corrosion

It is a form of corrosion where the material degradation is localized to small areas rather than over the entire surface uniformly [41]. Pitting corrosion is regarded as one of the most hazardous form of corrosion for marine and offshore structures. The total loss of the structure may be very small, but local rate of attack can be very large and can lead to early catastrophic failure. Pitting corrosion is a localized accelerated dissolution of metal that occurs as a result of a breakdown in the protective surface passive film on the metal surface exposed to the pitting environment. Pitting corrosion can produce pits with their mouth open (uncovered) or be covered with a semi-permeable corrosion products. Pits can be either hemispherical or cup-shaped. In some cases they are flat-walled, revealing the crystal structure of the metal but they may also have a completely irregular shape. Figure 2 shows the common pit shapes divided in two groups namely: trough pits (upper) and sideway pits (lower) [26]. In particular, the influence of local corrosion such as pitting corrosion is difficult to estimate accurately [38].

![Figure 2: Sketch of common pit shapes](image)

2.1.3. Grooving And Edge Corrosion

Grooving corrosion may occur at stiffener connections close to a weld between the longitudinal and the deck, while edge corrosion is normally found at the free end of stiffeners and around cut outs (Fig. 3) [40]. Intergranular corrosion may occur in the heat-affected zone with metal loss parallel to the weld. Although metallurgically unchanged, the unaffected base metal is likely to experience high residual tensile stresses, which may contribute to stress-corrosion cracking. It can be seen that welds may introduce considerable complexity to grooving corrosion. In terms of the edges of structural members, the complex geometry may result in a thinner coating, which makes this region more vulnerable to corrosion [23].

![Figure 3: Schematic of grooving and edge corrosion shown on the cross-section of a stiffened panel](image)
2.2 Factor Affecting Corrosion
The factors which influence corrosion in marine and offshore environments are depending on the types of marine environments, such as atmospheric, splash zone, tidal zone and shallow water immersion. These factors are categorised into four different types: (1) Physical factors; (2) Chemical factors; (3) Biological factors; and (4) Metallurgical factors.

Physical factors that affecting corrosion are including temperature, pH, salinity, high velocity of water, physical size of specimen, depth (pressure), thickness of specimen, atmospheric conditions, water current & tidal conditions, surface wetting, humidity, water hardness, initiation time, duration of exposure, suspended solid, sunlight/UV, and oil on water. Chemical factors that affecting corrosion are including high chloride ion concentration, high carbon contain, dissolved oxygen, hydroxide ion, carbon dioxide, rate of metabolism, halogen ions, carbonate solubility, and sulphur dioxide. Biological factors that affecting corrosion are including bacterial, marine growths, fouling, pollutants, and biomass. At last, metallurgical factors that affecting corrosion are alloy composition, steel type, surface conditions, surface roughness/surface finish, protective coating, null scale, effect of pitting resistance value, inclusions, conductivity, and grain boundary [26].

2.3 Method Of Corrosion Identification
The first and foremost stage in understanding corrosion is to correctly identify the phenomenon [26]. There are many techniques that can identify the presence of corrosion, such as visual inspection, weight loss, non-destructive testing (NDT), etc. Visual inspection can be done in ambient light to determine location and severity of corrosion. Photographic imaging is often used to document the difference in appearance of pits before and after removal of corrosion products [42]. This technique is inexpensive and easy to do because it does not require specialized equipment and skills [42]. The visual inspections can use video and robotics both remotely operated and autonomous to evaluate areas that are difficult or dangerous for personnel to access. Weight loss techniques are used to determine the amount of material lost due to corrosion with systematic measurement of the weight loss over a specific period of time. This method is most useful in evaluation of uniform corrosion.

Non-destructive testing (NDT) is a technique used in industry to evaluate, identify, monitor and qualify the current state of components and equipments during operations and short operational shutdowns in service and to aid in maintenance planning. NDT becomes more important for defect evaluation, because of Removal of components from a working facility is not practical. Many different types of NDT with different purposes and applications, are including radiography, electromagnetic, sonics, and penetrants [42]. Beside many technique above, the corrosion behaviours also can be characterized by two electrochemical methods: potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) [34, 43].

3.1 Corrosion in Offshore Wind Energy
Corrosion can occur in several parts of offshore wind turbine, such as control unit, cooling and ventilation system, tower, hub, stairs, doors, transition piece, boatlanding, J-tubes, main shaft bearing, gearbox, brake, monopile internal, and grid connection (Fig. 4). Offshore wind turbine foundation are also susceptible to corrosion risk, such as uniform corrosion, local corrosion, microbiologically influenced corrosion (MIC), and pitting corrosion [44].

Several reports and documents about corrosion that occurred in offshore wind turbine are published. Momber [45] reports about corrosion and corrosion protection of offshore wind energy towers. There are also examples of damages to the corrosion protection systems of offshore wind device parts (Fig. 5). It is shown that corrosion are still occurred in offshore wind tower foundation structures, although corrosion protection systems, like cathodic protection, are applied (Fig. 6) [45]. Site inspections on offshore wind power transmission platforms in the North Sea and the Baltic Sea have also done [25]. Several images of metal loss were taken with standard digital in offshore conditions without any modifications, provided in Figure 7 [25]. In July 2009, planned monitoring program inspections of the Offshore Wind Farm Egmond aan Zee were carried out. This farm is located 10-18 kilometers offshore from the Dutch coastal village Egmond aan Zee. The inner structure of the nacelle and main components were checked on corrosion and some bolts of the gearbox showed rust stains (Fig. 8) [46].

3.0 CORROSION IN THE MARINE RENEWABLE ENERGY
The corrosion that occurred in three main forms of marine renewable energy (offshore wind, tidal energy, and wave energy) that predominately developed are discussed here.
3.2 Corrosion in Tidal Energy

Steel is dominant material that used for the support structure, nacelle and hub of turbines in the manufacturing of tidal stream turbines. Steel is also used for the gravity base structure of OpenHydro and composite materials are used for the blades. Therefore, cathodic protection is often used as sacrificial anode, for example zinc or aluminium when general corrosion occurs. The use of cathodic protection on the OpenHydro can be seen highlighted in Figure 9. The 54.6 m tall monopole used to support the SeaGen turbine was also partially aluminium cathode protected [47].

The author also documented initial corrosion that occurred in vertical axis marine current turbine. This marine current turbine developed in Indonesian by Hydrodynamic Laboratory-Surabaya (Figure 10). This marine current turbine structure material is steel and the turbine blade material is aluminium.
The longest continuous device deployment, the SeaFlow tidal turbine, was commissioned at Lynmouth, Devon, in 2003. Its rotor blades are made of carbon/glass epoxy composite and are protected by antifouling paint. The structure material is steel grade, and it also uses painting system plus impressed current and sacrificial anodes for corrosion protection. After 3 years of operation in the sea, there are little signs of corrosion or marine growth. The photograph on the right of Fig. 12 was taken showing Seaflow turbine support structure raised out of the water. It is shown that there are little signs of corrosion or marine growth after 3 years of operation in the sea. Marine Current Turbines Ltd installed the world’s first offshore tidal turbine prototype in 2003 near Lynmouth, United Kingdom, called SeaFlow. The rotor blades are made of carbon/glass epoxy composite and are protected by antifouling paint. The structure material is steel grade and it also uses painting system plus impressed current and sacrificial anodes as corrosion protection.

3.3 Corrosion in Wave Energy

The industrial company, Kvaerner Brug, built a 500 kW cliff-mounted unit, oscillating water column’s wave energy type, in 1985 near Bergen. This unit was destroyed during storms in 1988. It has been reported that the failure was a consequence of corrosion fatigue in the bolts holding the device to the cliff. Until today, the corrosion experiences of wave energy devices, and ocean energy generally, that have been documented are still limited. Many of wave energy devices rely on cathodic protection system, and it is fully effective against this type of trouble.

The La Rance tidal power plant is located in the Rance Estuary, near Saint Malo in North-West France and was commissioned at various stages between August 1966 and December 1967. After ten years of experience, mechanical trouble emerged. Some metal components: stainless-steel runner blades of some turbines, steel gate components and ducting, were found to have suffered very rapid corrosion, mostly by sea water. Soon, it has been repaired by cathodic protection system, and it is fully effective against this type of trouble.

4.0 CHALLENGES IN MARINE RENEWABLE ENERGY AGAINST CORROSION

When the marine renewable energy device is affected by the environment, it becomes necessary to protect it against detrimental action of corrosion. Marine renewable energy devices need to be adequately protected from corrosion threats. It is important to find out a proper corrosion protection system for various specific environmental conditions. Many standards for corrosion protection systems for offshore wind turbine are available, but a comprehensive standard for corrosion protection systems for ocean energy is still limited.

The design of marine renewable energy devices are required to contain a certain corrosion allowance, for corrosion wastage together with corrosion protection and repair method. The value of the corrosion addition varies depending on device type and the structural location. Specifications for a corrosion protection system for offshore wind power constructions should address the following demands:

- high corrosive stress due to elevated salt concentration in both water and air;
- high corrosive stress due to fluctuating dry-wet cycles due to wave and water spray actions;
- mechanical loads due to ice drift or floating objects;
- biological stresses, namely underwater;
- notable variations in temperature of both water and air;
- long and irregular inspection intervals because of reduced accessibility; and
- high maintenance and repair costs in coating failure.

The most common method used for the protection of materials in offshore environments is the use of various types of coatings, and for the immersion zone, coatings combined with cathodic protection. Coatings are one of the most effective ways to protect a metallic structure against corrosion by applying a physical layer, such as an organic, inorganic or conversion coating. Application of coatings is the most suitable method to protect the metallic surfaces. Cathodic protection is the other type of corrosion protection and the main technique for preventing corrosion on external surfaces of carbon steel parts in the offshore submerged zone structures. The combination of cathodic protection and corrosion resistant alloys may be a convenient solution.
corrosion protection is not considered to be in a satisfactory condition. A comprehensive standard for corrosion protection systems is required to study and provide for the application of marine renewable energy devices, especially for ocean energy, to achieve a target life of service.

5.0 CONCLUSION

Marine renewable energy has undergone rapid growth and progress in both industry and academia development during this last decade. However, corrosion cannot be avoided because of marine renewable energy devices are exposed to aggressive marine and offshore environment. This exposure will give rise to very fast corrosion and damaged areas. So, the marine renewable energy devices need to be protected against the detrimental action of corrosion by the use of corrosion protection such as protective coatings and cathodic protection. A comprehensive standard for corrosion protection systems is further needed to study and provide for the application of marine renewable energy to achieve a target life of many years in service.

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