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Offshore Wind Turbine Life-Cycle-Cost Evaluation in Taiwan Under Impacts of Maintenance and Harsh Weather Conditions

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Abstract. Advances in technology have promoted offshore wind energy being one of the most promising renewable energy sources. Offshore wind farms are usually positioned in an opened space far away from the seashore where the wind is strong enough to generate electricity effectively and reliably. However, due to location characteristic hard–to–reach, the operation and maintenance cost of the offshore wind farms are high and the economic evaluation is uncertain. A huge number of researches about offshore wind energy have emerged recently in response to these issues. However, the researches considering the effects of various influential parameters to access the reliability of offshore wind turbine remain small and still limited, especially the parameters related to the dynamic weather conditions such as real-time utilization under typhoon and flood impacts. This paper proposes an approach to analyze the life–cycle–cost of the offshore wind turbines under maintenance scenarios and environmental influences, with the support of probabilities distribution method. The electricity generated by the offshore wind turbine is calculated based on the real weather conditions collected in a variety of locations throughout Taiwan such that the proposed life–cycle–cost model is more reliable and accurate than the conventional approaches. The results show that Typhoon and Maintenance cost occur 4.2% and 19.6% respectively. Moreover, offshore wind energy is an excellent environmental solution with high economic benefit on sites where the wind resource is abundant.

Keywords. Offshore wind energy, Life–cycle–cost, Cost estimation, Economic analysis, Maintenance, Harsh weather condition

Introduction

As an inexhaustible and free energy source, offshore wind energy has become a potential alternative for many countries to overcome the negative impacts on the environment of fossil fuels. Energy generated from offshore wind is rapidly emerging as one of the most important clean and renewable sources in the world. Despite the

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enormous wind sources, the installation capacity of offshore wind energy still remains a small portion. One of the key factors for this limitation is offshore wind system usually positioned far off coastline, causing high investment and risks, technological and logistical challenges. Moreover, while the technical feasibility of wind energy system may be visible in the technical documents and in most studies of wind energy [1-5], its economic evaluation under the real weather condition, maintenance, is limited.

Due to lack of indigenous conventional energy resources, development of wind energy has become an important issue for Taiwan's future energy supply. Based on outstanding benefits of the potential wind capacity and Taiwan's geographical location, offshore wind energy is regarded as one of the most attractive renewable energy to be developed. Recently, a huge number of studies of wind energy have been proposed. For instance, a list of 70 life cycle assessment research publications on wind energy was reviewed by [6]. Nevertheless, only 3% of them consider the "Business management: planning, financial, and administrative requirement", in which it is a few number of studies considering impacts of various influential parameters such as the practical weather conditions (typhoon and flood), and providing accurate and reliable economic evaluation based on those practical data. Therefore, the need for a accurate economic evaluation of the offshore wind system under consideration to the impacts of the real weather condition (including harsh weather condition such as typhoon and flood), the maintenance period and maintenance cost, is required.

In this paper, an approach to access the life–cycle–cost of the offshore wind turbine under the impacts of various influential parameters is proposed. The influential parameters are impacted by the maintenance cost during maintenance period (including labor cost, cost of power lost, transportation and replaced equipment cost), the real weather conditions (including harsh condition such as typhoon and flood). The variety of locations over Taiwan is taken into account to calculate the generated electricity according to the local weather condition in each location. In order to estimate the failure rate of each component of the offshore wind turbine system for maintenance, Weibull probability distribution is used in this paper.

1. Methodology

1.1. Offshore wind system life–cycle–cost overview

The framework addresses a life cycle cost (L_C) estimation process is shown in Fig. 1. As shown in Fig. 1, the L_C is the total cost of a wind turbine system during its lifetime including the capital cost; maintenance cost (preventive maintenance cost and corrective maintenance cost) and assembles cost against the harsh weather conditions. According to [7], the portion of the maintenance cost is 18% to 30% of the total L_C and the corrective maintenance cost is 30% to 60% of the total maintenance cost [8]. Besides the direct costs (to fix the failed components), the costs of production loss (generated electricity) due to inactiveness of the wind turbine also contribute considerably to the maintenance cost. Wind turbine is a combination of a number of critical components, and the electricity is generated only if all of these critical components are functional. Therefore, when a failure occurs for any critical component of the wind turbine, the entire wind turbine system has to be stopped for a certain period of time until the failed critical component is totally repaired. This period causes a loss of production (generated electricity) that must be considered in the life–cycle–cost analysis through the cost of production losses. Consequently, the L_C analysis method in this paper considers the real utilization time of the offshore wind system and the real electricity generated due to the harsh weather conditions and maintenance occasion.

In order to match the proposed approach to Taiwan, the weather conditions on a variety of locations throughout Taiwan, including majority of cities and counties are collected to calculate the real electricity generated in Taiwan.

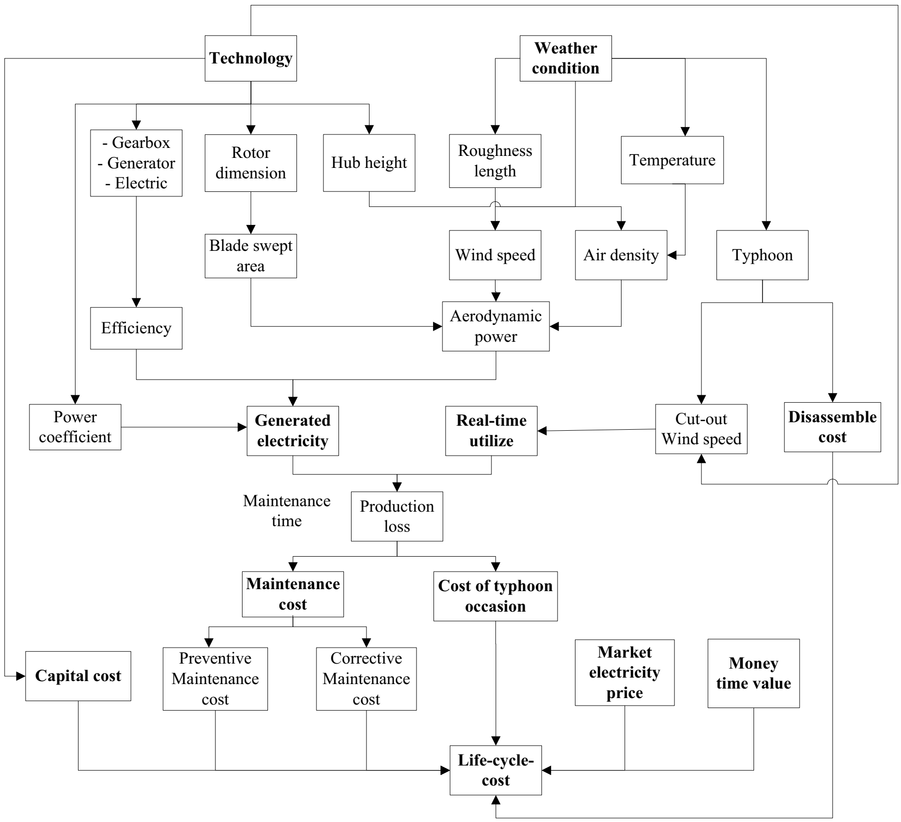

Figure 1. Life–cycle–cost estimation framework

1.2. Offshore wind system life–cycle–cost overview

1.2.1. Generated Electricity

As aforementioned, the production loss when a failure occurs for any critical component of the offshore wind turbine must be considered in the life–cycle–cost analysis through the cost of production losses. Moreover, to access the offshore wind system in a reliable and accurate manner, the economic analysis requires the generated electricity which is actually influenced by the environmental and weather conditions. The real generated electricity is typically significantly different from the theoretical generated electricity due to the impacts of environmental factors [9]. The method for computing the generated electricity in this paper carefully considers technical parameters and the influences of environmental conditions in variety of locations throughout Taiwan (12 cities and counties), so that the generated electricity estimates are more accurate and feasible for Taiwan. The nomenclature used hereafter is clearly illustrated in table 1.

The effective generated electricity (P_{op}) from a wind turbine to feed into grid is a function of the aerodynamic power (P_{pw}), under the efficiency of the gearbox (η_1), generator (η_2), electric (η_3) and the turbine power coefficient (C_P), is derived by equation (1).

$$P_{op} = C_p \eta_1 \eta_2 \eta_3 P_{pw} \tag{1}$$

in which the aerodynamic power (P_{pw}) of an air mass that flows at speed (v) through an area (A) of wind turbine generator can be calculated as follows:

$$P_{pw} = \frac{1}{2} v_h^{\,3} A \rho = \frac{1}{2} v_h^{\,3} \pi R(R+2r) \frac{\varphi}{GT}^{\frac{-gh}{GT}} \tag{2}$$

The blade swept area $A \approx \pi R^2$ when R >> 2r due to doubling the length of wind blades, the swept area can be increased by the factor up to 4.

Due to the increase in wind speed with altitude, evaluating for the effects of wind speed requires knowing the wind turbine hub height (h), and an approximation of surface roughness conditions (z_0). The surface roughness (z_0) of the sea is low compared to land surfaces. This is the main reason for the high wind speed of offshore wind turbines [10].

Therefore, the effective generated electricity from a wind turbine to feed into a grid is given by:

$$P_{op} = \frac{1}{2} C_p \eta_1 \eta_2 \eta_3 \left(v_{ref} \times \frac{\ln \frac{h}{z_0}}{\ln \frac{h_{ref}}{z_0}} \right)^3 \pi R(R+2r) \frac{\varphi}{GT}^{\frac{-gh}{GT}} \tag{3}$$

C_p represents the power conversion efficiency of a wind turbine and C_p is a function of the tip speed ratio, as well as the blade pitch angle in a pitch controlled wind turbine [8]. According to [9, 12], the theoretical maximum power coefficient reaches its maximum value of 0.593, a value determined by a fluid mechanics constraint known as the Betz limit. Hence, even if power extraction without any losses were possible, only 59% of the wind power could be utilized by a wind turbine.

The practical generated electricity of the offshore wind system could be calculated using the equation (3), wherein the wind speed (v_{ref}) is the wind speed at 10 meters above the sea level. In this paper, the wind speed data and weather conditions are collected from 12 different locations throughout Taiwan (12 different cities and counties), and the maintenance period and the types of maintenance are decided by the Weibull probability distribution. As such, the generated electricity in this paper is considered as the practical generated electricity of the offshore wind system in Taiwan.

Table 1. Nomenclature used in this paper.

	Power generation		Economic evaluation
P_{op}	The output power (W)	L_c	The Life – cycle – cost
C_P	The turbine power coefficient (%)	C_s	The capital cost
η_1	Gearbox efficiency	C_i^{cm}	Corrective maintenance cost in year i
η_2	Generator efficiency	C_i^{pm}	Preventive maintenance cost in year i
η_3	Electric efficiency	C_i^{as}	Disassemble cost if typhoon occur in year i
P_{pw}	The aerodynamic power of wind turbine generator (*W*)	$C_i^{P_T}$	Power loss cost if typhoon occur in year i
ρ	Air density (*kg/m*^{3})	C_i^L	Labor cost if a maintenance task is done
φ	Local air pressure (101325 Pa)	C_r^k	Replaced equipment cost of component *k*
R	Length of wind blades (*m*)	C_i^{trans}	Transportation cost (*$/km*)
r	Radius of the hub (*m*)	D	Distance to wind farm from seashore *(km)*
v_h	Wind speed at the height *h* (*m/s*)	P_i^e	Market electricity price in the year i (*$/kWh*)
v_{ref}	Wind speed at reference height *(m/s)*	τ_m	Time of a maintenance occasion (*hour*)
T	Local air temperature (*K*)	τ_T	Time of a typhoon occasion (*hour*)
G	Gas constant for air (287.05 J/kg-K)	τ_{as}	Time of a assemble occasion (*hour*)
z_0	Roughness length in the current wind direction (0.0001m with water surface)	β	The discount factor ($\beta = 1/(1+r_i)$ where r_i is the interest rate)
g	Gravity constant (9.81 *m/s*^{2})	h	Altitude above sea level (*m*)

1.2.2. The impact of typhoon to offshore wind system

With geographical characteristic located in North Pacific Ocean typhoon – prone area, every year an average of 3 to 4 typhoons pass through Taiwan. According to Taiwan Center Weather Bureau' statistics, there were 405 typhoons that hit Taiwan in the period from 1897 to 2014. The typhoon damages to offshore wind turbine and reduces system reliability. For instance, on September 28th 2008, typhoon Jangmi struck Taiwan with strong wind that brought down a large-scale wind turbine tower located in the Taichung harbor area. Typhoon Soudelor has hit Taiwan with damaging wind and caused damage worth an estimated NT$560 million (US$17.67 million) to eight wind turbines operated by Taiwan Power Company in 2015 [13]. Frequent typhoon raise great risks and obstacles to the development of offshore wind system, and increase life-cycle-cost of offshore wind turbine. This paper proposes a method to evaluate life cycle cost under the risks of typhoon on offshore wind system in Taiwan.

For offshore wind turbine, the mechanical brake would stop the turbine from rotating when the wind is too strong (above the cut out speed of 25 m/s). In general, once a typhoon occurs, there will be a high risk of grid failure, since it is not possible to adjust or stop the turbine and over-speed wind can damage the mechanical and electrical components. In more severe conditions, extreme high loads would cause the collapse of the turbine or breaking blade might hit and induce its tower to collapse.

It is supposed that wind turbine can withstand typhoon when wind speed in typhoon are lower than the cut out speed of turbine (Usually 25 m/s). The damage ratios of turbine become 100% when extreme wind speeds of typhoon reach the upper bound wind speed that is turbine could stand (α) (usually 75 m/s). When this situation occurs, disassembling the system is required to reduce the damage induced by typhoon. If wind speed is in interval between the turbine's cut out wind speed and the upper bound wind speeds (α), mechanical brake would stop the turbine from rotating without the need for disassembling the wind turbine. Therefore there is no cost for disassembling the wind turbine, however in this period the cost of production loss should be added in life cycle cost of the system.

1.3. Life–cycle–cost model formulation

a. Maintenance cost

Maintenance is desired component performance by maintaining or returning the component's ability to correctly function [14]. The maintenance cost includes corrective maintenance cost (C_i^{cm}) and preventive maintenance cost (C_i^{pm}).

Let *F(i)* denotes the probability that a component fails in the year i with the failure rate function following the Weibull distribution.

$$\mathrm{F(i)} = \frac{\varepsilon}{\sigma}\left(\frac{i}{\sigma}\right)^{\varepsilon-1} e^{-\left(\frac{i}{\sigma}\right)^{\varepsilon}} \tag{4}$$

where ε is the scale parameter and σ is the shape parameter. When $\varepsilon = 1$ the failure rate is constant and the Weibull distribution is equal to the exponential distribution. Because the failure rate of offshore wind turbine increased with time as ageing component, the scale parameter will greater than 1 ($\varepsilon > 1$).

Let [ψ, γ] denote for lower bound and upper bound of the failure interval. Call x_i^k and y_i^k are the binary variables denoted for the corrective occasion and the preventive occasion performed at year i. And χ_i denotes for the binary variables whether maintenance occasion is performed in year i.

$$x_i^k = \begin{cases} 1 & \mathit{If}\ \ F(\mathrm{i}) > \gamma \\ 0 & \mathit{Otherwise} \end{cases} \tag{5}$$

$$y_i^k = \begin{cases} 1 & \mathit{If}\ \ \psi \le F(\mathrm{i}) \le \gamma \\ 0 & \mathit{Otherwise} \end{cases} \tag{6}$$

$$\chi_i = \begin{cases} 1 & \mathit{If}\ \ \sum (x_i^k + y_i^k) \ne 0 \\ 0 & \mathit{Otherwise} \end{cases} \tag{7}$$

Maintenance is performed if any of the preventive maintenance or corrective maintenance task is performed. The component k will received corrective maintenance at the year i if $F(i) > \gamma$. The component k will received preventive maintenance at the year i if $\psi < F(i) < \gamma$. And no maintenance occurs when $F(i) < \psi$.

Consequently, the maintenance cost in year i (C_i^m) is derived as follow:

$$C_i^m = \left(\sum_{j=1}^{k} x_i^k c_r^k + \sum_{j=1}^{k} y_i^k c_r^k \right) + \chi_i \left(C_i^L + D \times C_i^{trans} + P_{op} \tau_m P_i^e \right) \tag{8}$$

b. The costs occur in a typhoon occasion

As aforementioned, when the typhoon occurs with the wind speed greater than the upper bound wind speed (α), disassembling the wind turbine system is required to reduce the damage induced by typhoon. As a result, the cost for disassembling the wind turbine and the cost of production loss due to inactiveness of the wind turbine are added to calculate the life cycle cost. Otherwise, if the wind speed of the typhoon is in interval between the turbine's cut out wind speed and the upper bound wind speed (α), the mechanical brake would stop the turbine from rotating without the need for disassembling the wind turbine. Consequently there is no cost for disassembling the wind turbine, however in this period the cost of production loss should be added in life cycle cost of the system.

Let $[W_L, W_B]$ respectively denote the cut-in wind speed and cut-out wind speed. It is noted that the wind turbine is normally operated when the wind speed is greater than the cut-in wind speed and lower than the cut-out wind speed. A typhoon occurs when wind speed is greater than the cut-out speed (w_i): $w_i > W_B$. Call α is the upper bound wind speed which is the maximum wind speeds allowing the wind turbine withstands without damage. Thus, the cost for disassembling the wind turbine is occurred only when wind speed (w_i) is greater than the upper bound wind speed ($w_i > \alpha > W_B$). Call s_i and z_i are the binary variables denoting whether the disassembling operation and the production loss occurred in typhoon occasion at year i.

$$s_i = \begin{cases} 1 & If \quad w_i > W_B \\ 0 & Otherwise \end{cases} \tag{9}$$

$$z_i = \begin{cases} 1 & If \quad w_i > \alpha \\ 0 & Otherwise \end{cases} \tag{10}$$

Consequently, the costs occur in a typhoon occasion is derived as follow:

$$C_i^T = s_i P_{op} \tau_T P_i^e + z_i \left(C_i^L + D \times C_i^{trans} + P_{op} \tau_{as} P_i^e \right) \tag{11}$$

c. Life cycle cost model

The Life–cycle–cost of an offshore wind system is the total cost during its lifetime including the capital cost, maintenance cost (preventive maintenance cost and corrective maintenance cost) and disassembling cost against the harsh weather conditions, in which the annual maintenance cost during the life cycle of the wind turbine is not always the same due to the variation of time value of money. Therefore, it's necessary to discount the maintenance cost of every year to current time point with discount rate (β) such that calculated life-cycle-cost is accurate and reliable. The life–cycle–cost model formulation is derived by equations (12) and (13) below.

$$L_c = C_s + \sum_{i=1}^{n} (C_{cm}^i + C_{pm}^i + C_{P_T}^i + C_{as}^i) \beta^i \tag{12}$$

$$L_c = C_s + \sum_{i=1}^{n} \left[\begin{array}{l} \left(\sum_{j=1}^{k} x_i^k c_r^k + \sum_{j=1}^{k} y_i^k c_r^k \right) + \chi_i \left(C_i^L + D \times C_i^{trans} + P_{op} \tau_m P_i^e \right) \\ + s_i P_{op} \tau_T P_i^e + z_i \left(C_i^L + D \times C_i^{trans} + P_{op} \tau_{as} P_i^e \right) \end{array} \right] \times \beta^i \tag{13}$$

where the nomenclature used in the equations (12) and (13) are illustrated in table 1.

2. Results and discussion

The proposed approach calculates the life–cycle–cost for an offshore wind system with 50 turbines located in 12 different locations in Taiwan, each of the turbines has 4 critical components including rotor, bearing, gearbox and genarator. The daily climate data used for this study is collected from 2003-2015 and mainly collected from "Taiwan Central Weather Bureau".

In this paper, the Vesta V82 wind turbine is used for calculation. According to (15), Vesta contributes the highest percentage in the worldwide turbines manufactures with 34%. Further, V82 has been installed by many countries due to its highly efficient operation and flexible configuration. The parameters of a typical V82 are provided in table 2 by the manufacturer.

Table 2. Parameters of Vesta V82 offshore wind turbines.

Items	Parameters
Diameter	82 m
Swept Area	5281 m2
Tower height	78 m
Rated Power	1.65 KW
Cut-in wind speed	3-5 m/s
Cut-out wind speed	25 m/s
Nominal wind speed	12 m/s

Using the collected climate data and equations (1–3), the monthly averaged values of the wind speed, the temperature, the air pressure, and the power generation of offshore wind system which located in 8km distance from shore, are calculated and shown in Figure 2.

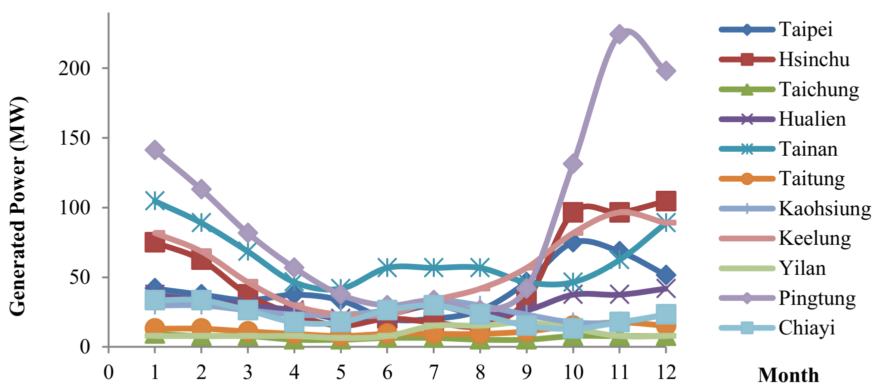

Figure 2. Generated power at each location monthly.

The results show that wind speed has the most impact to the offshore wind system. Due to the difference of wind speed at different locations, the generated power departs significantly among the investigated locations. For instance, Penghu has the highest wind speed with 8.5m/s in average and with maximum up to 11m/s. Accordingly, the average power generated is also the highest with 1254 MW. By contrast, Taichung has the lowest wind speed and the power generated is also lowest with the average of 7MW.

This paper proposes an approach to analysis real time utilization of the offshore system during life cycle time. As shown in figure 3, each year offshore wind turbine activates with 83% time, and deactivates 17%, in which 3.2% due to typhoon, 2.3% due to extreme wind speed and 10.5% due to deactivated components.

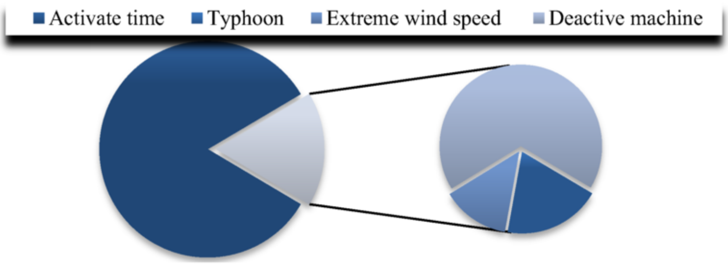

Figure 3. Real time utilization of offshore wind turbine.

According to Taiwan Center Weather Bureau, Taiwan has average of 6 typhoons annually and a severe typhoon in each three years; bring out many damages for offshore wind turbines. The results of the proposed approach show that life cycle cost of the wind turbine increases 4.5% by the damage of the typhoon (shown in Figure 4).

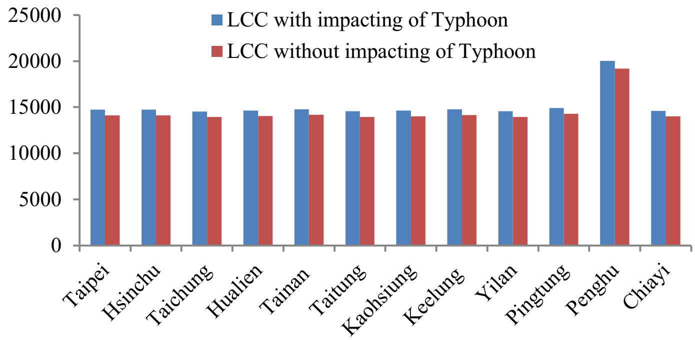

Figure 4. Offshore wind turbine life–cycle–cost with and without impacting of typhoon.

Although Penghu has the highest life cycle cost, the benefit of the offshore wind system in this place is the highest due to the highest power generation.

As shown in figure 5, in the life cycle time, an offshore wind turbine system needs to pay 19.6% for maintenance cost, 6.1% for operation cost, and 4.2% for typhoon occurred cost.

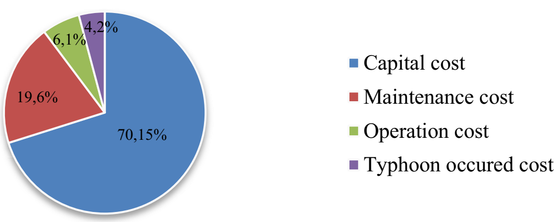

Figure 5. Life–cycle–cost components of offshore wind turbine.

3. Conclusions

While natural resources are limited and environmental problems are becoming more seriously the offshore wind energy with its advances is considered as one of the best solution for future energy needs. In order to confirm the benefit of the offshore wind system, this paper proposes a new approach to analysis life–cycle–cost of the offshore wind system under the influences of maintenance and typhoon.

Besides examining the aspect of harsh weather conditions, this paper also considers other aspects in maintenance cost such as different failure modes of the components and time of maintenance action to estimate production loss. All these factors render critical implications in the actual offshore wind system life cycle cost.

The case study of 12 locations in Taiwan shows that the life–cycle–cost is considerably lower when the impacts of typhoon are not considered. However, it is lack of accuracy and reliability when such an important weather condition as typhoon is not considered in calculating the life cycle cost of the offshore wind system. The results also show that offshore wind energy is an excellent environmental solution with high economic benefit on sites where the wind resource is abundant.

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