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Concept Design of Floating Wind Platforms of Y-Wind and T-Wind for South East Offshore of Korea

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1. Introduction

Offshore winds are one of the most abundant resources of renewable energy so that many countries including Europe and USA are moving toward the offshore from the land to get benefit of improved power production due to better wind quality and higher capacity factors, although there are technical and cost challenges. Most of the existing wind farms are located at a shallow water depth and use fixed foundations. An alternative solution to remove the depth limit of fixed foundations is a floating foundation (platform) which can be kept in place in deep water with various station keeping systems, for instance, catenary mooring or tendon mooring, depending on the floating foundation type.

According to the weather resource map, Korean offshore has a great potential for wind energy in especially South-East (SE) and Jeju Island offshores(1-2). As deeper or farther offshore locations provide better wind quality, floating wind platforms would be a good option for those locations. Although there are many technical and cost challenges in the floating platforms, Korea has a long vision to develop a deep-water floating wind farm based on the "Renewable Energy 3020 Plan", to meet the future energy demands.

The floating platform technologies including mooring have been well proved in the oil and gas sectors. Thus, only system integration technologies of the turbine to platform would be a technical gap to be resolved. Most challenging work would be cost reduction of each component of the platform to lead to a commercially viable level without sacrificing the platform integrity.

Although the floating options are more expensive than the fixed ones, there are many advantages to overcome, for instance, more power production with a higher capacity factor, minimal social issues with fishing industries, higher space utility, no sight line objections, etc.

Technology and cost can differ by floating types of spar, Semi, TLP and barge. However, in Korea there are no sheltered offshore areas with a water depth of a minimum of 100 m to integrate the turbine on the spar type wind platform and there is no large floating crane vessel available for lifting and installing the turbine to the platform offshore. As such, the spar type platform was opted out in the screening. As a result, semi and TLP type platforms were selected for the present work.

Series of Y-Wind semi and T-Wind TLP type platforms to support wind turbines of 3 to 8 MW, have been developed by author's team. Among them, a 5 MW wind turbine rather than a bigger turbine is selected for Korea wind farm, considering the technical maturity of turbines available within Korea. Details of 5 MW Y-Wind semi platform targeting for US offshore can be found in prior publications(3-5).

Wind farm site considered is located at about 50 km SE offshore from the Gori nuclear plant and Ulsan Port, which enables to use the existing grid. Actual water depth of the proposed site in the bathymetry map is about 150 m, but for a conservative design in terms of platform design and cost, a water depth of 200 m is considered.

Y-Wind semi platform for Korean offshore has been modified from the existing Y-Wind for US offshore(3-5). The T-Wind TLP type platform has been designed specifically for Korean offshore application, to accommodate the high variation of the water level induced by tide and storm surge and also avoid the complex operation risk during the platform tow and installation. With these pre-set design considerations, T-Wind platform is designed to integrate the wind turbine quayside on its hull. The T-Wind with turbine has a shallow light draft and sufficient hydrostatic stability so that local towing vessels readily available in Korea can be used for towing and installation of the platform, instead of using expensive dedicated vessel rented from abroad. This operation can reduce the overall platform CAPEX at the end. Similar features are used for Y-Wind described in

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the prior publications.

The Y-Wind and T-Wind platforms were compared to identify the technical and cost features for SE Korea offshore application. Design of the platforms were validated with relevant design standards of ABS and API, for the various design conditions of operating, extreme and survival sea states of SE Korean offshore environments. CAPEX costs of the platforms installed were estimated, based on a 200 MW wind farm with 40 units of 5 MW turbine.

2. Basis of Design

2.1 Site and Metocean Condition

Floating wind platform of Y-Wind or T-Wind with 5 MW turbine is considered installed about 50 km offshore from the Gori nuclear plant and Ulsan City of Korea as depicted in Fig. 1.

Site wind and wave data are not known at this time so that the weather buoy (129.5E, 35.0N) data located at about 50 km SE of Gori nuclear plant presented in Fig. 1 was considered. A total of 38-yr measured data from the buoy is used. Winds and waves for the operating, 50-yr extreme and 100-yr survival conditions are estimated, using VLO software "*Weather Data Analysis*"[6] and the buoy data. The surface currents, tide and storm surges are obtained from the public data near the site. Metocean conditions for the present work are summarized in Table 1. Here HSWL and LSWL are determined with tidal elevation plus storm surge.

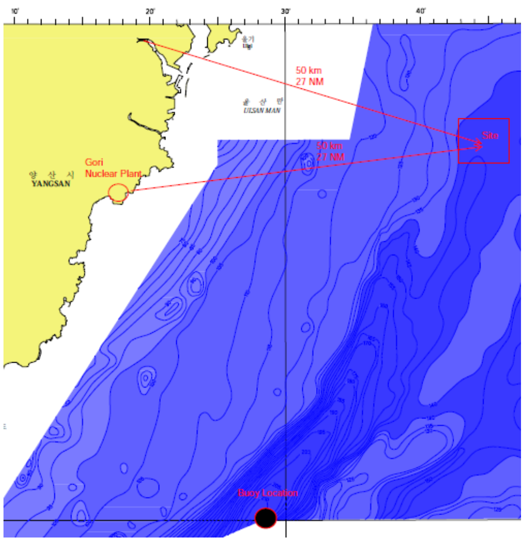

Fig. 1 Floating wind farm site and weather buoy location

Table 1. Metocean condition

Platform Condition	Operating		Extreme	Survival
DLCs (ABS)	1.3	1.6	6.1	SLC
Turbine Condition	Prod.	Prod.	Parked	Parked
Environ. Condition	Vr	Vo	50-yr	100-yr
Wind 10min@hub (m/s)	11.4	25.0	39.3	41.1
Wave Hs (m)	3.61	5.62	6.68	7.13
Tp (s)	8.68	7.94	10.14	10.40
Gamma	1.0	2.2	3.0	3.0
Current (m/s)	1.4	1.4	1.6	1.7
HSWL(+), LSWL(-)	±0.38	±0.38	±0.77	±0.77

The Design Load Cases (DLCs) in Table 1 are based on ABS Guide[7]. The operating condition is for the case that the turbine is in power production from cut-in to cut-out wind speeds, while the turbine will be parked or idle under the 50-yr extreme and 100-yr survival conditions.

2.2 Design Criteria

The offshore floating wind turbine platform moored at a water depth of 200 m is designed to produce the power of 5 MW for a service life of 20 years under the metocean conditions in Table 1. Floating offshore wind turbine platform design requirements specified in ABS[7-10] and API[11-12] are summarized in Tables 2-6. Y-Wind mooring line and suction pile design Factors of Safety (FoS) are based the non-redundant condition whereas the T-Wind tendon and driven pile FoS are for the redundant conditions. The bias factors (or *B*-factors) to determine the FoS in Table 6 were obtained with modifying the recommended values in API[12]. The platform mean heel angle target is given for turbine performance. Also the platform dynamic heel angle of 10 degrees and nacelle acceleration of 0.4g (3.92 m/s^2) are selected according to the oil and gas offshore platform design practices and floating wind turbine design.

Table 2. Floating wind platform design criteria

Load Condition	Mean Heel (deg)	Dyn. Heel (deg)	Accel. (g)	Air Gap (m)
Operating	$\leq$ 4.0	$\leq$ 10	$\leq$ 0.4	-
Extreme		-	-	$\geq$ 1.5
Survival		-	-	$\geq$ 0.0

Table 3. FoS for Y-Wind catenary mooring design

Load Condition	Line Condition	FoS
Extreme	Intact	2.0
Survival	Intact	1.05

Note: FoS for non-redundant mooring case

Table 4. FoS for T-Wind tendon design

Load Condition	Line Condition	FoS
Extreme	Intact	1.67
	One Line Damage	1.25
Survival	Intact	1.05

Table 5. FoS for Y-Wind suction pile design

Load Condition	Line Condition	Axial FoS	Lateral FoS
Extreme	Intact	2.4	1.92
	Damage	1.8	1.44
Survival	Intact	1.05	1.05

Note: FoS for non-redundant mooring case

Table 6. FoS for T-Wind driven pile design

Load Condition	API Safety Category	Tendon Condition	FoS
Operating	A	Intact	2.4
Extreme	B	Intact	2.25
Survival	S	Intact	1.5
Survival	S	One Tendon Removed	1.5

2.3 5MW Wind Turbine

The NREL 5MW reference wind turbine[13] summarized in Table 7 is considered. The tower base and hub are located at 10 m and 90 m above SWL respectively.

Table 7. Wind turbine data

Power Rate	MW	5
Rotor Diameter	m	126
Number of Blades	ea	3
Tower Height	m	77.6
Tower Diameter Top / Base	m	3.87 / 6.5
Cut-in V_{in} / Rated V_r / Cut-out V_{out}	m/s	3.0 / 11.4 /25.0
RNA Weight	ton	350
Tower Weight	ton	250

3. Y-Wind and T-Wind Platforms

The Y-Wind semi type and T-Wind TLP type wind turbine platforms are designed to support the 5MW wind turbine on the top of the center column. The platforms consist of three outboard columns and one center column. The outboard columns are connected to the center column with corresponding rectangular pontoon. The platforms have no decks and braces which can facilitate the efficient construction of the hull and remove the potential risk to the deck structure slamming induced by the storm loads.

Proper lightship draft of Y-Wind and T-Wind platforms was taken into account to enable the integration of the tower and rotor assembly at quayside and wet-tow out to site with no expensive and dedicated vessel. To achieve this goal, the pontoon and column sizes were determined with iterative manner. Also at the concept design stage, a heel angle of the Y-Wind or T-Wind platform due to the peak rotor thrust at the rated wind speed was considered such that platform mean heel angle during the turbine operation is maintained below 4 degrees. In addition, it was considered if the platforms have a sufficient positive metacentric height specifically in wet-tow condition. In order to improve the motion performances of Y-Wind, Motion Attenuation Structure (MAS) were introduced. All these design parameters were implemented to the VLO's in-house platform sizing program to design the Y-Wind and T-Wind platforms.

The Y-Wind and T-Wind platform particulars are summarized in Table 8. Fig. 2 depicts the Y-Wind platform where the MAS is not shown. The T-Wind has similar shape with Y-Wind but T-Wind has no MAS.

The total weight of the platform for the in-place conditions was estimated considering the hull structure, appurtenances including anodes, marine growth, ballast, turbines and marine system, where an appropriate contingency was applied based on the past experiences of the oil and gas platform design.

Table 8. Y-Wind and T-Wind particulars

Items		Y-Wind	T-Wind
Displacement	ton	7,770	5,321
Draft – Design	m	18.0	17.0
Offset Column Center R.	m	35.0	27.0
Column OD	m	10.5	9.0
Outer Column Height	m	29.5	28.5
Center Column Height	m	28.0	27.0
Pontoon Width, Height	m	4.5, 4.0	4.0, 4.0
Hub Height above SWL	m	90.0	90.0
Number of Mooring Lines	-	3	6

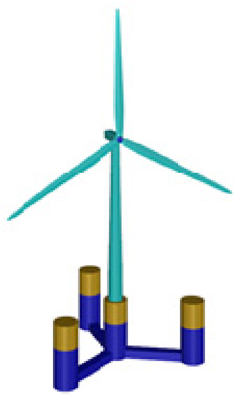

Fig. 2 Y-Wind platform (MAS omitted)

4. Mooring Configurations

The Y-Wind and T-Wind platforms are moored with a total of three catenary chain lines and six wire tendons at a water depth of 200m respectively. Table 9 summarizes the mooring line and tendon properties. One end of each mooring line or tenon is connected to a fairlead or tendon top connector located near the keel of the outboard column and the other end is connected to an anchor foundation. Figs. 3 and 4 present the layouts of the catenary mooring of the Y-Wind and tendon mooring of T-Wind.

Table 9. Y-Wind and T-Wind mooring properties

Items	Unit	Y-Wind	T-Wind
# of Lines	-	3	6
Length	m	800	183
Material	-	Chain Studless R3	Wire Spiral Strand
OD	mm	100	131
Weight in air	kg/m	200	89.3
MBL	kN	8,028	16,775

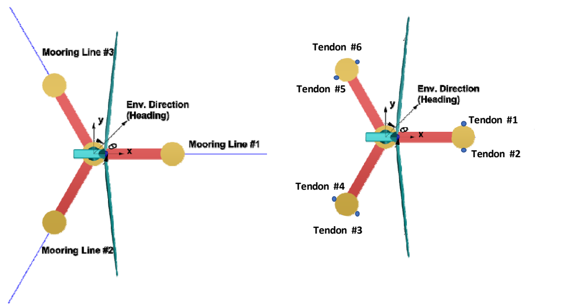

Fig. 3 Y-Wind catenary and T-Wind tendon mooring layout

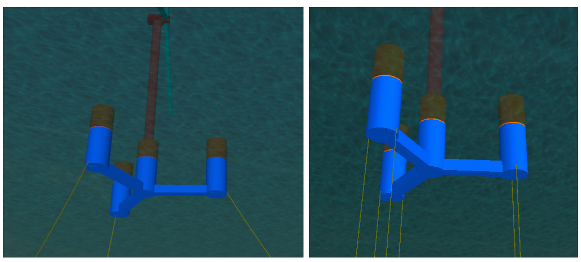

Fig. 4 Y-Wind and T-Wind mooring layout (3-D view)

5. Numerical Modeling

A time domain analysis was conducted to evaluate the responses of the platforms. The present time-domain run was based on a semi-coupled analysis in ABS[9], where the aero-elastic couplings are neglected. The tower and nacelle were modeled as part of the rigid body of the hull. The time varying rotor thrusts as a function of wind speed were input to the tower top for the power production cases every time step. Fully coupled analysis of Y-Wind can be found in reference[5].

Wind forces on the hull above the SWL and wind turbine tower were estimated based on ABS FPI[10] and input to the numerical model in terms of wind coefficients. The current loads on the platform and the mooring lines were represented in the model with the drag coefficients. Hull viscous damping was also presented in the model with the viscous drags, which can be found in references[3-4].

The forgoing numerical analysis was carried out for an environment heading of 180 deg which can cause dominant surge and pitch of the platform, and maximum tension on #1 mooring line of the Y-Wind or #1 and #2 lines of the T-Wind. Wind, wave and currents considered are co-directional.

6. Y-Wind and T-Wind Design Analysis

6.1 Platform Natural Periods

Natural priods of the Y-Wind and T-Wind platrom, determined from the free decay tests, are compared in Table 10. It is seen that heave, roll and pitch of the T-Wind is much lower than the Y-wind values due to very high axial stiffness and moment induced by the tendons.

Table 10. Natural periods of Y-Wind and T-Wind

	Surge	Sway	Heave	Roll	Pitch	Yaw
	sec	sec	sec	sec	sec	sec
Y-Wind	220.9	220.9	16.8	19.4	19.4	124.9
T-Wind	57.1	57.1	2.2	3.5	3.5	43.9

6.2 Platform Heave RAOs

Heave RAOs of both platforms are compared in Fig. 5. The RAOs were computed with a white noise technique under the 180-deg wave heading. Significant differences of the heave between the platforms are observed.

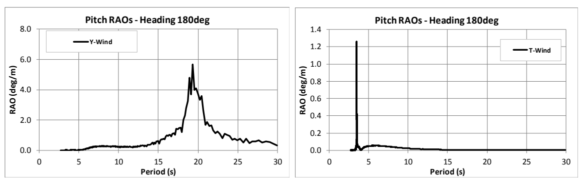

Fig. 5 Y-Wind and T-Wind Heave RAOs

6.3 Nacelle Acceleration RAOs

Fig. 6 represents the nacelle acceleration RAOs in the horizontal and vertical directions. The horizontal accelerations are strongly coupled with the platform pitch, whereas the vertical accelerations with the heave natural period.

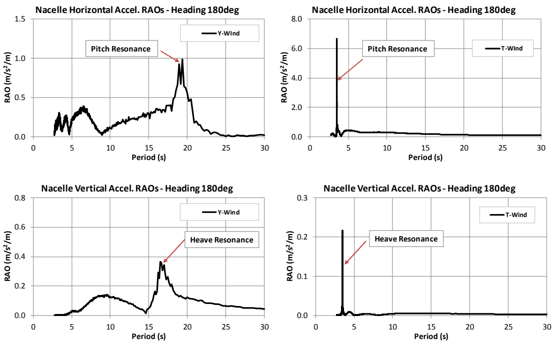

Fig. 6 Y-Wind and T-Wind acceleration RAOs

6.4 Platform Motions

Fig. 7 compares the motion responses of excursion, heave, pitch and mean heel angle for the rated, cut-out, extreme and survival conditions. The excursion ratios are ratio of the excursion to the water depth of 200 m. Each maximum or minimum value in the following sections was estimated with an extreme method of most probable maximum.

Excursion and heave of T-Wind are much smaller than the values of Y-Wind, which can benefit the wind turbine and dynamic power cable. The dynamic pitch angles of both platforms are lower than the design requirement of 10 deg. Mean heel angles under the power production are estimated to be also lower than the design target of 4 deg. These low pitch and mean heal angle can contribute to improve the turbine power production performances. Overall, T-Wind shows superior performances in the motions to Y-Wind.

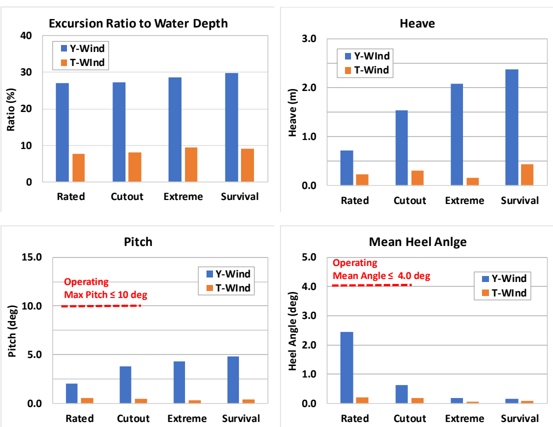

Fig. 7 Y-Wind and T-Wind motion responses

6.5 Nacelle Accelerations

Horizontal and vertical accelerations of the turbine nacelle of the platforms are shown in Fig. 8. Both values are lower than the design requirement of 0.4g for the operating conditions. It is seen that the horizontal accelerations of the platforms are greater than the vertical ones.

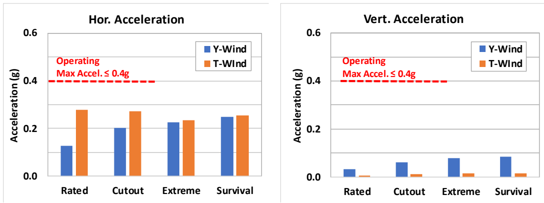

Fig. 8 Y-Wind and T-Wind nacelle accelerations

6.6 Mooring Tensions

Maximum catenary mooring tensions for Y-Wind or tendon tensions for T-Wind on the most loaded line and FoS of the lines are presented in Fig. 9. Minimum tendon tensions of T-Wind are shown in Fig. 10. Maximum and minimum tendon tensions of T-Wind were for the case of HSWL and LSWL respectively, according to the API RP 2T[12]. As T-Wind has redundant line, one tendon removal case of T-Wind was taken into account under a reduced extreme environment, which is considered a survival condition[12]. This case tension is presented as “Survival-d” in Figs. 9 and 10.

T-Wind tensions are much greater than the values of Y-Wind, as anticipated. It is seen that FoS of the mooring of Y-Wind and T-Wind comply with the criteria for the design extreme and survival conditions. Minimum tension of T-Wind is positive for all the conditions including the tendon removal case, which meet the T-Wind design requirement.

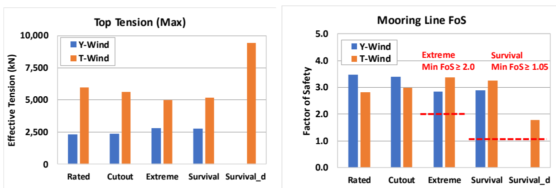

Fig. 9 Y-Wind and T-Wind mooring tensions and FoS

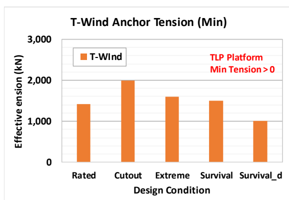

Fig. 10 T-Wind minimum tendon tension

6.7 Mooring Anchors

Anchor tensions of the platforms were utilized to derive the preliminary size of the suction anchor for Y-Wind and driven pile for T-Wind, considering the design FoS in Table 5 and 6. As no soil condition of the site is known yet, average pile dimensions determined from the soft and medium clays was taken and used for the mooring cost analysis. The suction and driven pile weights estimated are 36 ton and 156 ton in air respectively.

7. Y-Wind and T-Wind CAPEX Analysis

CAPEX per MW of Y-Wind semi and T-Wind TLP platforms were calculated, considering a 200 MW floating wind farm located 50 km off the coast specified in "Basis of Design", with 40 units of 5MW. The costs of the platform installed include the procurement, fabrication and integration of the wind turbine, installation of the floating foundation, mooring lines and anchors. All fabrication and procurement, and all installation activities offshore are assumed to be undertaken by 2nd tier Korean firms and suppliers. The execution plan assumes turbine integration quayside at the fabrication yard and then wet tow to site for installation. Insurance costs and contingencies for offshore operations are included.

Pre-sanction costs, such as project approvals, permitting, environmental impact studies, site metocean and seabed surveys are not included. Inter-array and export power cables and power substation are not included. However, CAPEX cost items excluded in the present work are used for NPV and IRR analysis of the 200 MW farm with Y-Wind platforms, which can be found in another work[14].

Figs. 11 and 12 present the cost per MW of Y-Wind and T-Wind platforms in terms of functional component and execution activity, respectively, based on 200 MW floating wind farm.

The CAPEX per MW for a Y-Wind semi design is about $4.56 million per MW which is slightly lower than the CAPEX of T-Wind of $4.92 million per MW, for a 200 MW farm. Wind turbine costs are the same for both designs. The differences arise in the other components. The floating foundation (platform hull) cost is lower for the T-Wind compared to the Y-Wind. However, the anchor costs for the T-Wind are significantly greater than the anchor costs for Y-Wind. Installation costs are also greater

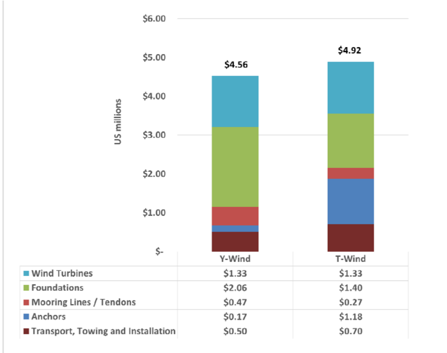

Fig. 11 CAPEX per MW by Functional Component

Fig. 12 CAPEX per MW by Execution Activity

for the T-Wind as six driven piles with longer penetration depth need to be installed for each T-Wind platform, as opposed to only three suction piles per Y-Wind platform. Therefore, more installation time offshore will be required for each T-Wind.

A brief comparison of technology readiness is shown in Table 11. Technology readiness for the Y-Wind semi type floating foundation is more mature than for the TLP type. Additional technology development for TLP type is required in tendon connectors and low-cost anchors so there might be a risk to estimate the cost with lack of the technology readiness. However, the platform cost analysis does not consider any potential difference due to technology readiness at this time.

Table 11. Y-Wind and T-Wind Technology Readiness

	Y-Wind Semi	T-Wind TLP
Wind Turbine (5MW)	Near ready for offshore	Near ready for offshore
Floating Foundation	Proven	Proven
Mooring, Tendon	Proven	Connectors for floating Wind in development but not yet deployed
Anchors	Suction Piles: Proven	Driven piles: not yet deployed for floating wind
Installation Offshore	Proven	Proven

While CAPEX analysis suggests that Y-Wind is less costly than T-wind, it may be stated that the operating and maintenance costs for T-wind will be lower than for Y-Wind. The lower observed T-wind motions will be better for turbine operating life and therefore additional analysis in the operating and maintenance cost aspects for Y-Wind versus T-Wind is recommended. It needs to be studied further if any operating and maintenance cost savings by T-Wind will be large enough to offset the CAPEX cost difference over the life of a wind farm.

Overall, the CAPEX costs calculated are conservative. With careful work scope and supply definition with some service providers and suppliers it is very possible to achieve lower costs for some components and activities.

8. Conclusion

The Y-wind semi and T-Wind TLP type floating wind platforms to support 5 MW turbine were designed to apply to a floating wind farm site located at 50 km of SE offshore of Korea at a water depth of 200 m. The platform designs were validated against the design requirements of ABS and API, considering the site metocean conditions including operating, extreme and survival conditions. In addition, cost per MW was estimated for respective Y-Wind and T-Wind, considering 200 MW farm with total 40 units of the Y-Wind or T-Wind. Technical and cost analysis results are summarized as;

1) It has confirmed that either the Y-Wind or T-Wind can be used for the Korea floating wind farm in the SE offshore as both platforms comply with the design requirements in motions, accelerations, mean heel angle and moorings.
2) The T-Wind has superior performances in motions compared to the Y-Wind so that better power production performances are expected. However, the T-Wind requires more advancement of the mooring system technologies along with lowering the anchor cost.
3) Cost per MW ranges from $4.56 million for the Y-Wind semi to $4.92 million for the T-Wind TLP.

Considering the technology readiness at present and platform cost, it is recommended that the Y-Wind platform be selected for a floating wind farm in SE offshore of Korea.

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