A TLP Floating Foundation Design with Novel Tendon Mooring Technology for Hawaii Offshore Wind

Sung Youn Boo, Steffen Shelley, Daejun Kim
VL Offshore LLC
Houston, USA

ABSTRACT

The Hawaii floating wind farm locations proposed are in very deepwater ranging to 1,000 m with steep bathymetry changes so that a semi or spar type floating foundation with catenary mooring may have a limitation for the locations. A new TLP type platform, called TX-Wind is thus developed. The TX-Wind platform supports a 6 MW wind turbine and is moored with eight tendons at 1,000 m water. The tendon system comprises wire and chain, with rotary latch type connections at the seabed anchor. To minimize the risk associated with such a deepwater application, the well-proven TLP technologies and experience in oil and gas are fully applied to the TX-Wind design, which includes the platform hull characteristics, stability, tendon connectors, tendon piles, wet-tow and installation, and execution strategy. Platform responses, pre-service stability and tendon mooring system performances are verified against industry standards, indicating that TX-Wind is technically feasible for very deepwater. CAPEX and LCoE analysis are completed for a wind farm with 34 units of TX-Wind. LCoE analysis suggests that TX-Wind may be an economically feasible solution for a Hawaii offshore wind farm. A qualitative assessment of other factors regarding the feasibility for application offshore Hawaii, including the availability of offshore infrastructure and support services, are also discussed.

KEY WORDS: TX-Wind; TLP; Floating Wind; tendon; CAPEX; LCoE; tendon connector

INTRODUCTION

There is considerable interest around many places in using floating wind to generate electrical energy. To date, most floating wind concepts and proposed applications are in relatively shallow waters and in regions that have extensive offshore infrastructure and support capabilities. Hawaii does not have shallow waters or extensive infrastructure to support offshore wind, yet Hawaii has set renewable energy targets that could include offshore wind. The state aims at reaching 30% of renewable energy by 2020, 70% by 2040 and 100% by 2045. Two locations offshore Hawaii have already been proposed by various industry consortia. Both locations are characterized by very deep waters between 800 to 1000 m depths. Existing semi-submersible or spar types with catenary mooring may not be feasible in those locations due to steep bathymetry variation which may not accommodate the wide foot prints of the catenary moorings. Instead, the site characteristics suggest that a Tension Leg Platform (TLP) type solution may be more feasible offshore Hawaii. Applying lessons learned from offshore oil and gas TLP projects, this study presents a new TLP foundation concept called TX-Wind, for floating offshore wind in deepwater applications. The novel TX-Wind concept incorporates tendon (vertical tether) mooring technology and components derived from the deepwater offshore oil and gas industry. The TX-Wind concept also incorporates features for offshore wind designed to make offshore wind installations as cost effective and productive as possible.

The TX-Wind for this study is moored at 1,000 m water depth and supports a 6 MW horizontal axis wind turbine. The vertical mooring tendon system comprises wire and chain with adapted rotary latch type connections in way of the seabed anchor. For this study, both driven piles and suction piles are considered. However, depending upon the results of future soil surveys of the site, drilled and grouted piles may be required. This study does not consider drilled and grouted piles at this time. The Hawaii wind farm considered is located about 20 km south of Diamondhead and consists of 34 units of 6MW TX-Wind, one floating power substation and power cables. The present study objectives are, thus, to assess the technical and commercial feasibilities of the TX-Wind for Hawaii offshore at ultradeep water of 1,000 m. We believe that no study of such ultradeep water floating wind with any type of floating foundation has been reported so far.

Another TLP type foundation, T-Wind to support 5 MW for 200 m water depth is designed and reported by authors (Boo et al, 2018). TX-Wind comprises four square shaped outboard and one center columns, whereas T-Wind has three circular outboard and one center columns. Levelized Cost of Energy (LCoE) and economic analysis of the T-Wind for a 200 MW farm are also presented in Shelley (2018a; 2018b). The TLP type foundations of TX-Wind and T-Wind are originated from a 5MW Y-Wind design, a semi-submersible type having excellent design features in terms of responses, fabrication and pre-service execution (Boo et al, 2017a; Boo et al., 2017b; Kim 2018).

Platform hydrodynamics, responses, pre-service stability and tendon mooring system performances are verified against industry standards. CAPEX and LCoE analysis of the TX-Wind farm consisting of 34 platforms of 6MW TX-Wind is carried out. A qualitative assessment of other factors regarding the feasibility for application offshore Hawaii, including the availability of offshore infrastructure and support services, are also discussed.

BASIS OF DESIGN

Site and Metocean Condition

The floating wind farm site considered is about 20 km south of Diamond Head of Oahu as depicted in Fig. 1. The bathymetry around the site varies sharply and the water depths are in the range of 800 m to 1000 m. For the present work, a water depth of 1,000 m is decided.

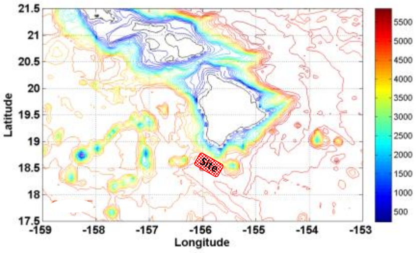


Fig. 1 Wind farm site and bathymetry

Metocean conditions of operating (power production), 50-yr extreme and 500-yr survival seas are estimated using VL Offshore software "Weather Data Analysis", based on the measured data for 39-yr from 1979 to 2017 near the site. Significant wave Hs and peak period Tp joint distributions are presented in Fig. 2. The color scale in Fig. 2 presents the number of occurrences of Hs-Tp distribution. Also, Hs and wind speed joint probabilities were derived and then the significant wave heights associated with the rated and cutout wind speeds were selected accordingly. The resulting Metocean data is summarized in Table 1. No site storm surge is available at this time so that the HSWL and LSWL for all conditions are assumed ± 1.0 m, which may be conservative for the operating conditions. The Design Load Cases (DLCs) are based on ABS (2015).

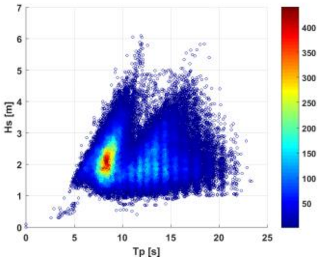


Fig. 2 Hs and Tp joint distribution

Table 1. Metocean Data at Site

Platform Condition	Operating		Extreme	Survival
ABS DLCs	1.3	1.6	6.1	SLC
Environment Condition	V_r	V_o	50-yr	500-yr
Turbine Condition	Prod.	Prod.	Parked	Parked
Wind 1-hr @ 10m (m/s)	9.2	19.1	21.4	24.2
10-min @ hub (m/s)	11.4	25.0	28.33	32.46
Wave Hs (m)	2.5	5.6	6.43	7.59
Tp (s)	8.5	11.40	11.80	12.20
Current @ Surface (m/s)	0.4	0.6	1.08	1.1
HSWL(+), LSWL(-) (m)	± 1.0	± 1.0	± 1.0	± 1.0

Design Criteria

The TLP type floating wind platform moored at a water depth of 1,000 m is designed to produce 6 MW of power for a service life of 20 years under the metocean conditions in Table 1.

The platform design complies with requirements recommended in *ABS Stationkeeping Systems* (ABS, 2013), *ABS Floating Offshore Wind* (ABS, 2014), *ABS Guide for Building and Classing* (ABS, 2015) and API 2T (2010) which are summarized in Tables 2-4. The bias factors (or B-factors) for driven pile Factor of Safety (FoS) in Table 4 are obtained from modifying the recommended values in API 2T (2010). Also, the platform dynamic heel angle of 10 deg and nacelle acceleration of 0.4g (3.92 m/s^2) are set as design targets according to the design practices of other floating wind turbine platform.

Table 2. Floating wind platform design criteria

Load Condition	Mean Heel (deg)	Accel. (g)	Air Gap (m)
Operating	≤ 4.0	≤ 0.4	-
Extreme		-	≥ 1.5
Survival		-	≥ 0.0

Table 3. FoS for tendon design

Load Condition	Line Condition	FoS
Extreme	Intact	1.67
	One line damage	1.25
Survival	Intact	1.05

Table 4. FoS for driven pile design

Load Condition	API 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

Table 5. FoS for suction pile design

Load Condition	Line Condition	Axial FoS	Lateral FoS
Extreme	Intact	2.4	1.92
	One line damage	1.8	1.44
Survival	Intact	1.05	1.05

Wind Turbine Data

Table 6 summarizes properties of a 6 MW wind turbine. Wind turbine thrusts are shown in Fig. 3. The tower base is located at 10 m above the SWL.

Table 6. Wind turbine data

Power Rate	MW	6
Rotor Diameter	m	154
Number of Blades	ea	3
Tower Height	m	88
Tower Diameter Top / Base	m	4.2 / 6.5
Cut-in V_{in} / Rated V_r / Cut-out V_{out}	m/s	3.0 / 11.0 /25.0
RNA and Tower Weight	ton	732

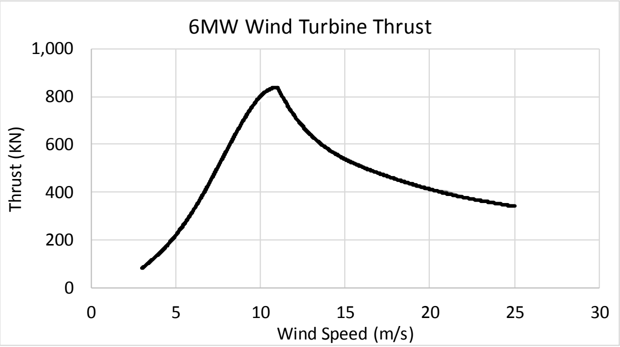


Fig. 3 Wind Turbine Thrusts

TX-WIND PLATFORM DESIGN

The TX-Wind is a TLP type wind platform moored with tendons (vertical tethers) and is designed to support the 6 MW horizontal axis wind turbine on the top of the center column. Fig. 4 depicts the TX-Wind platform perspective and elevation views. The TX-Wind comprises four outboard columns and one center column, forming an "X-shape". The shape of the columns is square with rounded corner, which enables the fabrication at a yard that has no facility to roll plate to form a cylindrical shape. The pontoons consist of parallel and tapered sections. There are no decks and braces which in turn facilitates the efficient construction of the hull and removes the potential risk to the deck structure of slamming induced by the storm loads.

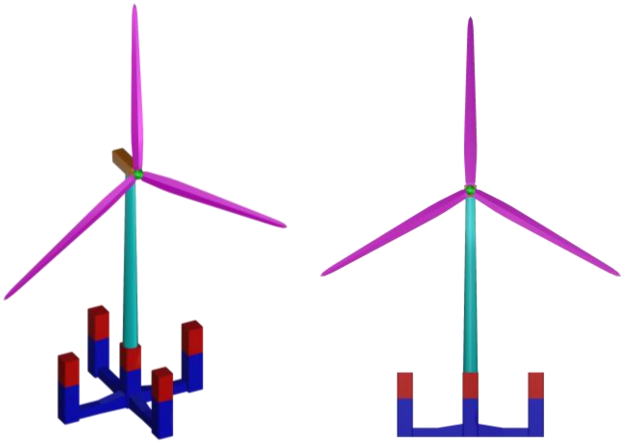


Fig. 4 TX-Wind platform

The lightship draft of TX-Wind is taken into account to enable the integration of the tower and rotor at quayside and for wet-tow out to site without requiring the use of expensive and dedicated vessels. More importantly, the TX-Wind design provides sufficient self-stability during the tower integration, wet-tow and installation operations, which avoids complex and risky pre-service operations in an offshore environment.

Table 7 summarizes the particulars of TX-Wind in service. The total weight of the platform for the in-place condition is estimated considering the hull structure, appurtenances, anodes, ballast, turbines, marine system and marine growth over the design life, where an appropriate contingency is applied based on the past experiences of the oil and gas platform design. The tendon locations are provided in the following section. The platform freeboard colored in red in Fig. 3 was decided accordingly considering the platform set-down, wave height and HSWL.

Table 7. TX-Wind 6MW platform particulars

Displacement	ton	5,860
Draft (design)	m	17.0
Draft (lightship)	m	4.9
Column Height	m	28.5
Span overall	m	64.9
Number of tendons	ea	8

TENDON SYSTEM DESIGN

The TX-Wind platform is vertically moored with a total of eight tendons at a water depth of 1,000 m. Table 8 summarizes the tendon properties. The tendon top connector is located near the keel of the outboard column and the other end is connected to an anchor foundation. Figs. 4 and 5 present the top and bottom connector arrangements for the TX-Wind mooring.

Oil States Industries (OSI) applied its extensive knowledge and experience with deepwater oil and gas tendon mooring technology for TLPs to develop a robust and low cost design solution for deepwater offshore wind using tendons.

Table 8. TX-Wind tendon properties

Items	Unit	Wire	Chain
Length per line	m	953.5	30
Material	-	Spiral strand	R4 studless
OD	mm	141	147

The OSI bottom connector assembly (Fig. 5) consists of a roto-latch type bottom connector and receptacle. A locking pin is fitted onto the bottom receptacle to prevent unlocking during tendon slack conditions. The bottom connector assembly can be integrated to either driven or suction piles. The bottom connector assembly technology is existing and has been proven over several decades of continuous use on deepwater oil and gas TLPs.

At the top of the tendon, a simplified top connector assembly (Fig. 6) is provided to hold the tendon in place. As with the bottom connector assembly, the top connector assembly is based upon proven oil and gas TLP technology. Tensioning of the tendon during installation is provided by a removable pull-in winch system that is temporarily mounted on the TX-wind outer columns.

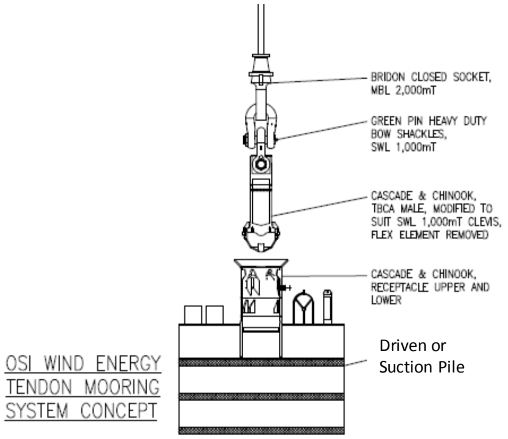


Fig. 5 TX-Wind tendon bottom connector configuration

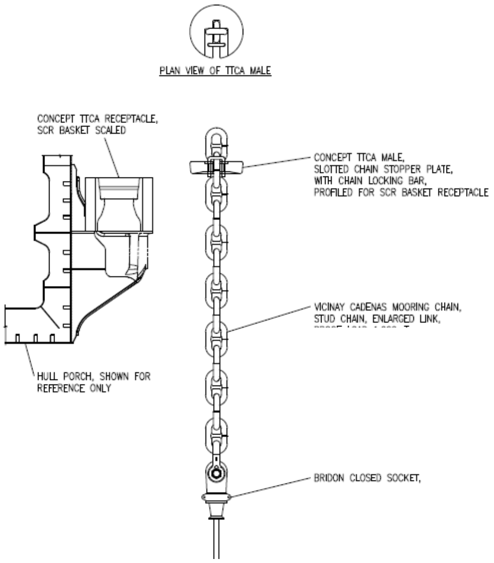


Fig. 6 TX-Wind tendon top connector configuration

TX-WIND PLATFORM DESIGN VALIDATIONS

Numerical Modeling for Platform Response Analysis

Coordinate system, environment heading definition and tendon numbers are presented in Fig. 7. Due to symmetry of the platform and tendons, 0 and 45 deg headings are considered for the numerical analysis.

A time domain analysis is conducted to evaluate the responses of the platform and tendons. The present time-domain run is based on a semi-coupled analysis in ABS (2015). The tower and nacelle are modeled as a part of the rigid body of the hull. The time varying rotor thrusts as a function of wind speed are input to the tower top at every time step.

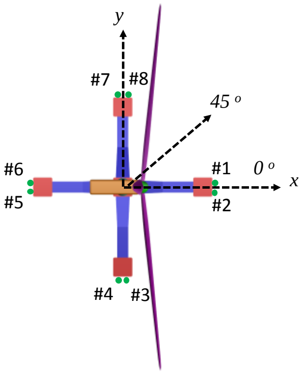


Fig. 7 Headings and tendon numbering

Wind forces on the hull and wind turbine tower are estimated based on ABS FPI (2013) and input to the numerical model in terms of wind coefficients. The current loads on the platform and the mooring lines are represented in the model with the drag coefficients. Hull viscous damping is also presented in the model with the viscous drags. Wind, wave and currents are considered co-directional.

The maximum or minimum response value in the following sections is estimated using a Rayleigh extreme method of the most probable maximum.

Platform Natural Periods and RAOs

The natural priods of the 6MW TX-Wind determined from the free decay tests are compared in Table 9. The water depth of 1,000 m is perceived as ultradeep water in floating wind communities but it is very promising that TX-Wind natural periods of the heave, roll and pitch fall in the natural periods of the TLPs for oil and gas. This results indicate that the TX-Wind can be technically applicable in an ultradeep water like convential offshore TLP platforms

Table 9. Natural periods of TX-Wind 6MW platform

Surge (s)	Sway (s)	Heave (s)	Roll (s)	Pitch (s)	Yaw (s)
145.6	145.6	4.4	5.5	5.5	103.0

RAOs are computed with white noise waves for the 0 and 45 deg headings. Fig. 8 shows heave and pitch RAOs of TX-Wind. Nacelle acceleration RAOs in the horizontal and vertical directions are compared in Fig. 9. The horizontal accelerations are coupled with the platform pitch (or roll), whereas the vertical accelerations are coupled with the heave natural period. Fig. 10 presents the tendon #5 tension RAOs, indicating that the tendon tensions are most strongly coupled with pitch (or roll) than heave.

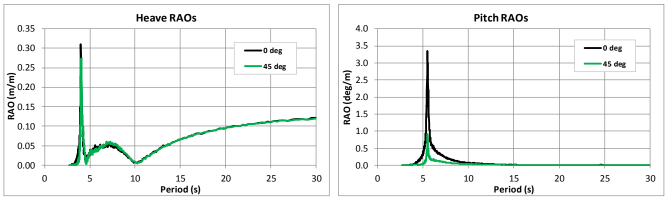


Fig. 8 TX-Wind heave and pitch RAOs

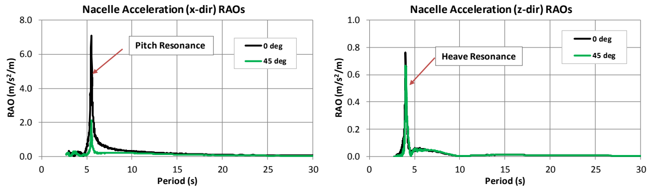


Fig. 9 TX-Wind x-dir and z-dir acceleration RAOs

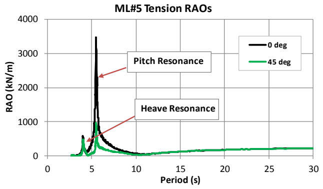


Fig. 10 TX-Wind tendon tension (tendon #5) RAOs

Platform Responses

The motion responses of excursion (offset), heave, pitch and mean heel angle for the operating (rated and cut-out), extreme and survival conditions are presented in Fig. 11. The excursion ratios are the ratios of the excursion to the water depth of 1,000 m. The excursions of TX-Wind are about 5% for the operating and 6% for the survival conditions. Both values are within the offset ranges recommended for a conventional TLP design. The dynamic max rotation angle is estimated to be small. Max mean rotation angle occurs during the operating case but is also much lower than the design target of 4 deg. These low rotation angles can significantly benefit the wind turbine power production performance, which is one of advantages of TLP type over other types of floating wind platforms.

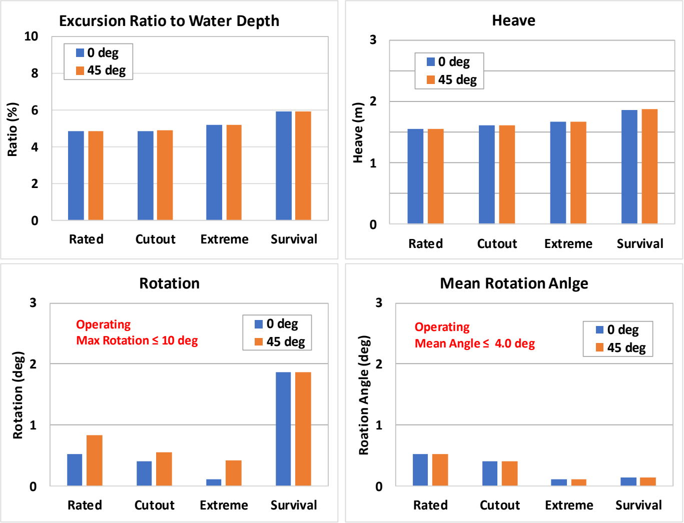


Fig. 11 Motion responses of excursion, heave and rotation

Nacelle Accelerations

Fig. 12 compares the horizontal and vertical accelerations of the turbine nacelle of TX-Wind. Both values are much lower than the design target of 0.4g. It is seen that the horizontal accelerations of the platforms are greater than the vertical ones, which is mainly due to the platform pitch and roll coupled motions. Note that the nacelle horizontal accelerations are computed by combining the accelerations induced by the platform roll and pitch.

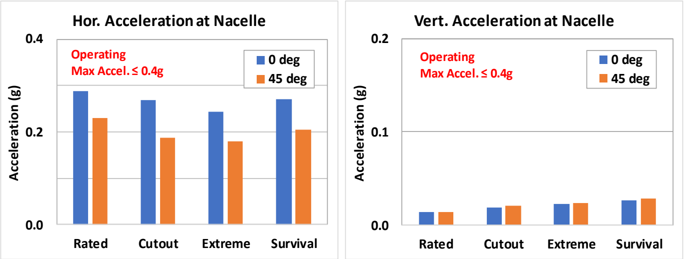


Fig. 12 Horizontal and vertical accelerations at nacelle

Tendon Tensions

For easier comparison purposes, normalized tendon tension Factor of Safety (FoS) is introduced. The normalized FoS is computed as the estimated FoS divided by the allowable minimum FoS in Table 3. As such, the normalized FoS for each case must be greater than 1.0 to comply with the design criteria for the operating, extreme and survival conditions. A one tendon removal (damage) case is considered. Tendon #2 is the most loaded line under the 0 deg heading condition and is thus selected to be considered damaged under the 50-yr extreme seas.

Fig. 13 compares the normalized FoS for all the Load Cases (power production or operating, extreme and survival) considered, including the damage case. Here, the max top tensions are computed for the water level of HSWL, due to the API 2T (2010). It is confirmed that the tendon FoS for each case of the TX-Wind comply with all criteria for the design operating, extreme and survival conditions.

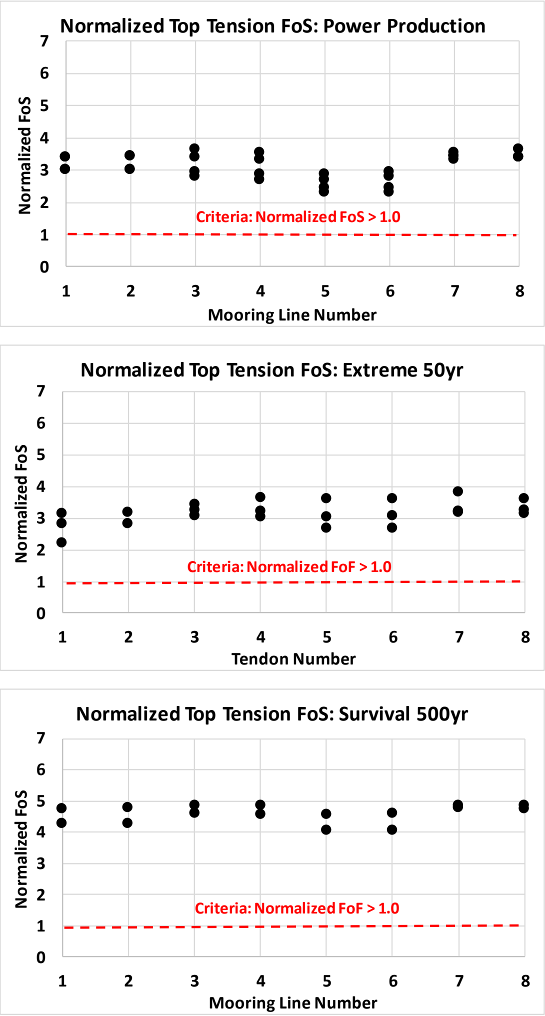


Fig. 13 Tendon tension normalized FoS

Pre-Service Stability

One of the featured characteristics of TX-Wind is self-stability during the pre-service executions of tower mating, wet-tow and installation. Stability validations are carried out for the lightship with tower, wet-tow and installation. Wind speeds utilized are 1-yr wind for lightship and wet-tow and 50-yr wind for the installation, according to ABS (2015).

Lightship and installation drafts are 4.9 m and 17.0 m respectively. For the present study, a wet-tow draft of 7.0 m is assumed but a shallower or deeper draft can be selected depending on the tow route water depth. Table 10Table 12 summarize the intact stability results. It is proven that Metacentric Heights (GMs), downflooding heights and area ratios are greater than the allowable minimum values. It is observed that the TX-

Wind has better stability performance at the installation draft, which ensures the safety and minimizes risks during the tendon connection to the platform.

Table 10. Lightship intact stability of TX-Wind

Axis angle (deg)	0	45	90	135	180	Req.
GM (m)	3.2	3.2	3.2	3.2	3.2	> 0
Downfl. height (m)	21.0	21.5	21.4	21.2	21.0	≥ 1.0
Area ratio	1.9	3.6	2.4	3.0	1.9	≥ 1.3

Table 11. Wet tow intact stability of TX-Wind

Axis angle (deg)	0	45	90	135	180	Req.
GM (m)	2.4	2.4	2.4	2.4	2.4	> 0
Downfl. height (m)	17.0	18.5	17.9	17.9	17.0	≥ 1.0
Area ratio	1.9	4.9	2.5	4.0	1.9	≥ 1.3

Table 12. Installation intact stability of TX-Wind

Axis angle (deg)	0	45	90	135	180	Req.
GM (m)	5.2	5.2	5.2	5.2	5.2	> 0
Downfl. height (m)	9.1	10.1	9.8	9.7	9.1	≥ 1.0
Area ratio	2.6	4.5	3.5	3.5	2.6	≥ 1.3

COST ESTIMATE

CAPEX and LCoE are estimated for 204 MW wind farm with 34 units of 6MW TX-Wind for four different mooring configurations. The four configurations consider 8 tendons with 8 driven piles, 8 tendons with four driven piles (pile sharing case), 8 tendons with eight suction piles and 8 tendons with 4 suction piles. The wind farm is located about 20 km off the Diamondhead, Hawaii. CAPEX and LCoE estimates take into consideration the execution strategy and plan, existing market conditions and financial factors.

Execution Strategy and Plan

The execution plan for the wind farm considered existing infrastructure in Hawaii to fabricate, integrate and install the wind turbine. The objective is to complete as much fabrication and work as possible in Hawaii in order to minimize transport costs associated with bringing components from elsewhere and to maximize local job benefits. However, while the harbor and port depths are sufficient to float the TX-Wind 6 MW design, existing fabrication (yard) infrastructure in Hawaii cannot build the TX-foundations on land, nor is there any supplier in Hawaii for the turbine blades. Thus, the main elements of the execution plan decided for this study are as follows.

The TX-Wind platform hulls will be fabricated on the U.S. West coast and then transported on barge to Hawaii. Similarly, turbine blades, towers and nacelles will be fabricated in the mainland U.S. and shipped to Hawaii. Once in Hawaii, turbines will be assembled and integrated onto the TX-Wind hulls. Primary Hawaii fabrication is assumed for mooring piles and power substation topside.

For installation of mooring piles, a deepsea construction vessel will be mobilized from the U.S. Gulf of Mexico. Additional tug services for towing and station keeping can be provided by local service providers.

For the estimate, the schedule assumes 3 years of work for permitting and site surveys, ahead of first TX-Wind platform installation. Mooring piles will be pre-installed ahead of the floating foundations. The floating power substation will be installed at the time of the first production TX-Wind installation. The wind farm export cable will be installed with the power substation and is assumed to be overlaid with mats offshore and trenched for about 2 km as it approaches the beach and shore gird connection. Inter-array cables connecting the TX-Winds to the power substation will be installed in a dedicated campaign for every 6 platforms installed. It is estimated the wind farm will be fully installed and operational within 18 months from first TX-Wind offshore installation.

CAPEX Estimate

CAPEX costs are estimated for each component and activity and incorporate industry data and published values and rates. CAPEX includes all costs to get the wind farm on site and ready to start operations. CAPEX includes project costs that apply to the project as a whole. Project costs include pre-construction planning and regulatory costs such as environmental studies, geotechnical surveys, and site surveys during the 3-year pre-production phase. In addition, a decommissioning fund is also included in the CAPEX as an expenditure because the monies are set aside at the beginning of the project. Decommissioning fund costs are calculated as defined by Beiter et al. (2016). Insurance costs of 2.1% of all offshore activity costs are also included. Global project contingency costs are not included in the CAPEX as global project contingency costs are determined by project developers and operators based upon their own risk assumptions about the project.

Windfarm layout is assumed to be approximately square with platform separation distances of about 10 times rotor diameter. Inter-array power cables will be supported in the water. Inter-array power cables connect one line of turbines to each other and then to the floating substation.

One export power cable will then run from the floating substation along the sea floor bottom to shore. The substation is assumed to be closest to shore and the export cable length is estimated to be about 22 km. The export power cable is assumed to be covered offshore and then buried (trenched) for about 3 km as it approaches the shore and up to the shore grid connection point.

Costs for power cables, including installation up to the shore grid connection point are included in CAPEX. However, shore grid connection costs or any other shore grid costs, such as extension of transmission lines, are not included in the CAPEX estimate.

CAPEX costs are presented in two different manners: as functional component costs or execution activity costs (Table 13).

Table 13. CAPEX cost organization

Functional Components
Global project services
Decommissioning fund
Wind turbine system
Floating foundation
Tendons
Anchors (driven or suction)
Tower integration (quayside)
Offshore installation
Inter-array and export cables
Floating substation

Execution Activities
Project management
Engineering
Certification, fees, insurance
Procurement
Construction, fabrication
Transportation and logistics
Hook up and commissioning

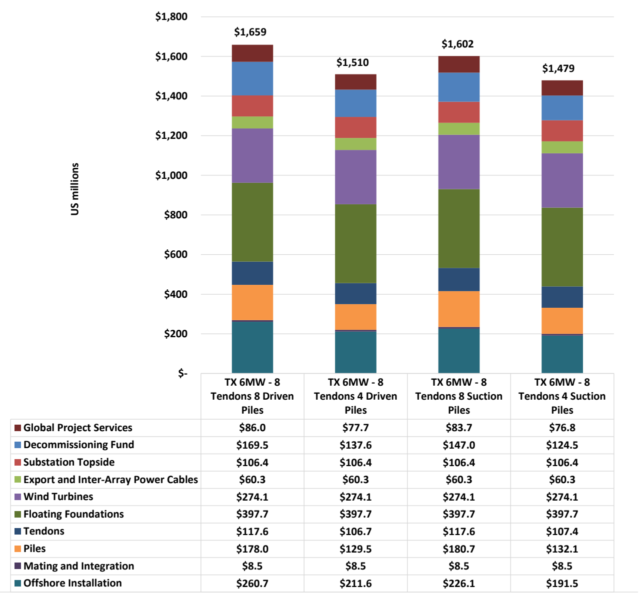
Functional component cost breakdown organizes all costs as they apply to identifiable and (mostly) physical components of the project such as the floating foundations or wind turbine systems. Global project service costs include costs which are not readily associated with one component or applicable to several components such as pre-production planning costs. Similarly, offshore installation costs are also applicable to several physical components (such as anchors and export power cables) because the costs associated with offshore vessels and resources used during installation are estimated in accordance with the assumed execution plan, which aims to combine installation campaigns in such ways to reduce vessel mobilization / demobilization costs and avoid any unnecessary costs such as vessel standby costs.

Organization of CAPEX by functional components facilitates project cost comparisons by suppliers of such components. Grouping all offshore transport and installation costs in this manner also allows for better assessment of the likely risks and insurance costs.

Organization of CAPEX costs by execution activities of engineering, project management to hook up and commissioning facilitates project cost evaluation by project developers and investors. It also serves to allow industry to gauge the risk and validity of the estimate by comparing the estimated activity costs against historical project activity costs. For example, it is common practice in the deepwater oil and gas industry to compare the estimated percentage of engineering costs for a new project against historical data in order to ascertain whether the estimate for the new project is feasible and to indicate whether there may be critical challenges with the proposed project.

Fig. 14 summarizes the CAPEX by functional component costs such as wind turbines, power cables, floating substation, floating foundations, mooring systems (tendons) and anchors (driven or suction piles). Fig. 15 summarizes the CAPEX by execution activity costs such as engineering, procurement and commissioning.

The cost of the floating wind farm of 204 MW with 34 units of 6MW TX-Wind will range from $1,479 to $1,659 million depending upon the mooring configuration. On a per MW installed basis, the cost ranges between $7.25 million/MW to $8.13 million/MW as shown in Table 14.



	TX 6MW - 8 Tendons 8 Driven Piles	TX 6MW - 8 Tendons 4 Driven Piles	TX 6MW - 8 Tendons 8 Suction Piles	TX 6MW - 8 Tendons 4 Suction Piles
■ Global Project Services	$86.0	$77.7	$83.7	$76.8
■ Decommissioning Fund	$169.5	$137.6	$147.0	$124.5
■ Substation Topside	$106.4	$106.4	$106.4	$106.4
■ Export and Inter-Array Power Cables	$60.3	$60.3	$60.3	$60.3
■ Wind Turbines	$274.1	$274.1	$274.1	$274.1
■ Floating Foundations	$397.7	$397.7	$397.7	$397.7
■ Tendons	$117.6	$106.7	$117.6	$107.4
■ Piles	$178.0	$129.5	$180.7	$132.1
■ Mating and Integration	$8.5	$8.5	$8.5	$8.5
■ Offshore Installation	$260.7	$211.6	$226.1	$191.5

Fig. 14 CAPEX of wind farm by functional component: 34 units of 6 MW TX-Wind

	TX 6MW - 8 Tendons 8 Driven Piles	TX 6MW - 8 Tendons 4 Driven Piles	TX 6MW - 8 Tendons 8 Suction Piles	TX 6MW - 8 Tendons 4 Suction Piles
■ Project Management	$13.3	$13.3	$13.3	$13.3
■ Engineering	$43.1	$43.1	$43.1	$43.1
■ Certification / Fees / Insurance	$21.0	$21.0	$21.0	$21.0
■ Procurement	$850.1	$795.2	$822.1	$781.4
■ Construction / Fabrication	$425.2	$380.5	$431.2	$383.6
■ Transportation / Logistics	$248.5	$199.4	$214.6	$180.7
■ Hook Up / Commissioning	$57.6	$57.6	$56.9	$56.1

Fig. 15 CAPEX of wind farm by execution activity: 34 units of 6 MW TX-Wind

Table 14. CAPEX of TX-Wind farm per MW

Mooring configurations	CAPEX (million $/MW)
8 tendons, 8 driven piles	8.13
8 tendons, 4 driven piles	7.40
8 tendons, 8 suction piles	7.85
8 tendons, 4 suction piles	7.25

If soil conditions are such that drilled and grouted piles are required for mooring, then the CAPEX cost of the mooring piles will increase between 15% to 20% compared to the driven pile cases. Additional cost increases will also arise for the longer offshore installation durations for drilled and grouted piles and for the associated insurance costs.

LCOE Estimate

Parameters considered for the LCoE estimate are summarized in Table 15. These parameters are set as the base case to compare with variance cases. Among the factors, the wind farm electricity price of $0.285/kWh equals the Hawaii industrial electricity price of January 2019 (U.S. EIA, 2019). The LCoE is calculated according to the NREL method (Short, 1995).

Table 15. Key inputs for LCoE calculation

Factors	Input Values
CAPEX	As above
Pre-production and planning phase	3 years
Production period	20 years
Discount rate	5.0%
Capacity factor	42.5%
Fixed O&M cost	$15.0/kWyr
Variable O&M cost	$0.025/kWh
Wind farm electricity selling price	$0.285/kWh
Cost escalation rate	2.3%

For a variance analysis of LCoE, two variance cases from the base case described above were considered below:

- *LCoE +5% Variance* in which the power output was reduced by 5% and all other costs were increased by 5%, and
- *LCoE -5% Variance* in which the power output was increased by 5% and all other costs were reduced by 5%.

The inputs for this variance analysis are summarized in Table 16. LCoE results of the base and two variance cases for the Hawaii floating wind farm with 34 platforms of 6MW TX-Wind are summarized in Table 17. The LCoE values for the base case range between $0.183/kWh to $0.201/kWh. The lower LCoEs are obtained for the pile sharing cases (4 driven or suction piles) due mainly to lower installation cost savings although there are some offsetting cost increases associated with the pile and bottom connector size increases. Variances of +/-5% extend the LCoE range between $0.165 to $0.224/kWh.

Table 16. Inputs for LCoE variance calculation

Factors	+5% LCoE Variance	Base Case	-5% LCoE Variance
CAPEX	+5%	As in Table 14	-5%
Discount rate	5.25%	5.0%	4.75%
Capacity factor	44.100%	42.5%	40.375%
Fixed O&M cost	$15.75/kWyr	$15.0/kWyr	$14.25/kWyr
Variable O&M cost	$0.02625/kWh	$0.025/kWh	$0.02375/kWh
Wind farm electricity selling price	$0.245/kWh	$0.258/kWh	$0.2709/kWh
Cost escalation rate	2.415%	2.3%	2.185%

Table 17. LCoE Results for base case and variances

Mooring configurations	+5% Variance ($/kWh)	Base Case ($/kWh)	-5% Variance ($/kWh)
8 tendons, 8 driven piles	0.224	0.201	0.181
8 tendons, 4 driven piles	0.209	0.186	0.168
8 tendons, 8 suction piles	0.214	0.196	0.176
8 tendons, 4 suction piles	0.203	0.183	0.165

For qualitative comparison of the TX-Wind farm LCOE, the Hawaii power price LCoE over the same time period with the same financial inputs is calculated to be $0.318/kWh. It is shown that TX-Wind farm LCoEs of the base and both variance cases are less than the Hawaii industrial power price LCoE. This indicates that the TX-Wind platform could be a commercially feasible solution for a very deepwater floating wind farm offshore, Hawaii. A large uncertainty remains with respect to the soil properties at site, which may require more expensive drilled and grouted anchoring technology to be used. However, even in this case, it is still likely that the TX-Wind will be commercially viable as configured.

CONCLUSION

A TX-Wind TLP type floating platform with 6 MW power is designed for an ultradeep water of 1,000m in Hawaii offshore. To minimize the risk associated with such deepwater application, the well-proven TLP technologies in oil and gas are fully implemented to the TX-Wind design, which includes the platform hull characteristics, stability, tendon connectors, tendon piles, wet-tow and installation. This ensures that the TX-Wind project can be streamlined from engineering to installation with no complex and high risk operations, which enables an efficient project and low cost overall.

In the present study, various assessments of the TX-Wind are carried out in terms of technical feasibility and overall project costs of wind farm. The considered wind farm has a power production capacity of 204 MW with 34 units of 6MW TX-Wind and is located at about 20 km south off Diamondhead, Hawaii.

The concept design of TX-Wind is accessed considering the site Metocean conditions of operating, 50-yr extreme and 500-yr survival for various aspects of platform natural periods, motion responses, nacelle accelerations, stabilities and tendon tensions. It is confirmed that TX-Wind design complies with the design criteria from industry standards of ABS and API RP 2T.

Project costs are estimated such that project duration includes 3 years of pre-operations for permitting and site preparation activities, followed by 20 years of production. CAPEX estimates of this novel TX-Wind floating foundation for offshore indicate that the total installed cost for the TX Wind farm off Hawaii will range from $1,479 to $1,659 million or $7.25/MWh to $8.13/MWh, depending on mooring anchor types and configurations.

LCoE analysis of the wind farm suggests that the TX Wind LCoE values will range from $0.183 to $0.201/kWh for the base case design with the input values. LCoE sensitivity analysis results with variances of +/-5% indicate that the LCoE ranges between $0.165 to $0.224/kWh. The LCoE values of the TX-Wind farm are below the Hawaii Industrial electricity price LCoE value of $0.318/kWh. This suggests that the LCoEs of TX-Wind farm using the proposed technology and execution plan may be in an acceptable range for a Hawaii floating wind project.

Although there is much remaining work to be followed, we believe that the present study is a pioneering work to opening ultradeep floating wind with a TLP type platform.

ACKNOWLEDGMENT

Oil States Industries is developing tendon connectors and tensioning technology in collaboration with VL Offshore for deepwater floating offshore wind. OSI provided technical information about its tendon mooring system specifically for this Hawaii wind study. OSI's contribution to this study is greatly appreciated.

REFERENCES

ABS (2015). ABS Guide for Building and Classing – Floating Offshore Wind Turbine Installations.

ABS (2013). ABS Design Guideline for Stationkeeping Systems of Floating Offshore Wind Turbines.

ABS (2014). ABS Guidance Notes on Global Performance Analysis for Floating Offshore Wind Turbine Installations.

ABS FPI (2013), ABS FPI Guide for Building and Classing Floating Production Installations.

API 2T (2010*). API RP 2T Planning, Designing, and Constructing Tension Leg Platform.*

Beiter, PW, Musial, W, Smith, A, Kilcher, L, Damiani, R, Maness, M, Sirnivas, S, Stehly, T, Gevorgian, V, Mooney, M, and Scott, G (2016).

NREL/TP-6A20-66579 (2016). “A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030”

Boo, SY, Shelley, SA, Kim, D (2017a). “Design and Dynamic Performances of Y-Wind Floating Offshore Wind Turbine Platform,” *Proceedings of the Twenty-seventh ISOPE Conference*.

Boo, SY, Shelley, SA, and Kim, D (2017b). “Dynamic Performance Analysis of a New Semi Type Floating Offshore Wind Turbine,” *Proceedings of the 22nd Offshore Symposium*, SNAME.

Boo, SY, Shelley, SA, and Kim, D (2018). “Concept Design of Floating Wind Platforms of Y-Wind and T-Wind for South East Offshore of Korea”, *KWEA Fall Conference*.

Kim, H and Boo, SY (2018). “Coupled and uncoupled analysis of Y-Wind semi Wind Turbine Foundation,” *Proceedings of the 23rd Offshore Symposium,* SNAME.

Shelley, SA, Boo, SY and Luyties, W (2018a). “Levelized Cost of Energy for a 200 MW Floating Wind Farm with Variance Analysis,” *KOSMEE Fall Conference.*

Shelley, SA, Boo, SY and Luyties, W (2018b). “Net Project Value Assessment of Korean Offshore Floating Wind Farm using Y-Wind Semi Platform,” *KWEA, Fall Conference*

Short. W, Packey, DJ and Holt, T (1955). NREL/TP-462-5173 “A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies”

US. Energy Information Agency, Hawaii State Profile and Energy Estimates (2019). https://www.eia.gov/state/data.php?sid=HI