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Concept Design of Floating Substation for a 200 MW Wind Farm for the Northeast U.S.

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Abstract

Floating offshore wind turbine technology, much of it developed domestically, is rapidly advancing and is in the early implementation phase, while floating substation technology is still at an early development stage. This study presents novel floating wind power substation platform designs for deepwater wind farm applications. Two types of floating substations configurations are considered to compare technical and cost performance: a semi-type “X-WindStation” and a TLP-type “TX-WindStation”. The floating substation platforms are considered for a 200 MW wind farm located in 100 m (328 ft) water depth off the Northeast coast of the United States. The floating substation supports a two-deck electrical power facility that provides sufficient electrical power equipment layout area and includes temporary quarters.

Both floating substation platforms are evaluated for global performance and mooring systems (catenary for semi-type and tendon for TLP-type) with the site design metocean conditions for the extreme and survival storm seas. The results are assessed in accordance with industry standards ABS and API, and offshore engineering practices.

Capital expenditure (CAPEX) of both substation platforms for a 200 MW farm is estimated by including the electrical substation, platform hull, mooring lines, anchors, integration, installation and commissioning costs. Installed CAPEX costs of the platforms show that the semi-type substation platform cost is lower than the TLP-type cost for the case where each tendon has a dedicated anchor, whereas the cost for the TLP-type with two tendons sharing an anchor is highly comparable to, if not less than, the semi-type platform.

Introduction

There is considerable offshore wind planning and development activity occurring along the U.S. East and Northeast offshore from Virginia north to Maine. Most recently a 2,640 MW wind farm by Dominion Energy has been announced for offshore Virginia, (Windpower, 2020) and several other projects are undergoing planning review for New York, Massachusetts and Maine. To begin with, all of these projects will be deployed in shallow water capable of economically using fixed foundations. However, later stages of these developments will most likely need to use floating foundations in water depths beyond the economic feasibility of fixed foundations. The first offshore wind farms in the United States will be in realtively shallow coastal waters, and fixed foundations for both production turbines and electrical substations will be used and will draw upon technology and experience developed in European offshore wind farms. However, for deepwater there is essentially no prior technology developed or deployed on a massive scale, and no technology developed for floating substations. Both the Hywind floating wind farm offshore Scotland (Power Engineering, 2017) and the WindFloat Atlantic project offshore Portugal (Simon, 2017) have only a small number of floating wind units which are directly connected to shore-based power collection points. Incorporating a floating substation to support large scale floating wind farms will be necessary at some point in the future, and the engineering design of a floating substation will, thus, also need to be completed before eventual deployment.

This paper considers concept designs for a floating substation of 200 MW power rating for application in a floating wind farm located approximately 16 km (10 miles) offshore in 100 m (328 ft) water depth. In order to evaluate the technical feasibility and cost advantages, two different types of substation platforms are considered: a semi-type “X-WindStation” and a TLP-type “TX-WindStation”. Both floating substation platforms consist of the electrical substation (topside), hull system and mooring system. The intra-field cables connected to the platforms and export cable are excluded in the present design and analysis. The floating substation platform sizing incorporates electrical equipment, deck supports and hull configurations sufficient to maintain the structural integrity and functional requirements of the platform during all transition phases (quayside integration, tow out and installation) and during all operating conditions, including storm events. For the electrical substation, no energy storage system is included, and all designs assume that the electrical substation gathers power from the floating wind platforms and then converts the voltage to HVAC (High Voltage Alternating Current) in order to export the power to an onshore grid connection. Both substation platforms are conceptually designed and evaluated against relevant offshore industry standards and criteria. Platform response and mooring system analyses confirm the design of the substation platforms.

CAPEX is estimated for X-WindStation and TX-WindStation platforms taking into account execution options based upon Northeast fabricator capacity and U.S. flagged and classed installation and support vessels of opportunity. In order to determine the CAPEX, heuristic means using available industry data and experience are utilized as there is a paucity of published data available for fixed and floating substations. Furthermore, compared to on-shore windfarms, offshore wind farms have more significant variances in cost due to such factors as metocean conditions and site water depth, as well as proximity to logistics support and fabrication supply. Therefore, these factors make it difficult to develop a universal cost estimating function for floating substations and therefore a site-by-site methodology is necessary as presented in this paper.

Basis of Design

The floating wind farm site for the present work is located 16 km (10 miles) from the Maine coast and Maine islands. The site is assumed near Monhegan Island as marked in the red box in Fig. 1 where the bathymetries are also shown. Site water depth considered is 100 m (328 ft). Metocean conditions of the site for the 1-yr operating, 50-yr extreme and 500-yr survival cases provided in ABS (2013) are used and summarized in Table 1. HSWL (High Sea Water Level) and LSWL (Low Sea Water Level) are determined with tidal elevation and storm surge.

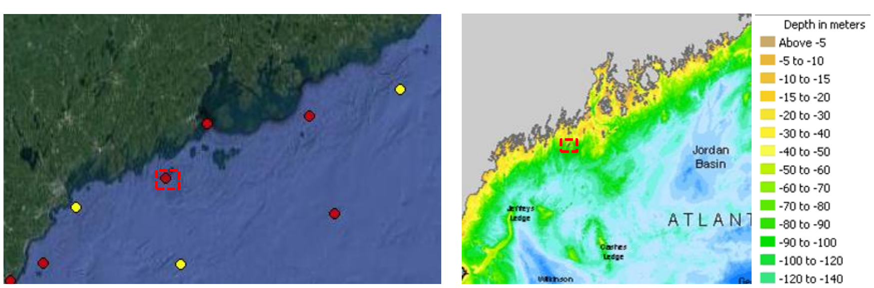


Fig. 1 Floating Wind Farm Site and Bathymetry of Gulf of Maine

Table 1. Metocean Condition of Wind Farm Site

Platform Condition	Operating	Extreme	Survival
Sea States	1-yr	50-yr	500-yr

Wave Hs (m)	6.73	10.66	12.97
Tp (s)	10.92	13.21	14.48
Gamma	1	2.4	2.4
Wind 1hr @ 10m (m/s)	19.41	26.7	30.94
Current @ Surface (m/s)	0.49	0.57	0.61
Storm Surge (m)	0.14	0.58	0.84
Tide (m)	2.06	2.06	2.06

The offshore floating substation platform is designed to support the topside (electrical substation) with a rated capacity of 200 MW for a service life of 20 years. The substation platform design is based on the offshore platform design practices and design codes and standards of ABS (2013, 2014, 2015), ABS FPI (2013), API RP 2SK (2005) and API RP 2T (2010).

Table 2 summarizes the design criteria of heel (roll and pitch combined) angle, acceleration at the topside and air gap of the substation platform. The heel angle and acceleration criteria are based on offshore oil and gas floating platform design practices whereas the air gap requirements are based upon ABS (2015) and ABS FPI (2013). Catenary and tendon mooring design requirements are provided in Table 3. The tendon type used for the TX-WindStation is chain instead of the steel tubulars typically used for the oil and gas TLP tendons, thus the Factor of Safety (FoS) of the tendon considered is the same as the catenary mooring design, as recommended in ABS (2013). Table 4 presents the FoS of the driven pile design where the bias factors are incorporated, for TX-WindStation (API RP 2T, 2010).

Table 2. Floating Substation Platform Design Criteria

Sea States	Dynamic Heel (deg)	Acceleration @ Deck (g)	Air Gap (m)
50-yr	≤ 10	≤ 0.4	≥ 1.5
100-yr	-	-	≥ 0.0

Table 3. FoS for Catenary and Tendon Mooring Design

Sea States	Line Condition	FoS
50-yr	Intact	1.67
	One Line Removed	1.25
500-yr	Intact	1.05

Table 4. FoS for TX-Wind Driven Pile Design

Sea States	Tendon Condition	FoS
1-yr	Intact	3.0
50-yr	Intact	2.25
500-yr	Intact	2.25
50-yr	One Line Removed	2.25

Floating Substation Platform Configurations

The X-WindStation and TX-WindStation have an "X" shape hull form consisting of four outer columns and one center column. The center column is considered to reduce the deck steel weight. The X hull form is evolved from the TX-Wind, a TLP-type floating wind platform (Boo et al., 2019). The topside (electrical substation) dimensions, deck area and weight for 200 MW are determined through a regression analysis from the existing fixed offshore wind substations. Typically, a three-level deck has been used for the fixed substations. However, a two-level deck is implemented for the floating substation while maintaining the required deck area such that the resulting deck footprint becomes wider. This benefits the platform by lowering its center of mass. The evolution of the floating substation concept is illustrated in Fig. 2.

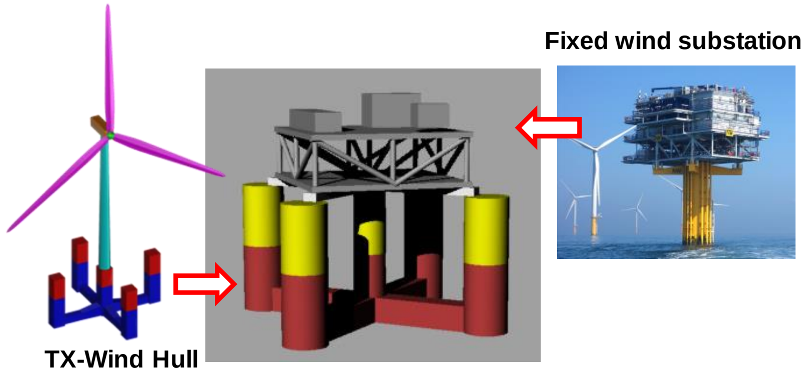


Fig. 2 X-Hull Form Floating Substation Evolutions from Floating Wind and Fixed Substation

The X-WindStation and TX-WindStation platform particulars are summarized in Table 5. The total weight of the substation platform is estimated considering the hull structure, topside, appurtenances, marine growth, ballast and marine system, with an appropriate contingency. Freeboard height and draft for TX-WindStation are adjusted to meet the requirements of the air gap at HSWL and minimum tension at LSWL. Each platform is sized to comply also with the hydrostatic stability requirements (ABS FPI, 2013) including transit operations.

In order to improve the platform responses of X-WindStation semi-type platform, Motion Attenuation Structure (MAS) (also called damping plates) is implemented at the keel of the platform. Details of the MAS can be found in Kim and Boo (2018) and Boo et al. (2017). Fig. 3 depicts the X-WindStation and TX-WindStation platforms.

Table 5 X-WindStation and TX-WindStation Platform Particulars

Items		X-WindStation	TX-WindStation
Displacement	ton	5,883	4,803
Draft – Operating	m	14.0	14.5
Deck Dimension (L,B,H)	m	30, 30, 14	30, 30, 14
Outer Column Center Radius	m	27.0	25.0
Outer Column OD	m	8.5	8.0
Center Column OD	m	8.5	4.2
Column Height	m	25.0	26.5
Pontoon Width, Height	m	4.8, 4.8	4.2, 4.2
Number of Mooring Lines	-	8	8

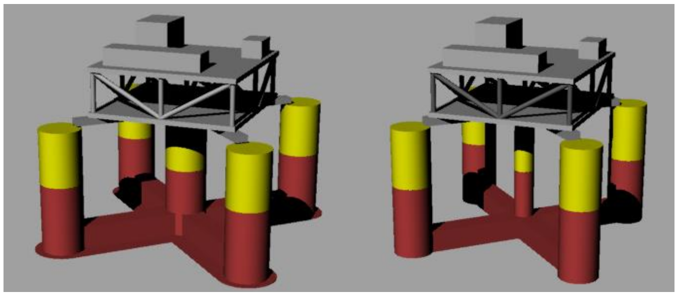


Fig 3. X-WindStation semi (left) and TX-WindStation TLP (right) type platforms

Multiple intra-field cables interconnect the turbine platforms and substation, and a single export cable connects the substation to the shore grid as depicted in Fig. 4, where 40 units of 5 MW floating wind platforms are assumed. Among options for power transmission to shore HVAC is selected based on the distance to grid and the electrical transformer equipment weight and cost.

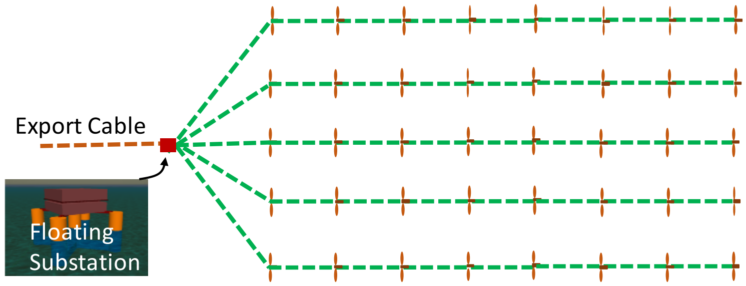


Fig. 4 Floating Substation and Typical 200 MW Wind Farm Layout with 5MW Floating Wind Platform

Mooring Configurations

The X-WindStation and TX-WindStation platforms are moored with eight catenary chain lines and eight chain tendons at a water depth of 100 m (328 ft), respectively. Table 6 summarizes the mooring line and tendon properties. One end of each mooring line or tendon is connected to a fairlead or tendon top connector located near the keel of the outer column, and the other end is connected to an anchor foundation consisting of a drag anchor for the catenary lines and driven pile for the tendons. Fig. 5 presents the layouts of the catenary and tendon mooring. Mooring line numbers for the catenary mooring for X-WindStation are shown in Fig. 6. The tendons for TX-WindStation are numbered in the same manner.

Table 6 X-WindStation and TX-WindStation Mooring Properties

Items		X-WindStation	TX-WindStation
# of Lines	-	8	8
Length	m	700	85.5
Material	-	Chain Studless R4	Chain Studless R4
OD	mm	111	111
Pre-Tension	kN	5,056	13,110

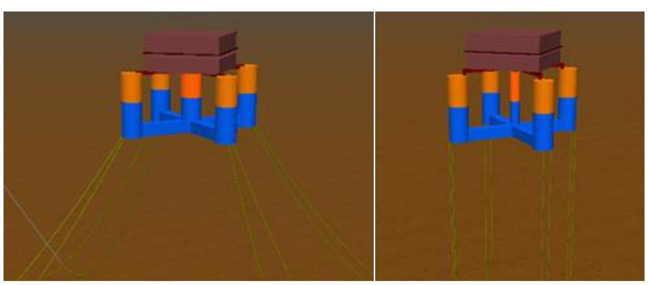


Fig. 5 Mooring Layouts of X-WindStation (left) and TX-WindStation (right) from Numerical Model

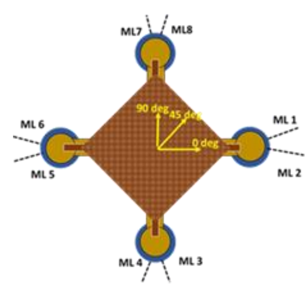


Fig. 6 Catenary Mooring Line Numbering and Heading Definition

Responses of X-WindStation and TX-WindStation

Numerical Modeling

A time domain analysis was conducted to evaluate the responses of each platform. Wind loads were implemented in the numerical model in terms of wind coefficients. The current loads on the platform and the mooring lines were represented in the model using drag coefficients. Hull viscous damping was also included using Morison drag elements. The foregoing numerical analysis was carried out for environment headings of 0 and 45 degrees, taking advantage of symmetry of the hull and mooring. The heading definition is shown in Fig. 5, where 0 and 90 deg headings are aligned with the positive x- and y-axis, respectively. Wind, wave and currents are co-directional. The mooring line damage (removed) condition assumes ML5 is the damaged line.

Sea water levels associated with the sea states can affect platform responses, particularly air gap, tendon top and anchor tensions for TLP-type platforms. Thus, for the TX-WindStation, the air gap and tendon top maximum tensions were simulated with HSWL cases. In contrast, the minimum tensions at the anchor for TX-WindStation were simulated with LSWL cases. Other responses for TX-WindStation and all the responses of X-WindStation were computed for MSL (Mean Sea Level) conditions. Maximum (or minimum) values of responses are estimated with Rayleigh Most Probable Maximum (MPM) values.

Platform Natural Periods

Natural periods of the substation platforms were determined through free decay motions (i.e., imposing an initial offset and allowing the platform to oscillate on its mooring system) and are compared in Table 7. It is seen that heave, roll and pitch periods of the TX-WindStation are much lower than the X-WindStation values due to very high axial stiffness and moment induced by the tendons.

Table 7 Natural Periods of Substation Platforms

Platforms	Surge sec	Sway sec	Heave sec	Roll sec	Pitch sec	Yaw sec
X-WindStation	52.2	52.2	15.9	17.4	17.4	38.3
TX-WindStation	44.7	44.7	1.6	1.4	1.4	32.0

Substation Platform Air Gaps

Air gaps to the bottom of the substation deck were measured for the water level of MSL for X-WindStation and HSWL for X-WindStation. Fig. 7 shows the air gaps for both platforms. The minimum air gaps for the extreme and survival conditions for both substation platforms are greater the required minimums.

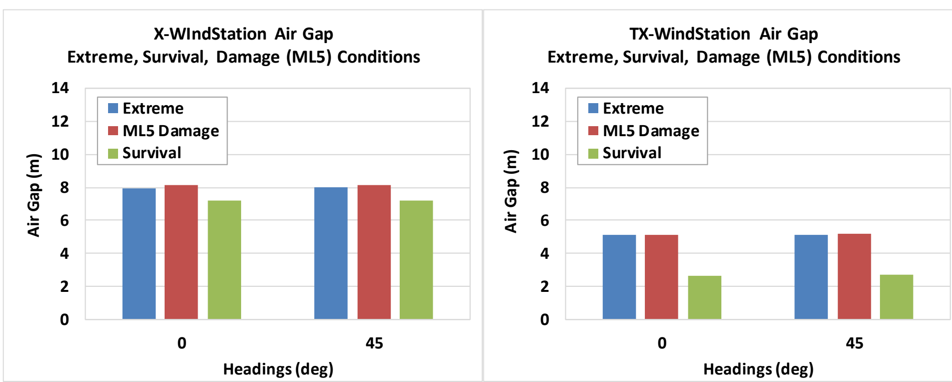


Fig. 7 Air Gaps of X-WindStation and TX-WindStation

Substation Platform Rotations

Fig. 8 compares the rotation angles for the operating, extreme, survival and mooring line damage conditions. It is confirmed that the rotation design requirements for both substation platforms are met. The rotations for the 45 deg heading are the combined angles with the roll and pitch. Due to the tendon effects on TX-WindStation, its rotations are much smaller than those of X-WindStation.

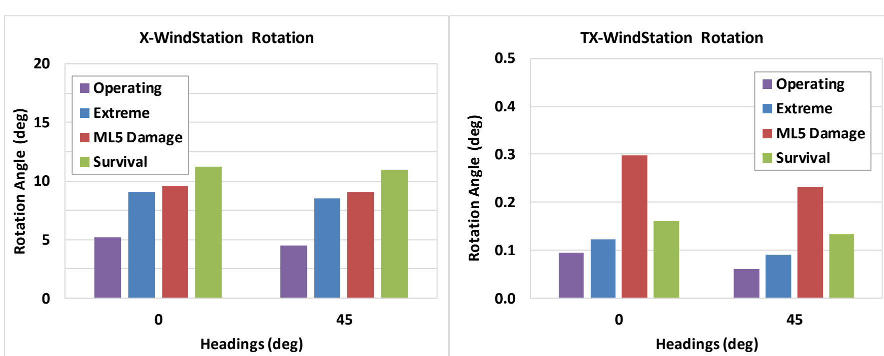


Fig. 8 Rotation Angles of X-WindStation and TX-WindStation

Substation Platform Accelerations

Horizontal (lateral) and vertical accelerations at the deck center of the substation platforms are shown in Fig. 9. The accelerations were determined with the accelerations induced by both rectilinear and angular motions of the platform. Both values are lower than the design requirement of 0.4g for the extreme conditions. It is seen that the vertical accelerations of the TX-WindStation are very small compared to the values of X-WindStation, again due to the tendons.

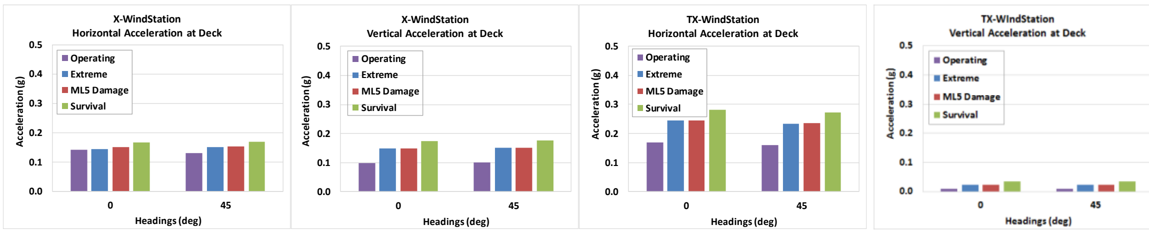


Fig. 9 Horizontal and Vertical Accelerations of X-WindStation and TX-WindStation

Mooring Maximum Top and Minimum Anchor Tensions

Maximum mooring top tension "normalized FoSs" of each line are compared in Fig. 10, where the normalized FoS is determined by "FoS estimated" divided by "FoS required" in Table 3. Therefore, each normalized FoS must be greater than 1.0 to comply with the requirements for the extreme, survival and mooring damage conditions. It is observed that the FoSs of the TX-WindStation are lower than the values of the X-WindStation. The lowest normalized FoS for both platforms occurs on the neighboring mooring line of the damaged line.

Fig. 11 presents the minimum anchor tensions of TX-WindStation for the LSWL case. It is confirmed that the minimum tension at the anchor is positive for all the considered design sea states, complying with API RP 2T (2010).

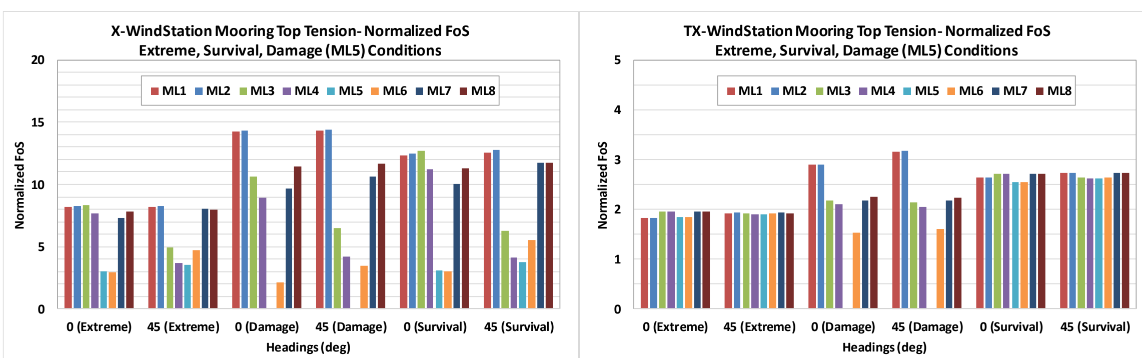


Fig. 10 Maximum Mooring Top Tension FoSs (Normalized) of X-WindStation and TX-WindStation

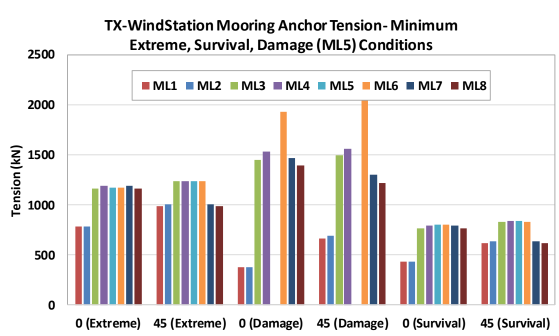


Fig. 11 Minimum Anchor Tensions of TX-WindStation

Cost Estimate

CAPEX costs of the floating substation platforms are calculated for three configurations depending on the anchor foundation arrangement as described below:

- *X-WindStation*: with eight catenary lines and a dedicated drag anchor for each line
- *TX-WindStation A*: with two tendons and a shared driven pile per column (total eight tendons and four driven piles), where the tendons are slightly angled toward each dedicated bottom connector with a separation on the top of the shared anchor pile
- *TX-WindStation B*: with eight tendons and a dedicated driven pile for each mooring tendon.

CAPEX of each platform configuration includes the procurement, fabrication and integration of the topside onto the hull, installation of the platform, mooring lines and anchors, and commissioning. Insurance costs and contingencies for offshore operations are also included. Pre-sanction costs, such as project approvals, permitting, environmental impact studies, metocean site and seabed surveys are excluded. In addition, the costs of subsea cables between turbine platforms and to the substation, the export cable from the substation to shore, and an onshore substation at the grid tie-in location are also excluded from the estimate.

The relatively compact size and shallow lightship draft of the floating substations, allow for fabrication of the substation hull in a Northeast U.S. fabrication yard (Elkington, 2014). Supply of all electrical equipment and assembly thereof into a functioning substation is also assumed to occur regionally in the Northeast. Mooring chains, anchors and piles can also be sourced regionally. However, for the tendon mooring systems, tendon connector supply is assumed from the U.S. Gulf of Mexico or from Europe, depending upon which specialist supplier is selected. Input factors for the CAPEX calculations are summarized in Table 8.

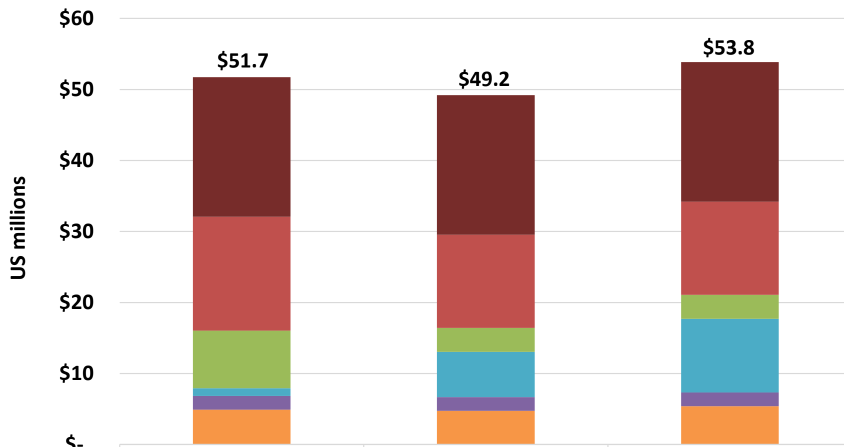
Table 8 CAPEX Input Component Descriptions

Component or Activity	Descriptions
Electrical Substation (Topside)	Parametric costs based upon fixed wind farms in Europe (Gonzalez-Rodriguez, 2017), with suitable adjustments for US marketplace
Floating Hull (Foundation)	Hull cost components using NREL unit costs (Beiter et a., 2016)
Mooring System	Mooring lines, connectors and anchors sourced from U.S. suppliers in the Northeast, except for the specialist tendon mooring connectors
Integration	Cost for lifting, integrating and quayside pre-commissioning of the substation
Installation and Procurement	All costs for installing the floating substation platform at site, including pre-installation and subsequent connection of mooring lines are included.

Because of the relatively short distance from shore, no helideck on the substation platform is considered, and all access to the platform is assumed to occur via boats. The substation is also assumed to be unmanned, though temporary shelters are included in the cost to allow for temporary, short term sheltering of work crews.

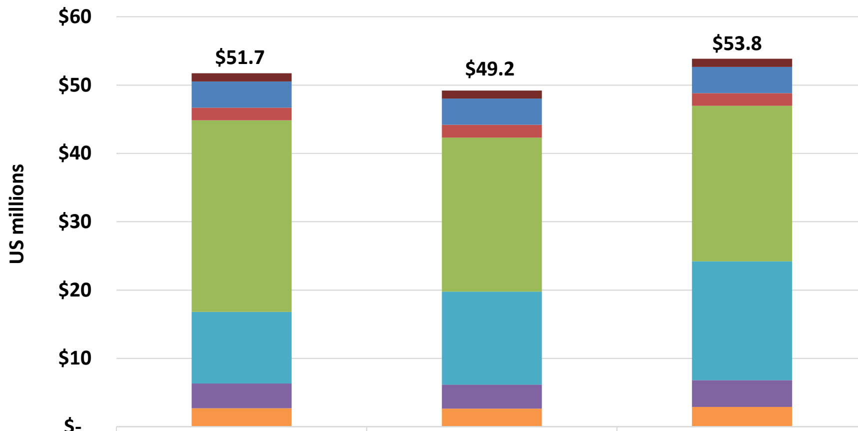
The cost of the HVAC electrical equipment is entirely based upon parametric values and a contingency of 30% is included to allow for specification variances for future wind farm operators. It should also be noted that there are several large and mid-sized firms that are technically capable of supply HVAC systems in modular format for installation on board a substation hull, and therefore competition may actually result in lower electrical substations costs than calculated in this study.

Figs. 12 and 13 compare the floating substation costs for all three configurations considered. It is seen that the semi-type substation platform cost is lower than the TLP-type cost in the no anchor sharing case due to mainly anchor cost, whereas the TLP-type with anchor sharing is highly comparable to the semi-type platform. The highest cost functional component of the floating substation platform is the electrical substation followed by the floating hull. Similarly, the highest cost execution activity is procurement. Procurement cost can be broken down approximately as 35% equipment (primarily for the topside) and ranges from 18% materials (hull steel, mooring lines and anchors) for the semi-type and 8% (hull steel, tendons and anchors) for the TLP-type foundations. Depending upon the floater type and mooring system selected, the CAPEX ranges from $49 to $54 million.



	X-WindStation	TX-WindStation A	TX-WindStation B
Electrical Substation (Topside)	$19.66	$19.66	$19.66
Floating Hull (Foundation)	$16.03	$13.12	$13.12
Mooring	$8.09	$3.38	$3.38
Anchors	$1.10	$6.38	$10.35
Mating and Integration	$1.94	$1.94	$1.94
Transport, Towing and Installation	$4.91	$4.75	$5.40

Fig. 12 Floating Substation Platform CAPEX by Functional Component



	X-WindStation	TX-WindStation A	TX-WindStation B
Project Management	$1.19	$1.19	$1.19
Engineering	$3.83	$3.83	$3.83
Certification / Fees / Insurance	$1.86	$1.86	$1.86
Procurement	$28.03	$22.54	$22.76
Construction / Fabrication	$10.49	$13.63	$17.39
Transportation / Logistics / Installation	$3.61	$3.51	$3.90
Hook Up / Commissioning	$2.71	$2.65	$2.91

Fig. 13 Floating Substation Platform CAPEX by Execution Activity

The floating substation cost is approximately 50% greater than the cost of a fixed offshore substation platform including the substructure and electrical substation (Gonzalez-Rodriguez, 2017). However, for this study, we assumed a water depth of 100 m (328 ft) for the floating substation, while fixed substations are installed in water depths typically of less than 40 m (131 ft), which contributes to some of the difference. However, fixed substations are limited by depth, and at some water depth the cost of the fixed foundation will become more expensive than a floating substation. Additional study to determine the water depth limits for fixed foundations compared to floating wind foundations may be beneficial in two ways: first, it would identify technology limits for foundations, and, secondly, it would allow for additional wind farm site planning to locate the substation as close to shore as possible in order to possibly realize some project cost savings. However, it should be noted that subsea power cables are quite expensive (Beiter, 2016), and even if one places the substation much closer to shore, the intra-field power cable costs to the substation may mitigate any possible savings in siting the substation near shore on a fixed foundation.

For the electrical substation (topside), no energy storage system is included, and all design assumes that the electrical substation gathers power from the floating production platforms and then converts the voltage to HVAC in order to export the power to an onshore grid connection. Though energy storage systems have shown benefits in stabilizing power grids and provided surge power capacity, the size and role of the energy storage system if included on a substation will need to be defined by the utility's requirements. While some energy storage has already been installed and trialed on the Hywind Scotland wind turbines, it may be worthwhile completing a technical and economic analysis of including energy storage on a substation compared to distributing energy storage across multiple production units.

Summary and Recommendations

The technology for offshore wind has advanced using high efficiency foundation (platform) designs and by implementing offshore design technology. For floating wind farms, the technology is also advancing by incorporating low cost mooring and optimizing execution options, however floating substation designs are at a relatively very early stage compared to the progress observed in floating production platforms. All existing substations are for fixed wind farms located near shore and shallow water. To date, no offshore floating substations have been installed because the size and location of floating farms do not yet justify the cost of a substation. This will likely change in the future, and floating substations will eventually be required for large floating offshore wind farms in water depths deeper than can be economically support fixed substations.

Two different types of floating substation platforms of X-WindStation semi-type and TX-WindStation TLP-type have been developed for a 200 MW wind farm located at 100 m (328 ft) water depth, for an application for the Northeast U.S. offshore. Both designs are confirmed to comply with ABS and API requirements for global performance and mooring systems as well as reasonable operational parameters from offshore oil and gas floating platform design practices.

Installed CAPEX costs of the substation platforms were estimated for three configurations. The semi-type substation platform cost is lower than the TLP-type cost in the case where anchors are not shared between two tendons, whereas the TLP-type with anchor sharing is highly comparable to, if not less expensive than, the semi-type platform. CAPEX analysis suggests that a floating substation for 200 MW rating would cost in a range between $49 and $54 million, depending on the type and mooring arrangement of the substations. The CAPEX of the floating substations is found to be more expensive than the fixed offshore substation platform cost due to various associated factors with floating platforms.

While there are efforts to develop cost optimized floating wind platforms, few have yet addressed or developed floating substation designs, and, consequently, opportunities still exist for developing and optimizing such systems. Furthermore, while some attempts may merely adapt floating wind foundations for electrical substations, such an approach may not always be optimal, as the dynamic load characteristics of the substation platform differs markedly from a wind turbine.

Results from the current analyses of the X-WindStation and TX-WindStation floating designs are sufficiently robust to suggest that they will be technically feasible and able to support a floating wind farm in deeper water such as in the Northeast U.S. and elsewhere in the U.S.

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