Application of Novel Offshore Oil & Gas Platforms to the Support of Large Wind Turbines
Final Report

(Milestone #8)

Prepared for National Offshore Wind Research & Development Consortium
Project #120 PON 4476

Deep Reach Technology

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X01	26 August 2022	Review Draft
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NOTICE

ABSTRACT

Floating wind is expected to grow from 121 MW in 2021 to more than 25 GW in the next decade. Only a few wind concepts have been installed on small demonstration projects. To meet the challenge of building 100s of floating substructures a new paradigm for fabrication and installation is required. Current methods require months for fabrication of a single platform. This study examines the "Application of Novel Offshore Oil & Gas Platforms to the Support of Large Wind Turbines", and more particularly the application of innovative manufacturing and installation methods. The objective is to see how these platforms can be applied to solve the challenges of building an economic wind farm with floating substructures. Our approach has been to investigate automated manufacturing methods, that have been applied to monopiles, for cost reduction to the components of floating systems, particularly cellular spar hulls. These methods allow local fabrication of the platforms and expedited manufacturing expected to achieve production of one turbine substructure per week rather than months for typical offshore platform fabrication. We have concluded that these methods can potentially achieve LCOEs in deep-water approaching those of current shallow water floating and fixed installations.

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ACRONYMS

ARPA-E: Advanced Research Project Agency – Energy (US Dept of Energy)
CAPEX: Capital Cost
DLC: Design Load Case
DOE: Department of Energy
DRT: Deep Reach Technology, Inc
EERE: DOE Office of Energy Efficiency and Renewable Energy
FCR: Fixed Charge Rate
FCR: Fixed Rate Charge method for LCOE calculations
FFRDC: Federally Funded Research and Development Centers
IEC: International Electrotechnical Commission
LCOE: Levelized Cost of Electricity
NCR: Net Capacity Factor
NOWRDC: National Offshore Wind Research and Development Consortium
NREL: National Renewable Energy Laboratory
NYSERDA: New York State Energy Research and Development Agency
OPEX: Annual Operating Cost
RNA: Rotor and Nacelle Assembly
TLP: Tension Leg Platform
TBT: Tension Buoyant Tower
TVO: Trendsetter Vulcan Offshore, Inc.

1 Executive Summary

This project examined the application of novel platforms currently being used in the offshore oil and gas industry for use as floating offshore wind turbine foundations. The platforms include the cell spar, moored buoyant tower, tension buoyant tower (TBT) and a mini-tension leg platform (TLP), see Figure 1. Designs were developed for two sites: California's Humboldt Bay BOEM Call Area, water depths of 500 and 1000m, and the Gulf of Maine, water depth of 150m. The designs assumed the NREL 15MW "reference turbine" (Gaertner, et al., 2020). (References are at the end of this document.)

The cell spar was shown to be feasible in California but is not suitable for depths of 150m or less. The moored buoyant tower is suitable for these depths. The Tension Buoyant Tower was eliminated because it lacked the yaw stiffness required. The TLP design, based upon the Glosten PelaStar® concept, was suitable for both sites. In all cases "feasibility" required upgrade of the tower specified from a monopile in the original 15MW turbine specification to a stiffer design like that proposed for the VolturnUS wind turbine (Allen, et al., 2020).

Of particular importance for the spar designs is the introduction of an automated manufacturing method which is especially suited to mass production of these wind farm foundations, see Figure 2. Using this automated method reduces the time to construct a unit for conventional ship or fabrication yards from months to weeks and reduces the cost per tonne of fabricated steel by an order of magnitude.

A new method of installing the turbine on spars is also introduced, which eliminates the need for floating offshore vessels to install the turbines. This utilizes a fixed tower, e.g. the substation tower, to serve as a base for transferring the RNA and blades to the tower, Figure 3.

Cost estimates for construction and turbine installation using these methods were used, together with published "balance of system" costs to produce LCOE estimates, shown in Figure 4. The range of LCOE costs is based on whether the "Balance of System" costs take advantage of estimated reductions due to the size of the turbine, e.g. fewer platforms per MW, are considered.

It was concluded that further work on these platforms, particularly the spar concepts, required optimization of the structure in conjunction with turbine and control systems design; further design and assessment of the manufacturing and installation plan; and investigation of the feasibility of incorporating a fixed platform for the substation and turbine installation at a suitable depth, particularly for the Pacific sites.

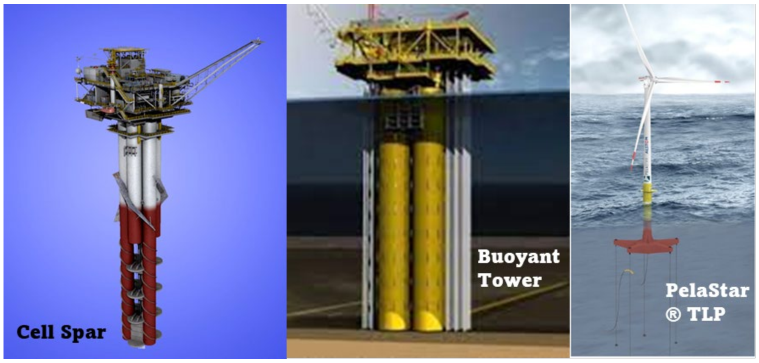

Figure 1 Cell Spar, Buoyant Tower and PelaStar® TLP[1]

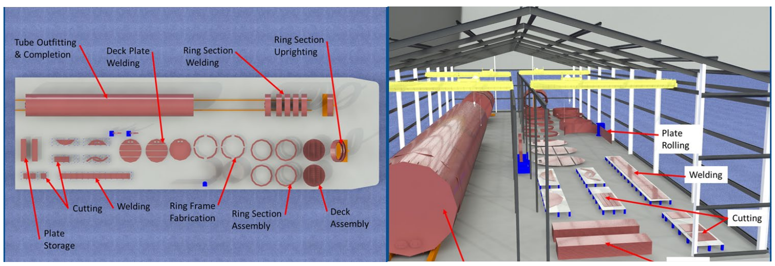

Figure 2 Automated Spar Manufacturing

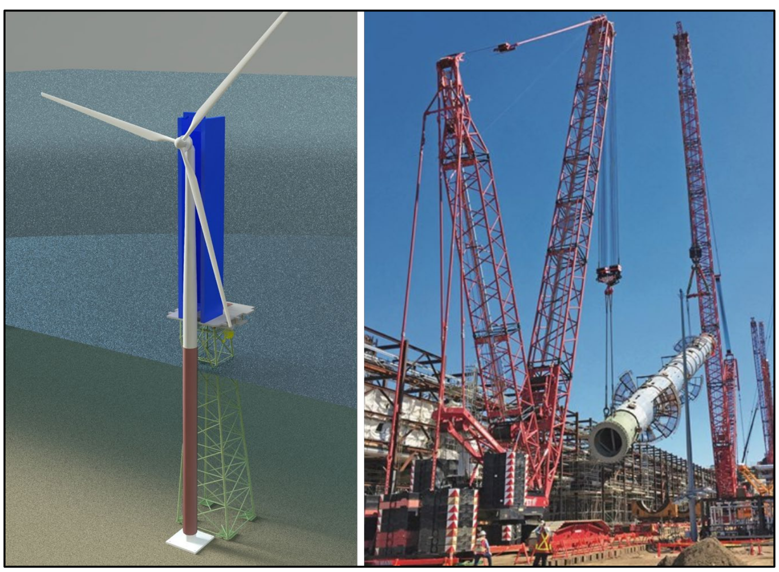

Figure 3 Spar Turbine Installation from a Fixed Platform (Source: Mammoet)

[1] Sources: (Reuters, 2015) (ENB, 2012) (Pelastar LLC, 2022)

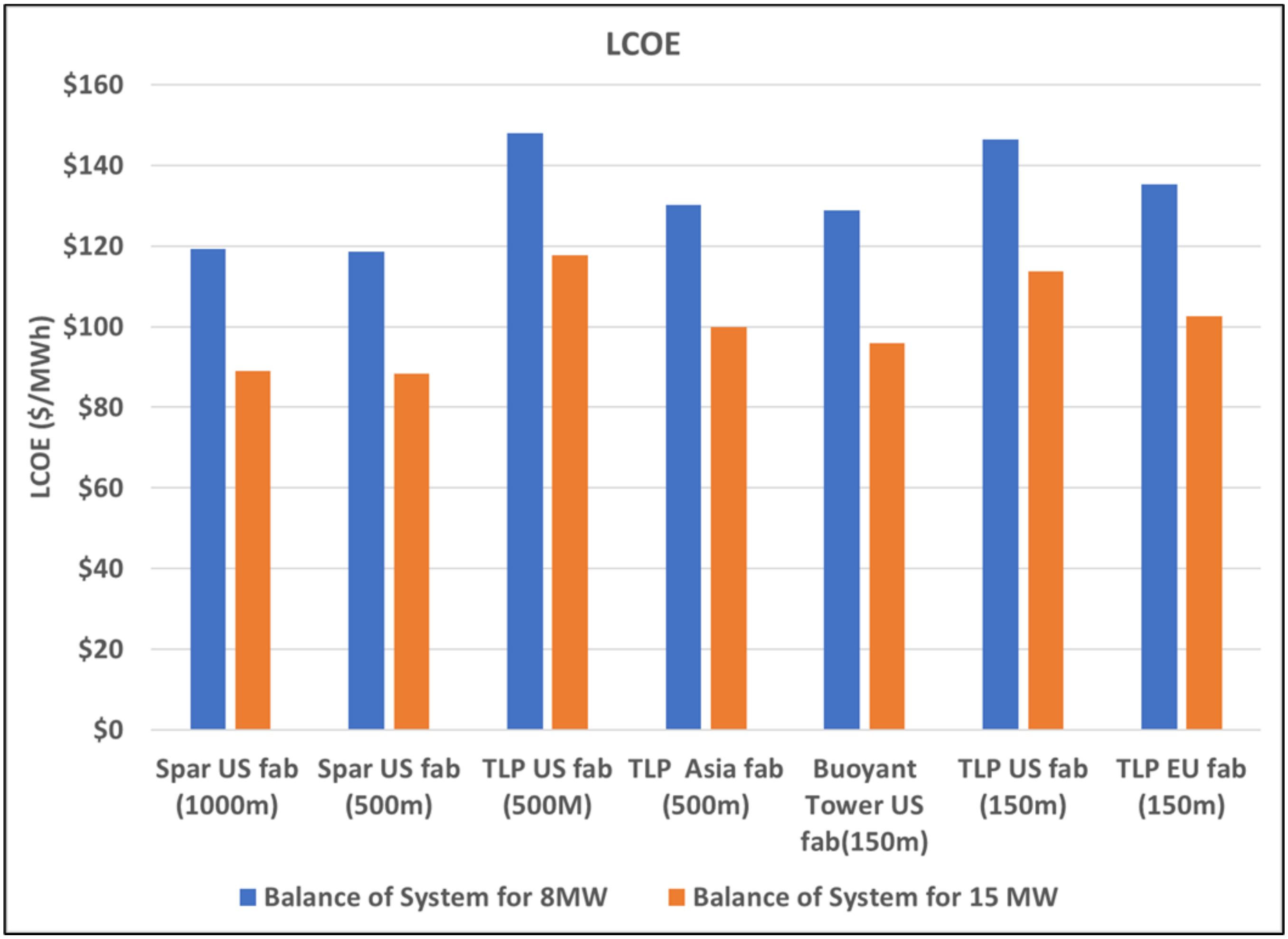

Figure 4 Summary of LCOE Results

2 INTRODUCTION

This report represents the completion of NOWRDC Project #120 under NYSERDA Program Opportunity Notice (PON) 4476. Deep Reach Technology, Inc. (https://www.deepreachtech.com/) is the prime contractor. Subcontractors include Trendsetter Vulcan Offshore (TVO) (https://www.trendsetterengineering.com/), Glosten (https://glosten.com/), and GE Research (GE) (https://www.ge.com/research/). TVO provided support in project management and specifically manufacturing and installation methods for the spar. Glosten prepared designs and cost estimates for their proprietary PelaStar® tension leg platform. GE participated in reviews and specifically prepared comments on the installation methods proposed for the spar (GE, 2022).

The project consisted of eight Tasks as listed below, each completed with its own internal report. The Sections of this report generally follow the sequence of these Tasks.

Task 1 – Basis of Design

Task 2 – Concept Design (sizing)
Task 3 – System Analysis and Mooring
Task 4 – Platform Costing
Task 5 – Study of Horizontal Turbine Installation
Task 6 – Mooring and Installation Costs
Task 7 - LCOE Assessment
Task 8 - Final Report

3 Summary of the Basis of Design (from Task 1 Report)

The Basis of Design is presented in (DRT, 2022a). This section summarizes the main elements.

3.1 Wind Turbine

The IEA 15 MW Offshore Reference Wind Turbine (Gaertner, et al., 2020) is utilized for this study. Properties of the RNA and tower are reported in the Table 1. The turbine thrust and power curves are also provided in Figure 1 below.

The original IEA document (Gaertner et al., 2020) which defines the 15-Megawatt Offshore Reference Wind Turbine considered the case of a fixed-bottom monopile support structure. Thus, the tower was designed for fixed bottom turbine design conditions which are generally milder than the criteria for floating offshore wind turbines.

Later the IEA published a technical report (Allen, et al., 2020) which defined the University of Maine (UMaine) VolturnUS-S semisubmersible designed to support the International Energy Agency (IEA)-15-240-RWT 15-megawatt (MW) reference wind turbine. The tower scantlings were modified to meet the requirements of the floating semi-submersible foundation. Figure 6 and Figure 7 compare the scantlings and section moduli for the two towers, and the masses and natural frequencies are compared in Table 2. For this study, the thrust and scantlings for the original monopile design were used unless otherwise indicated.

3.2 Site Conditions

Two sites are considered for evaluating the proposed concepts:

- Atlantic – Gulf of Maine
- Pacific – Humboldt Bay Call Area

The Atlantic site considered was in the Gulf of Maine about 25 km to the southwest of Monhegan Island and 65 km east from Portland. The Metocean data was compiled from studies done by the University of Maine (Allen C. , 2020) (Viselli, Forristall, Pearce, & Dagher, 2015). The studies collected data from 3 buoys near the site location from which Metocean parameters were extracted.

The Humboldt Call Area was chosen as the Pacific site. The location information is presented in Figure 8 (BOEM, 2020). Metocean conditions for this study were derived from NDBC Buoy 46022 at the location shown in the Figure (NOAA, 2022).

The most important metocean conditions for this study were those associated with IEC Design Load Cases 1.6 and 6.1 (IEC, 2019), Power Production and Survival (Parked) conditions respectively. Specifically, for the Power Production scenario the most important conditions considered were Severe Sea States associated with the rated wind speed, V_r = 10.9 m/sec at hub height, and the cutout wind speed, V_{out} = 25 m/sec. For the Gulf of Maine, the severe sea state was taken as the 1-yr significant wave height and associated period. For Humboldt Bay, buoy data from 2009 – 2021 was used and the Severe Sea State was taken as the maximum significant wave height recorded over that period at the associated wind speed. The periods associated with the maximum wave heights in both cases, T_p = 15.8 and 14.8 sec respectively, represent swell. Insofar as it is likely the dynamic response of the spar and tower will be governed by lower period resonant responses, and additional load case was added represented a sea state with approximately a 50-yr return period for T_p<10 sec.

For the Parked (Survival) condition, extreme sea states corresponding to 50-year return period were used (DRT, 2022a).

The soil conditions are derived from public information. Gulf of Maine data is derived from (Fugro Marine Geoservices, 2017). Pacific soil data was derived from (Cooperman, et al., 2022).

3.3 Load Cases and Sizing Criteria

The above data was used to derive load cases for analysis of the concepts considered here. Since the design utilizes a predesigned turbine, a reduced load matrix can be used for the analysis. The turbine is designed to a Class IB, and therefore wind loads are bound. Load cases relevant to the turbine design can thus be eliminated. Hull structural response is a consideration. Thus, the focus of the load cases is to gauge if the turbine capacity would be sufficient to withstand the additional loads due to floater motion, and whether the hull structural loads are adequately accounted for in the novel hull designs. For this purpose, a limited number of load cases have been identified for this study (IEC, 2019):

- Power Production (IEC DLC 1.6)
- Parked (IEC DLC 6.1)

The Load Cases are shown in Table 3 and Table 4 (DRT, 2022b). Condition criteria for sizing of the platforms per DNV-RP-0286 (DNV, 2021) were used in accordance with recommendations from the NOWRDC Advisory Board.

Table 1. Original IEA 15 MW Properties (Gaertner, et al., 2020)

Parameter	Value
Power rating [MW]	15
Turbine class	IEC Class IB
Specific rating [W/m^2]	332
Number of blades	3
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	10.88
Cut-out wind speed [m/s]	25
Design tip speed ratio	9
Minimum rotor speed [rpm]	5
Maximum rotor speed [rpm]	7.56
Maximum tip speed [m/s]	95
Rotor diameter [m]	240
Hub height [m]	150
Hub diameter [m]	7.94
Hub distance from center to blades [m]	3
Hub Overhang [m]	-11.01
Blade mass [t]	65
RNA mass [t]	1017
Tower mass [t]	859.8

Table 2 Comparison of Mass and Natural Frequencies

Parameter	Monopile	Volturn Semi
Tower Mass (t)	860	1263
Hub Ht (m)	150	150
RNA Mass (t)	**1016.6**	**991**
Tower+RNA (t)	1876.6	2254
Tower Nat Freq (Hz)	0.17	0.49
Tower Nat Freq (s)	5.9	2.0

Table 3 Load Case Table – Gulf of Maine

	Gulf of Maine		
Condition Criteria	Power Production Mean Tilt< 5 deg; Max Tilt< 10 deg; RNA accel<0.3 g		Survival Max Tilt<15 deg; RNA Accel< 0.6g
Metocean Basis	V_r Hs,sss (sea)	V_{out} Hs,sss (exp)	50-yr Extreme Wind and Wave (ESS)
Load Case	M1.6-1	M1.6-2	M6.1-1
Depth, m	110, 150	110, 150	110, 150
MSL, m	1.62	1.62	1.62
Highest Astr. Tide, m	3.22	3.22	3.22
Lowest Astro. Tide, m	0	0	0
Waves			
Hs, m	6.4	6.4	9.8
Tp. Sec	11.7	11.7	14.2
Jonswap, γ	2.75	2.75	2.5
Wind, m/sec			
Uw, 10-min ave @ 10 m elev	7.5	17.1	27.4
Uw, 10-min ave @ 150 m elev	11.0	25.0	40.0
Current, m/sec			
U @ MWL	0.3	0.6	0.9
U @ 50 m	0.3	0.6	0.8
U @ 100 m	0.2	0.2	0.5
U @ 200 m	0.2	0.2	0.4
U @ depth	0.2	0.2	0.2

Table 4 Load Case Table – Humboldt Bay Call Area (DRT, 2022b)

Humboldt Bay Call Area						
Condition Criteria[2]	Power Production Mean Tilt< 5 deg; Max Tilt< 10 deg; RNA accel<0.3 g			Survival (Parked) Max Tilt<15 deg; RNA Accel< 0.6g		
Metocean Basis	V_r Hs,sss (swell) [1]	V_r Hs,sss (sea) [2]	V_{out} Hs,sss (Exp.) [3]	50-Yr Extreme Swell & Associated Wind [4]	50-Yr Extreme Sea & Associated Wind [5]	50-yr Extreme Wind and Associated Wave [6]
Load Case	H1.6-1	H1.6-2	H1.6-3	H6.1-1	H6.1-2	H6.1-3
Depth, m	500, 1000	500, 1000	500, 1000	500, 1000	500, 1000	500, 1000
MSL, m	1	1	1	1	1	1
Highest Astr. Tide, m	2.6	2.6	2.6	2.6	2.6	2.6
Lowest Astro. Tide, m	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Waves						
Hs, m	8.1	4.6	4.4	10.6	5.9	6.4
Tp. Sec	16	8.2	13.1	15.0	8.2	14.2
Jonswap, γ	2.8	1.8	2.8	2.8	2.0	2.8
Wind, m/sec						
Uw, 10-min ave @ 10 m elev	7.5	7.5	17.1	16.5	9.9	25.3
Uw, 10-min ave @ 150 m elev	11.0	11.0	25.0	26.3	14.5	37
Current, m/sec						
U @ MWL	0.5	0.5	0.8	0.8	0.7	1.0
U @ 50 m	0.4	0.4	0.7	0.7	0.6	0.9
U @ 100 m	0.2	0.2	0.2	0.2	0.2	0.5
U @ 200 m	0.2	0.2	0.2	0.2	0.2	0.2
U @ depth	0.2	0.2	0.2	0.2	0.2	0.2

[2] (DRT, 2022e)

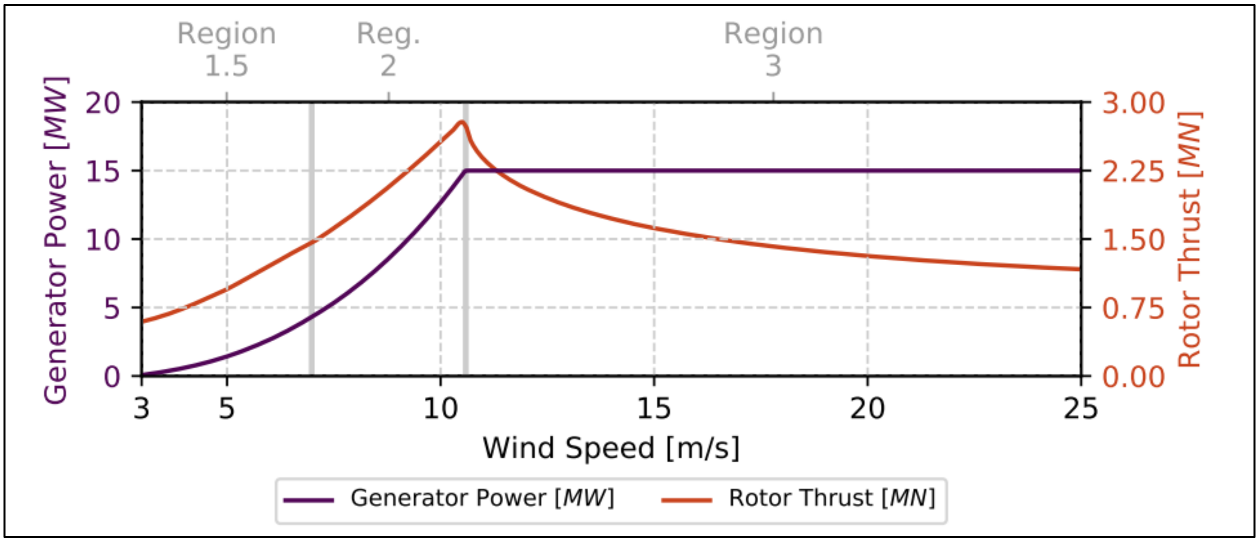

Figure 5 Power and Thrust Curves for IEA 15MW Turbine (Gaertner, et al., 2020)

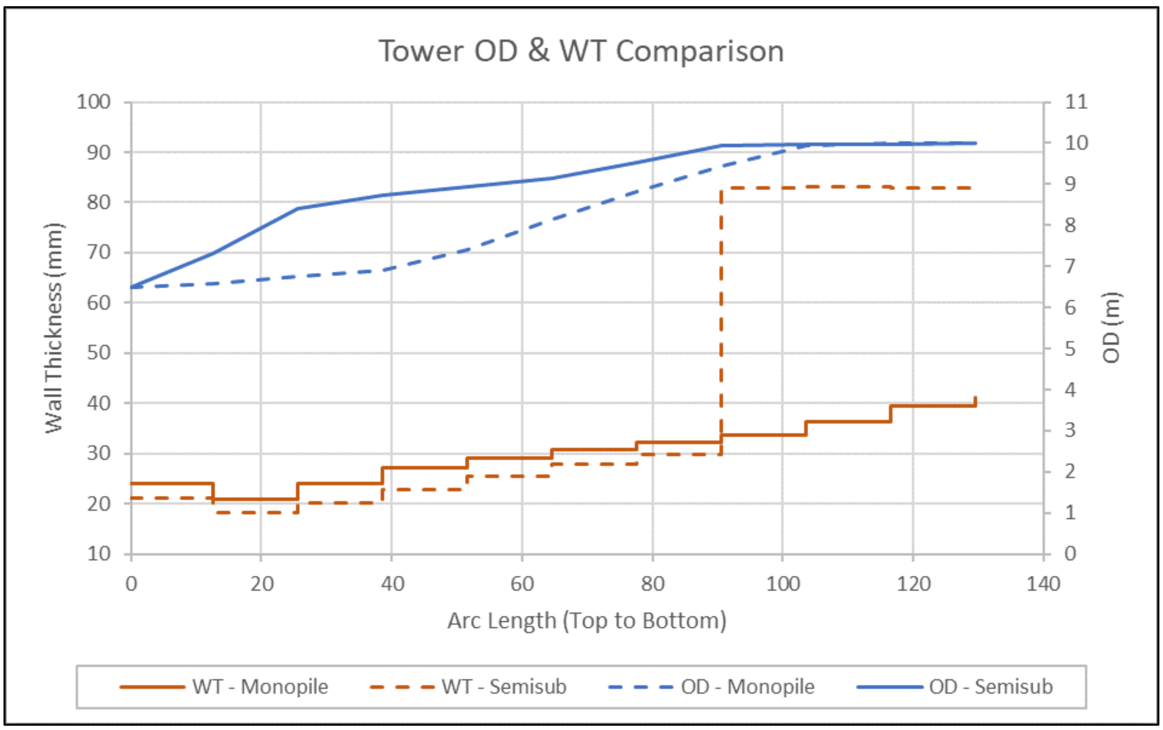

Figure 6 Comparison of Tower Scantlings

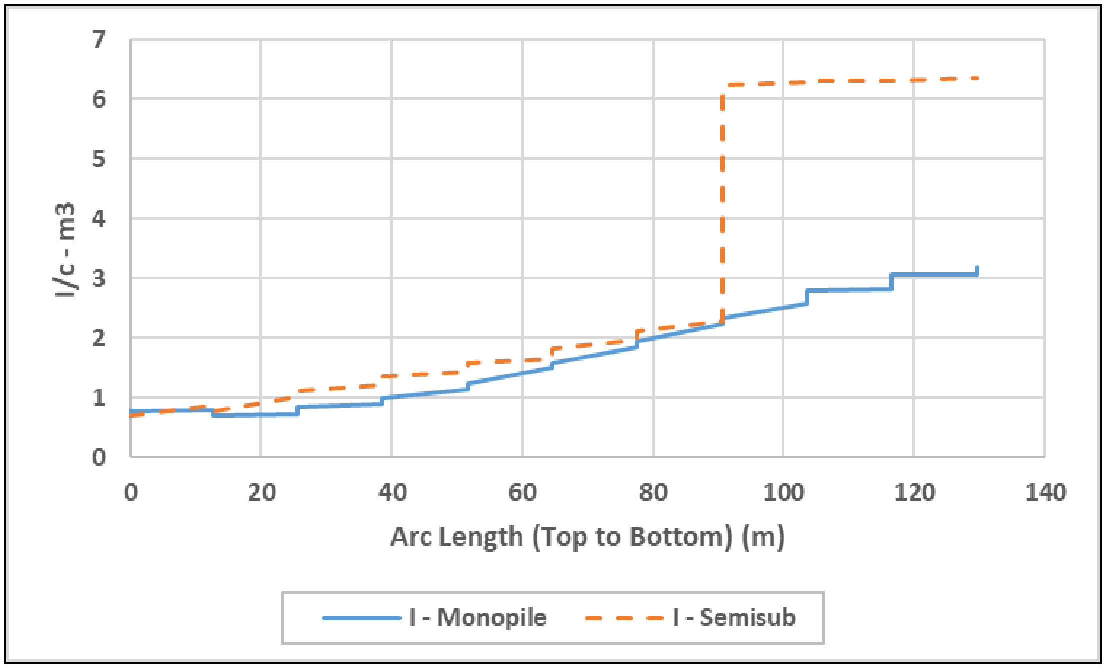

Figure 7 Comparison of Tower Section Modulii

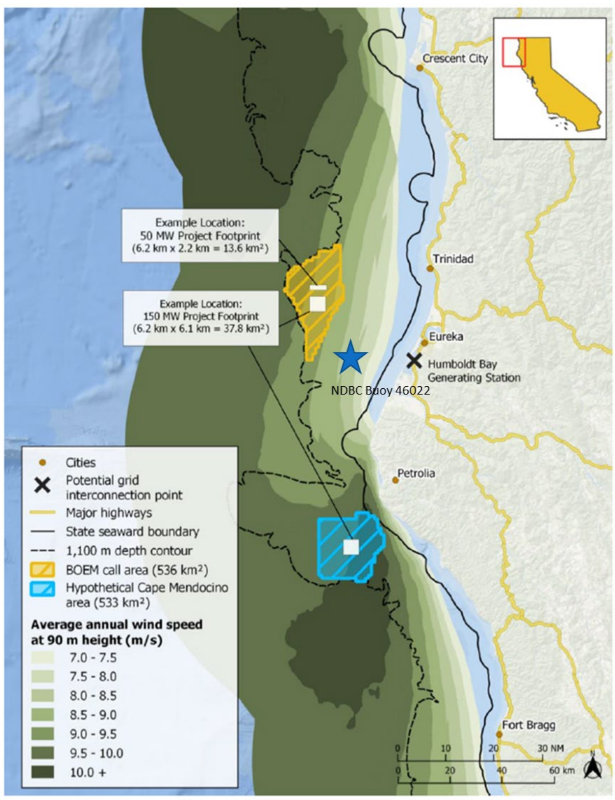

Figure 8 Humboldt BOEM Call Area (BOEM, 2020)

4 Description of the Concepts Developed (from Task 2 Report)

The Section describes the sizing of the various concepts. It is based primarily on the criteria shown in the load case Tables, Table 3 and Table 4. Specifically:

- For Power Production: Mean Tilt< 5 deg; Max Tilt< 10 deg; RNA accel<0.3 g in a severe sea state
- For Parked condition: Max Tilt<15 deg; RNA Accel< 0.6g in an extreme sea state

For the spar cases, the process involved selecting dimensions and ballasting which resulted in the mean tilt angle criteria under severe operating conditions being met, then performing dynamic analysis using Orcaflex to confirm the other parameters were met. There was no attempt to formally optimize the hull designs for the spars or buoyant towers. The designs here generally are based on the largest diameter believed to be feasible for a cellular design (based upon experience with previous spars and buckling considerations). This single-cell design is assumed to result in the lowest cost, however if further analysis suggests, for example, a shallower draft is desirable, multi-column designs could be considered. Glosten performed sizing of the Pelastar® TLP using their proprietary optimization software.

4.1 Cell Spar

Unlike almost every other floating platform, the spar achieves its stability by having its center of gravity below its center of buoyancy. This means it does not depend on the moment of inertia of the waterplane area for stability, and it is impossible to capsize. Initially, sizing involves selecting the main parameters, cell diameter, number of cells and draft such that the hull has enough buoyancy that it can support enough ballast to make it sufficiently stable for achieving the required tilt angles and accelerations.

The main parameters for the cell spar are shown in Table 5 and illustrated in Figure 9 and Figure 10.

4.1.1 Static Cases

The static sizing involves checking two conditions:

1. For power production under the rated thrust the static tilt angle must be five degrees or less, and
2. For installation, after upending before the fixed ballast is added, the GM must be greater than zero.

We assume for this purpose that the RNA will be installed after the spar is upended and fixed ballast is added, so condition #2 is evaluated without the RNA weigh, but with the tower weight, Table 6, shows the results of the static cases for the cell spar. The first two columns represent a single cell solution with 150 m draft and 13.8 m cell diameter. The first column represents the operating condition with the rated thrust and the second column the installation condition without the RNA in place.

The other columns represent a 4-cell spar with 8 and 6.9 m diameters respectively. The single cell design is considered the "base case" as it will be lower cost to fabricate. These backup cases are also considered because the existing base case is at the outer limit of what can be fabricated using this method. If during detailed design there is a need to increase overall platform capacity (larger turbine, etc.) these other cases can be good options that involve only a small increase in cost and complexity.

4.1.2 Layout and Mooring

The spar/buoyant Tower mooring spread assumes the following:

The wind farm will consist of 66 FOWTs with a capacity of 990MW

- The platforms will have a spacing of 1.6 km, see (Beiter, et al., 2020)
- The spread is illustrated in Figure 11 and Figure 12
- Each platform has four mooring lines
- The anchors are designed to hold the loads and service up to four lines tied to a single anchor, resulting in 264 mooring lines and 149 anchors (see Figure 11)

The water depth considered here varies from 150 m for the Buoyant Tower in Maine to 1000 m for the Humboldt Bay area[3]. Various mooring configurations could be used depending on the water depth, e.g.:

- Catenary with steel wire and chain: most suited for very shallow sites (<500 m)
- Taut or semi-taut steel wire & chain: Intermediate and deeper waters (500 – 1000 m typically) (Kuuri, Lehtinen, & Miettinen, 1999)
- Taut Polyester moorings: Intermediate to very deep waters (>500m).

Polyester moorings have been shown feasible for spar wind platforms as shallow as 180 m depth (Azcona & Vittori, 2019).

We assume the anchors will be subsea micropiles, Figure 13. This is a new development in anchoring which allows anchor templates to be installed in all types of soil and rock using a subsea robotic drill to install drilled and grouted piles to secure the template to the seafloor (Subsea Micropiles, 2022). It is capable of handling large horizontal and vertical loads (Robertson, 2018). The technology is currently in the demo phase and is expected to be commercially proven by 2023. DRT is supporting Subsea Micropiles development, and through a separate DOE SBIR is developing a method of instrumenting the micropiles that will allow taking of geotechnical data during pile installation which would eliminate the need for boreholes to be drilled prior to anchor installation (U.S. Department of Energy, 2021). However, for the purposes of this cost estimate, geophysical survey and boreholes at each anchor location are included.

[3] The Humboldt Bay call area includes depths to 1300 m.

4.1.3 Ballasting

Ballasting the spar is key to its functioning and stability. A large amount of fixed ballast is required to meet the operational requirement. Based on past spar experience the most economical solution is to pump magnetite (iron ore) into the fixed ballast tanks after upending. This leads the requirement that the upended spar be stable (positive GM).

The spar is divided into ballast compartments by horizontal bulkheads (decks). There is no longitudinal subdivision. The compartments are pressurized and flooded by depressurization and drained by pressurization by compressors. There are no pumps or other outfitting below the waterline.

4.1.4 Dynamic Analysis

Preliminary dynamic analysis was performed for the cell spar, Humboldt Bay load cases presented above to check dynamic tilt and RNA accelerations for the load cases defined in Table 3and Table 4 above. See (DRT, 2022c) Appendix.

Further dynamic results for all the concepts and cases will be presented in the next Milestone 3 report. If necessary, the hull parameters will be updated.

4.2 Pelastar® Tension Leg Platform

The Pelastar TLP has been under development by Naval Architecture firm Glosten (https://glosten.com/) since 2006 see e.g. (Hurley & Nordstrom, 2014). The concept, Figure 14, consists of a tower supported on five pontoons which are moored to the seafloor with taut synthetic cables. Glosten prepared two designs for this project: Humboldt Bay, 500 m water depth and Gulf of Maine, 150 m water depth. Principle parameters are tabulated in comparison of the main parameters for the platforms is shown in Table 7, Table 8 and Figure 15.

Table 5 Parameters for Static Sizing of Cell Spar

Parameter	Comment
INPUT	
Water depth, m	Depth of sizing of mooring
Freeboard, m	Distance from waterline (MSL) to deck
Draft, m	Distance from waterline to bottom of spar (keel)
Length, m	Total length = Draft + Freeboard
Mooring below WL, m	Distance from waterline to mooring attachment (fairlead)
Cell Diameter, m	Outer diameter of cell
No. Cells	Number of cells, see Figure 9
Ballast Draft, m	Distance from waterline to top of ballast (fixed + variable)
wt, mm	Wall thickness of cell for weight and stiffness estimate
RNA Wt, t	Mass of the Rotor Nacelle Assembly (including turbine)
RNA Elev, m MSL	Elevation of the RNA above the waterlin
Tower wt, t	Mass of tower supporting the RNA (above the deck level)
Tower Elev, m MSL	Elevation of tower center of gravity above the waterline
Max Thrust, tf	Rated turbine thrust
Steel Density, t/m3	Hull weight density based on previous designs (metric units)
Steel Density, lb/ft^2	Hull weight density based on previous designs (English units)
COMPUTED	
Hull wt, t	Total Hull Mass
Fixed Ballast, t	Fixed Ballast Mass
Fixed Ballast Ht, m	Height of Fixed Ballast
Water Ballast, t	Height of Variable (water) Ballast
Total Mass, t	Total Mass including Ballast
Gyradius, m	Radius of Gyration including Ballast
KG, m	Distance from keel to center of gravity
GM, m	Distance from center of gravity to metacentric height
Heel, deg	Heel angle under constant thrust
Tpitch, sec	Natural period in Pitch

Table 6 Cell Spar Cases

Case	Draft 150	Draft 150 w/o turbine	Draft 150 4 Cells 8 m Dia	Draft 150 4 Cells 8 m Dia w/o turbine	Draft 150 4 Cells 6.9 m Dia	Draft 150 4 Cells 6.9 m Dia w/o turbine
Freeboard	12	12	12	12	12	12
Draft	150	150	150	150	150	150
Length, m	162	162	162	162	162	162
Mooring below WL	20	20	20	20	20	20
Cell Dia	13.8	13.8	8	8	6.9	6.9
No. Cells	1	1	4	4	4	4
Ballast Draft, m	105	34.9	65	32.7	90	34.9
wt, mm	77.5	77.5	44.8	44.8	38.7	38.7
RNA Wt, t	1016	0	1016.0	0.0	1016.0	0.0
RNA Elev, m MSL	150	150	150	150	150	150
Tower wt, t	1263	1263	1263	1263	1263	1263
Tower Elev, m MSL	54.1	54.1	54.12	54.12	54.12	54.12
Max Thrust, t	280.6	0.0	280.6	0.0	280.6	0.0
Steel Density, t/m3	0.17	0.17	0.17	0.17	0.17	0.17
Steel Density, lb/ft^2	10.51	10.51	10.48	10.48	10.50	10.50
Hull wt, t	4082.3	4082.3	5469	5472	4077	4077
Fixed Ballast, t	14545.8	0.0	8437	0	11118	0
Fixed Ballast Ht, m	31.4	0.0	14	0	24	0
Water Ballast, t	2089.5	17651.3	14728	24178	5523	17657
Total Mass, t	22996.6	22996.6	30913	30913	22997	22997
Gyradius, m	59.8	34.7	54	32	60	35
KG, m	52.2	69.8	57.8	68.6	54.7	69.8
GM, m	22.8	5.2	17.2	6.4	20.3	5.2
Heel, deg	5.2	0.0	5.16	0.00	5.86	0.00
Tpitch, sec	35.6	43.1	36.8	36.2	37.7	43.2

Table 7 PelaStar® TLP Principal Characteristics

Site	Humboldt Bay (Pacific)	Gulf of Main
Water Depth, m	500	150
Arm Radius, m	55	52
Depth, m	79	77
Low water design draft, m	53	51
Mean Sea Level, m	54.61	52.61
High Water Design Draft, m	56.22	54.22
Hub Height Abv Baseline, m	204.61	202.61
Hub Height above MSL, m	150	150
Max Blade Tip above Baseline, m	324.61	322.61
Turbine rating, MW	15	15
50-yr Significant Wave Ht, m	10.6	9.8
Hull Lightship Weight, mt	3382	2876
Rotor-Nacelle Assby Weight, mt	1021	1021
Turbine Tower Weight, mt	1271	1221
Total Lightship weight of Platform, mt	5674	5118
Operational Seawater Ballast, mt	9217	5498
Total Installed Weight of Platform, mt	15044	10737
Platform and Turbine Vertical Center of Gravity	33.41	41.8
Installed Salt Water Displacement, mt		
LWDD	20473	15438
HWDD	20726	15685
Tendon Tension (Disp - Weight), mt		
LWDD	5429	4701
HWDD	5682	4948

Table 8 Weights/Displacement of Platforms

Case	Spar Humboldt Bay	Buoyant Tower Gulf of Maine	Pelastar Humboldt Bay	Pelastar Gulf of Maine
Water Depth	**1000**	**150**	**500**	**150**
Draft	150	150	54.6	54.6
Mooring Vert Preload, t	650	650	6039	5102
Hull Diameter, m	13.8	13.2	20	20
RNA Wt, t	1016	1016	1016	1016
Tower wt, t	1263	1263	1263	1263
Hull steel wt, t	4082	3728	3382	2876
Fixed Ballast, t	14546	12728		
Water Ballast, t	1439	2805	9217	5498
Total Weight + Mooring Loads, t	22997	22190	20917	15755
Buoyancy, t	22997	21040	20917	15755
Weight-Buoyancy, t	0	1149	0	0

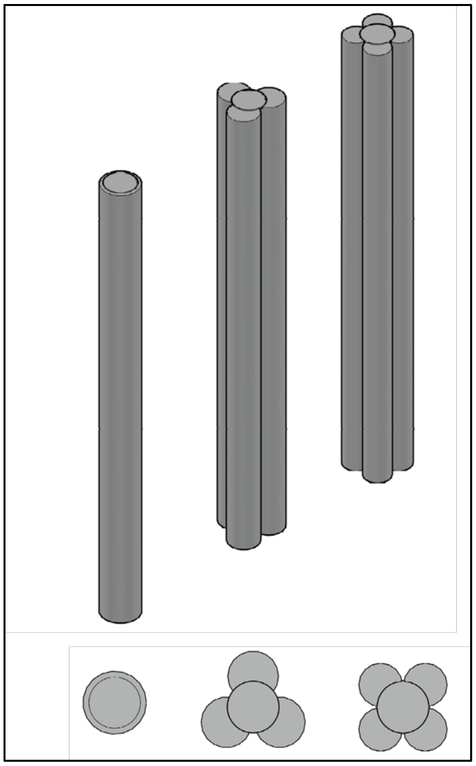

Figure 9 Cellular Configurations: 1-, 4- and 5- cells

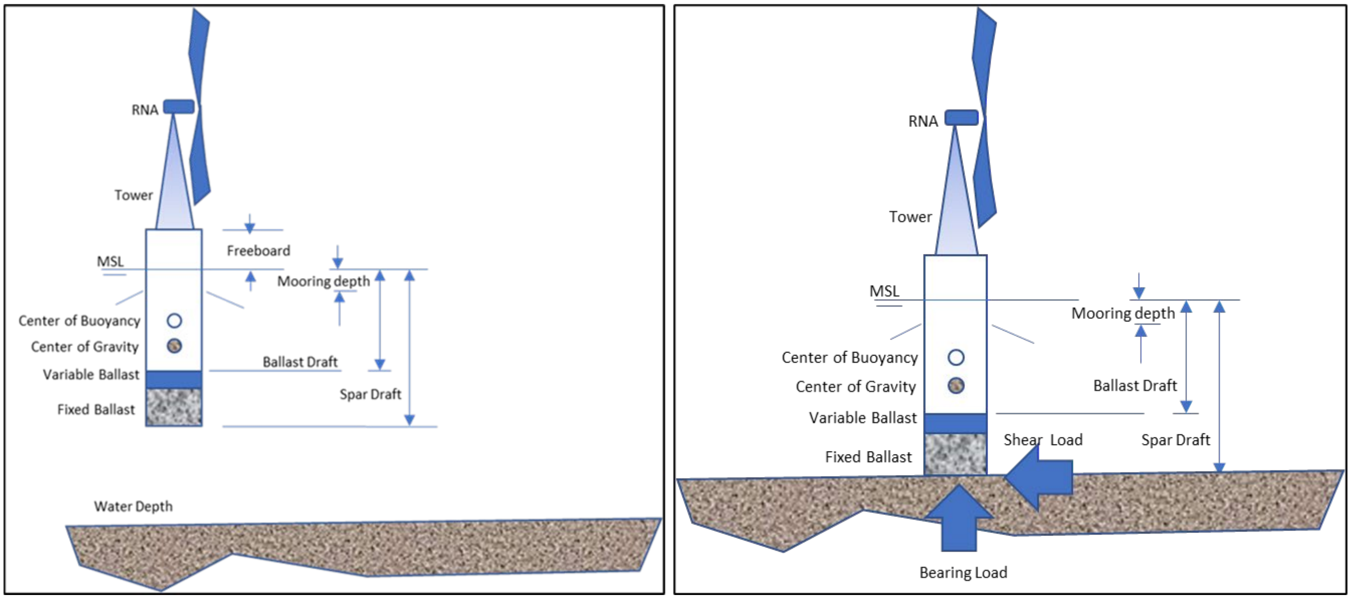

Figure 10 Sketch of Cell Spar (left) and Buoyant Tower (right)

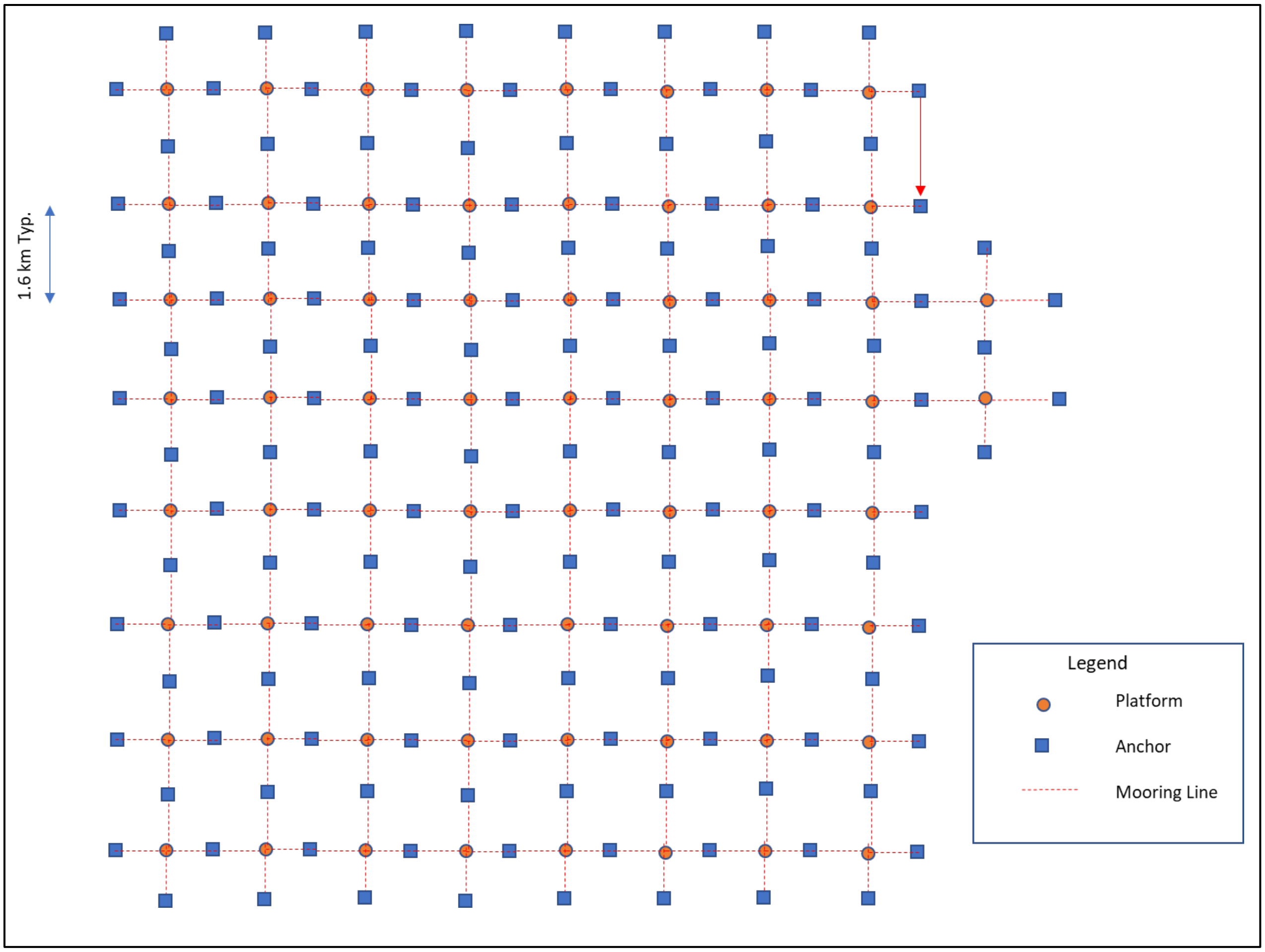

Figure 11 Wind Farm Layout

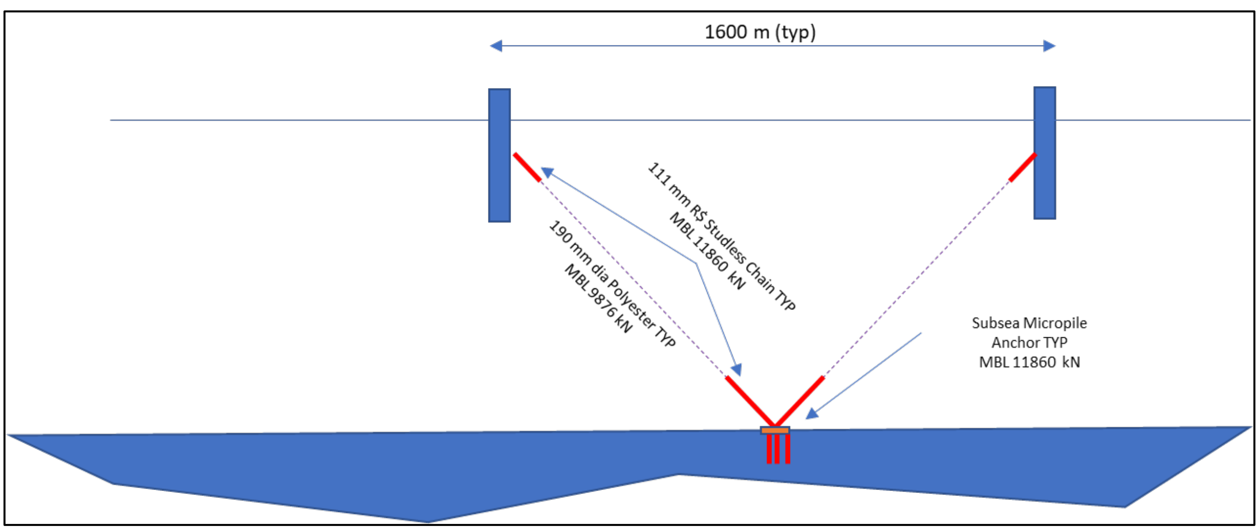

Figure 12 Profile of Mooring for This Study

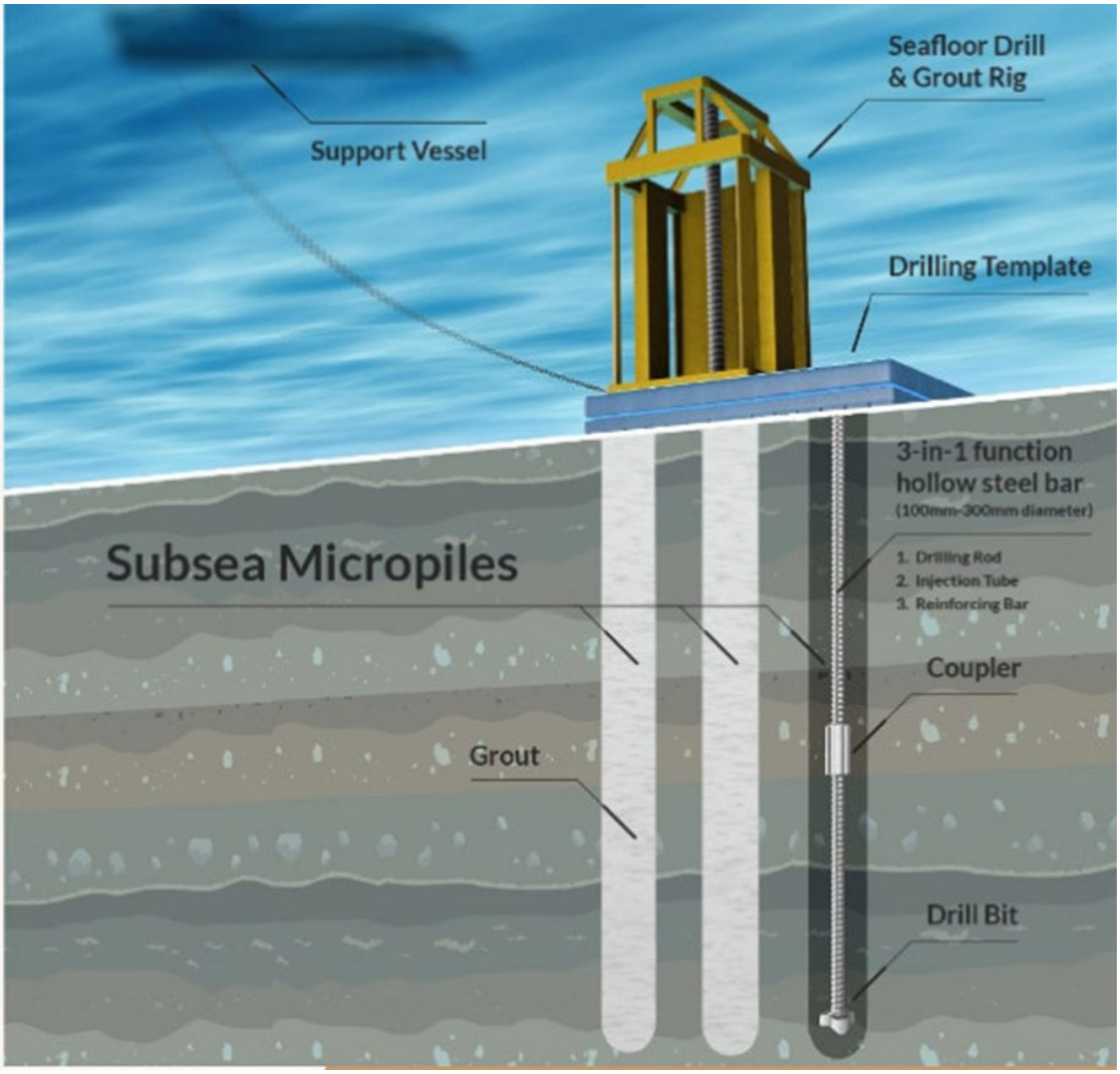

Figure 13 Subsea Micropile Anchor

Figure 14 Pelastar ® TLP Platform (source: Glosten, https://pelastar.com/)

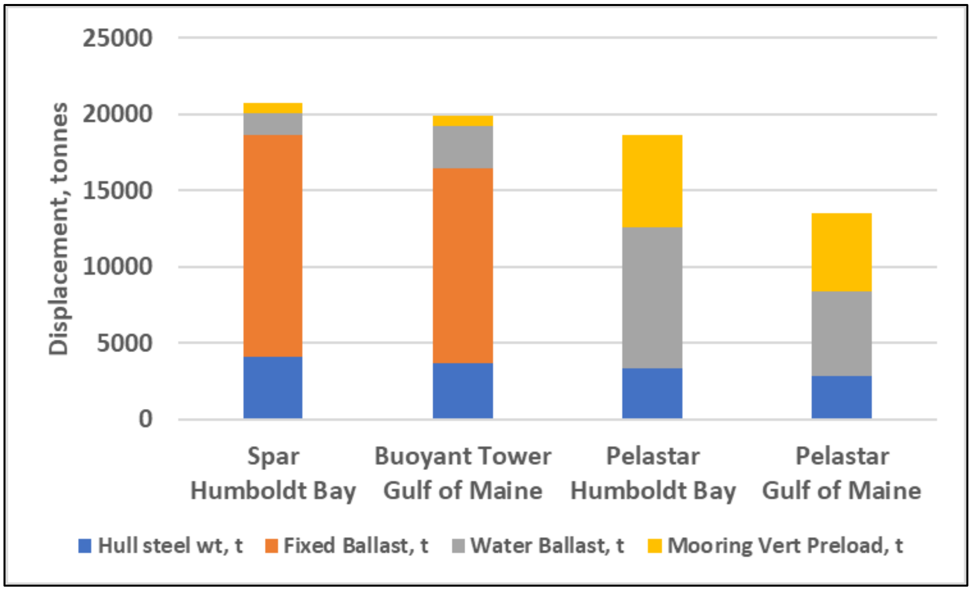

Figure 15 Comparison of Displacements

5 Results of Analysis and Conclusions about the Adequacy of the Designs (from Task 3 Report)

The primary goal of this analysis, see (DRT, 2022d), is to gage the dynamic characteristics of the cell spar platform while attached to the IEA 15MW Wind Turbine in deep water at the Humboldt Bay site for the purposes of verifying the adequacy of the spar design. The key factors involved in the platform design are identified by performing a coupled aero-servo-hydro-elastic analysis in Orcaflex. Analysis of the Pelastar® Tension Leg Platform for both the Humboldt Bay and the Gulf of Maine site, was also performed by Glosten. The Basis of Design and Sizing of these platforms is discussed in (DRT, 2022a) and (DRT, 2022c) respectively.

A single cell spar is analyzed for both production and survival conditions corresponding to IEC load cases 1.6 and 6.1 (IEC, 2019): Power Generation and Parked Turbine conditions, respectively. This analysis has been based on a limited set of environmental cases, see (DRT, 2022a) and (Halkyard, 2022) . The 170m and 150m Cell Spar cases were simulated for the Load Cases corresponding to the Humboldt Bay Call Area. Key parameters reported here include nacelle (RNA) acceleration, platform surge and pitch motions, spar and tower bending moments, and mooring line tensions. All analysis assumes co-linear wind and waves.

Target limits on nacelle accelerations and pitch angles were assumed to be the following as discussed with the NOWRDC Advisory Board (DRT, 2022e):

- Operating, Load Case DLC 1.6: acceleration<0.3g, Mean Heel < 5 deg, Max Pitch < 10 deg
- Survival (Turbine parked) DLC 6.1: acceleration<0.6g, Max Pitch<10 deg

Criteria for the other parameters, especially structural criteria, have been considered based upon current offshore platform design practices.

5.1 Cell Spar – Humboldt Bay

Utilization factors for the key variables is summarized in Table 9. Values in parentheses are utilization factors equal to the ratio of computed responses divided by the allowable (or target) responses. It is seen that the acceleration and tower bending moments in this example exceed the allowable for the low period (wave) environments. This result is due primarily to the dynamics of the tower which would have been adequate if the VolturnUS tower (Allen, et al., 2020) had been used.

The high acceleration is due to spar platform and tower dynamics and is specifically dependent upon the stiffness of the tower and the energy in low period severe wave environments. Spectral analysis, Figure 16, indicated the RNA accelerations included a low frequency component (around .02 Hz) corresponding to the natural rigid body pitch period, and a high frequency component (0.35 Hz) presumably corresponding to the 2nd mode of the tower vibration. (This is also the 3P modal frequency, however the spectral analysis showed a strong peak at 0.35 Hz even with the turbine parked.) Sensitivity analysis indicated that RNA accelerations could be reduced by around 30% doubling the stiffness of the tower. The IEA 15MW tower scantlings used here are based on a fixed monopile design. Modification to the tower to account for floating platform behavior is necessary. Bending stresses, which appear dominated by a first mode resonance of around 0.18 Hz, Figure 17, were reduced about 37% based upon the sensitivity results.

Low frequency pitch affects, at least during power production, may be mitigated by implementing pitch damping control into the turbine control system.

Other parameters fall within acceptable values indicating the cell spar design is reasonable pending further rigorous analysis, particularly finalization of scantlings and performing buckling checks on the hull.

Initial calculations with a low pretension on the mooring lines did result in excessive yaw motions, but this was corrected by increasing pre-tension and introducing a "crawfoot" in the mooring line connection to the spar (i.e. a bridle is used to connect the mooring line to two opposed points on the spar). This method is used on the Equinor HYWIND spars to reduce yaw motions.

The above results were seen to be very sensitive to the low period waves specified in the Basis of Design. The initial analysis used lower wave heights for the sea conditions which were increased after attempting to align the severe sea states with the conditional 50-yr values from the buoy data (Halkyard, 2022), and the accelerations and bending moments were significantly less than shown above. This points to the importance of acquiring accurate metocean data and statistical analysis as recommended in the IEC Guidelines (IEC, 2019) which is beyond the scope of this study.

5.2 Buoyant Tower – Gulf of Maine

Analysis of a Buoyant Tower with lateral moorings included two environments for DLC 1.6 and one for DLC 6.1. The results were like the spar cases above, i.e RNA accelerations exceeded the criteria for the operating case, however the tower design used was the original IEA 15MW monopile tower and stiffening of the tower is expected to result in acceptable accelerations. The Buoyant Tower without lateral moorings was deemed unsuitable due to the large amount of fixed ballast required to counter the turbine thrust, and lack of yaw stiffness (DRT, 2022c).

5.3 Tension Buoyant Tower – Humboldt Bay

Limited analysis of the TBT for Humboldt Bay indicated extreme yaw motions which would represent a feasibility issue for this concept. The advantages of the TBT are a) heave motions are eliminated, and b) a mooring spread is not required. Limited heave motions are not necessarily required for a wind platform, and the advantage of reducing the mooring spread can be partially mitigated by designing the anchors to support multiple platforms. Hence, we propose to discontinue consideration of the TBT for this study.

5.4 PelaStar® Tension Leg Platform

Glosten performed Oracflex analysis on the TLPs sized for Humboldt Bay, 500 m water depth, and the Gulf of Maine, 150 m water depth, see (DRT, 2022c) for parameters of the TLP. The TLP is constrained in pitch motions and exhibits less surge/pitch dynamic effects resulting in lower RNA accelerations than the spar.

5.5 Conclusions

The overall conclusion based upon this analysis is that the configurations selected for this study are reasonable and can meet all the criteria with relatively minor structural modifications. Further strengthening of the tower is required to reduce dynamic responses but will be required for any floating vessel.

Further conclusions include:

- The structural implications of the dynamic response of the spar + tower will require further study in the next design iteration,
- The sensitivity of the responses to low period wave energy indicates that careful assessment of the Metocean conditions is important. We would recommend long term hindcast analysis of the areas to validate the assumed wave conditions.

- The six-line mooring system used for these calculations needs to be optimized at the next stage of engineering. Three lines would be preferable (lower cost) and the crawfoot configuration needs to be optimized for maximum yaw stiffness.
- Low frequency pitch and surge responses may be mitigated by implementing pitch and surge damping in the turbine control system[4] .

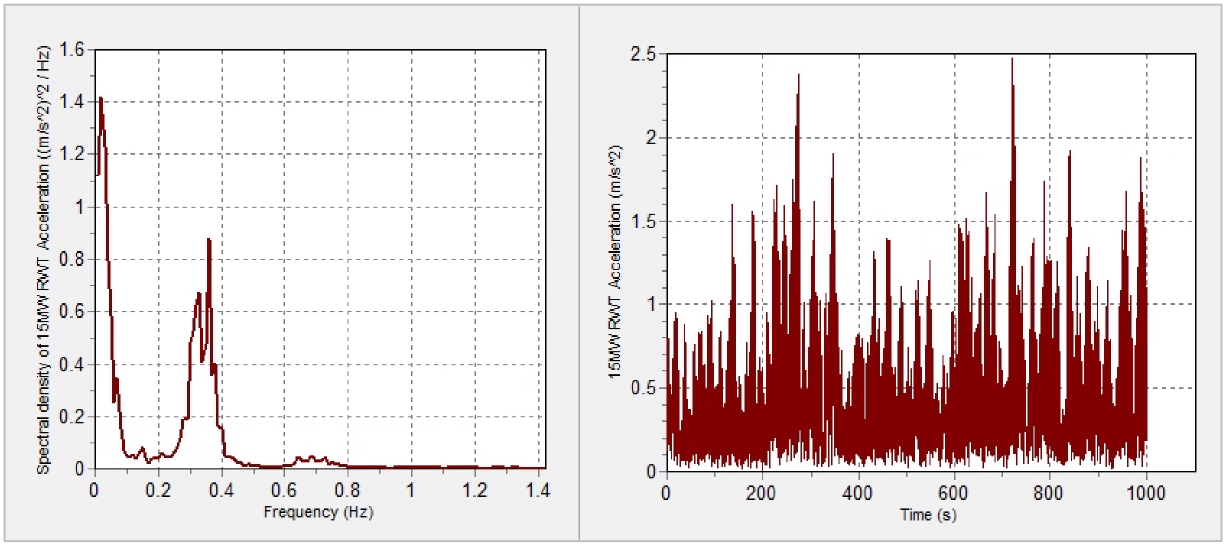

Figure 16 Nacelle Horizontal Acceleration Time History and Spectrum (DLC H1.6-2)

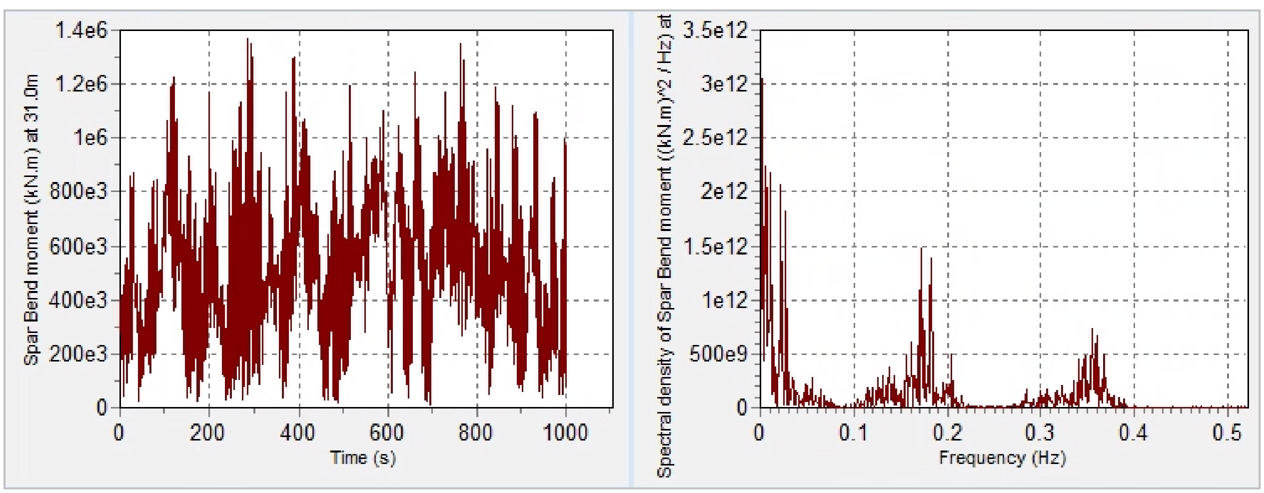

Figure 17 Preliminary Results: Time Series and Spectral Density for Spar Bending Moment (DLC H6.1-2)

[4] Personal communication, Bjorn Shaare, Equinor, 20 Apr 2022

Table 9 Results for Updated Analysis – Cell Spar at Humboldt Bay

Parameter	Operating LC H1.6	Survival LC H6.1
Acceleration, g	.48 (1.6)	.82 (1.4)
Bending Moment, Spar, kNm	1.1E6 (.6)	1.7E6 (.9)
Bending Moment, Tower, kNm	9.0E5 (1.1)	1.4E6 (1.7)
Pitch, deg	7.9 (.8)	7.2 (.5)
Tension, kN	3338 (.9)	3714 (.7)

6 Results of the Feasibility Assessment of Horizontal Installation of the Tower and Turbine (from Task 5)

This study has focused on two innovative cost saving concepts for spar floating wind execution:

1. An automated method of construction which reduces the cost per ton of construction to a minimum, and allows local fabrication of the spar, and
2. An installation method for the turbine that doesn't require a floating-to-floating crane or other novel floating installation vessel, see (DRT, 2022f).

Spar construction is discussed in the following section.

Installing the tower and turbine on deep draft spar platforms has proven to be a drawback compared to, for example, semi-submersibles which can install the tower and turbine on the platform in-shore. In fact, in 2014 Equinor initiated a "Hywind installation challenge" specifically to invite companies to propose innovative solutions to this problem, see (Ramachandran R. , Desmond, Judge, Serraris, & Murphy, 2021). Deep draft spar platforms typically require an offshore "floater to floater" turbine installation using a heavy lift crane vessel. An exception in the Tampen project which performs this operation in-shore, in a Norwegian Fjord (Navingo BV, 2022), however this is unique to the Norwegian platforms.

Our original proposal suggested installing the tower and turbine on the spar horizontally, in-shore, and towing the spar complete with the tower and turbine installed offshore where it would be upended and towed to the installation site, Figure 18. Subsequently, we proposed an alternate solution whereby the tower (without the turbine) is installed in-shore on the spar, horizontally, without the turbine. The spar + tower is then towed offshore, upended, and secured to a fixed platform, e.g., a substation platform. The turbine and blades are then installed by a special self-erecting crane situated on the fixed platform which can then install the turbine and blades without being sensitive to metocean conditions, Figure 19.

The latter approach is currently our preferred option, although we discuss both options in this report. Our conclusion is that both are feasible, however the horizontal installation has several challenges we have not addressed. These include, for example (GE, 2022):

- A significant amount of analysis has to be performed to verify that the ULS loads that the turbine components experience during towout and installation are not exceeded. This includes load cases 8.1 – 8.4 in IEC 61400.
- The tower is expected to need support during transport in horizontal orientation to the wind farm site. While gravity loading on the blades in horizontal condition may not exceed the thrust loading in production, the 8.x simulations are necessary to determine if blade support structures are necessary to avoid excessive blade loads and deflections, particularly due to wave-induced vibrations.
- During tow-out and up-ending, various locking devices (e.g. blade pitching, rotor, and yaw drive) will have to be enabled. Consideration should be given to the loading of these locking devices during tow-out and up-ending to ensure these devices can withstand the loads in this configuration.

Advantages of the “base case” is that the tower does not have to accommodate large bending moments from the weight of the turbine and blades during towing and upending, and while it is still necessary to carry out the analysis prescribed by load cases 8.1 – 8.4 as mentioned above, the operations involved have precedents in other offshore applications.

The advantage of horizontal towing and installation is elimination of the necessity of an offshore fixed platform, should the substation not be available.

6.1 CONOPS

The proposed installation method for the spar, and buoyant tower, involves these steps:

1. Spar is manufactured on land or on a barge and offloaded to a semi-submersible barge
2. The semi-submersible barge is positioned next to the quay where the tower is aligned with the spar and the two are joined by welding or mechanical connection, Figure 18. A transition piece may be integral with the spar or tower.
3. The barge is ballasted to remove the tower from supports on land and towed to a deep-water area where the barge is submerged and the spar + tower are floated off, Figure 21.
4. The spar is flooded to upend, Figure 22
5. The spar is positioned next to the fixed tower (substation tower) and secured for installation of the turbine (RNA and blades)
6. Fixed ballast is added to the spar by a separate barge (not shown here) to provide stability for when the turbine is installed. The fixed ballast operation is common to all spars in service.

7. Nacelles and blades are stored on the platform or an adjacent barge. The fixed self-erecting crane on the platform installs the nacelle and blades on the vertical spar tower, Figure 19.
8. Sufficient water ballast is discharged from the spar, using compressed air, to float the spar and remove it from the constraints holding it to the fixed platform. The ballasting sequence is described in Figure 26.
9. The spar with tower and turbine is towed vertically to the installation site where an Anchor Handling Tug hooks up pre-installed moorings. This procedure is identical to that used on HYWIND spars (Ramachandran R. C., Desmond, Judge, Serraris, & Murphy, 2021).

6.2 Analysis

Static and dynamic analysis of the spar + tower configuration was performed using in-house software and Orcaflex. Figure 23 shows a definition of terms for the horizontal towing configuration. Table 10 shows results of the static analysis for three ballast conditions:

- No ballast
- 1000 t fixed ballast
- 4500 t fixed ballast

While it appears feasible to tow without ballast, adding some portion of the fixed ballast prior to floating the spar from the barge increases its stability and increases the angle so the top of the tower is more clear of the free surface, and less of the tower is submerged, at the expense of higher stresses in the tower.

Figure 24 shows the static tow configuration with 4500 t ballast. Dynamic analysis performed using Orcaflex for an annual extreme swell condition indicated a maximum stress of about 120 MPa, Figure 25. These results are for the stiffened semisub tower, see Figure 6 and Figure 7.

Additional analysis was performed to estimate loads on the spar and fixed platform which indicated the spar could add around 1400 t of load to the platform in a 1-yr storm event (DRT, 2022f).

6.3 Discussion

Both methods of installing the turbine presented here are considered feasible. However, the method involving mating the tower in-shore and installing the turbine from a fixed platform offshore is considered to have a higher Technology Readiness Level (TRL) because there is precedent for each of the operations involved in the offshore industry. This does depend upon availability of a suitable fixed platform in 150 m+ of water. We have assumed in our economic case that a substation tower could be available for this. This needs to be confirmed. If a special purpose tower is required, we still believe it is reasonable to use this approach albeit the cost of the tower, and demobilizing it, will have to be considered.

In the event this is not possible the horizontal installation can be pursued. It will require further tower strengthening. If we use a barge to support the tower more engineering and testing is required to bring the TRL level to a higher status.

In either case the solution will be somewhat project and site specific. We suggest the way forward is to pick a specific site, for example Humboldt to Morro Bay, and define the logistics of spar construction (see next section), tower mating and fixed platform location, design, construction, and installation. Substation and tower installation requirements need to be considered in specifying the fixed platform design and location. A suitable functional requirements definition needs to be developed.

The CONOPs of the tower-platform mating, RNA blade offloading need to be investigated taking into consideration metocean conditions.

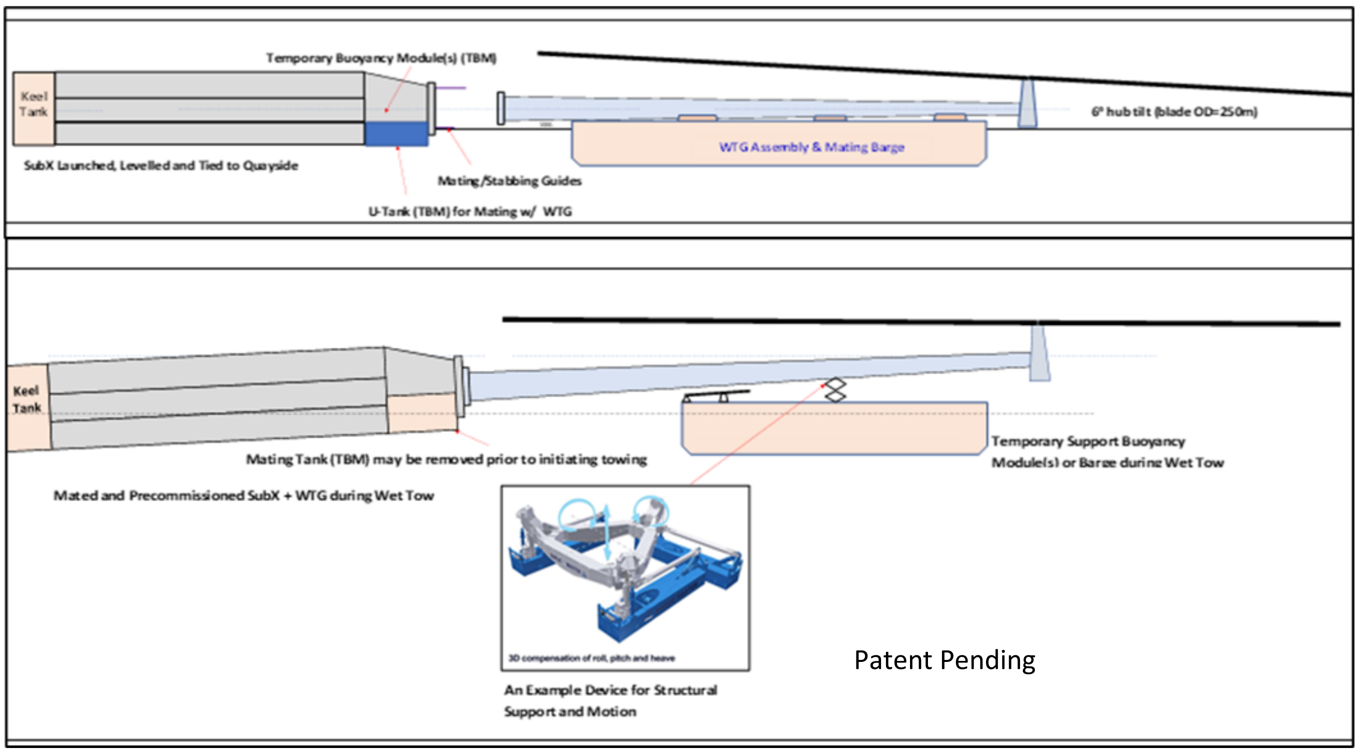

Figure 18 Concept for Horizontal Installation of Tower and Turbine

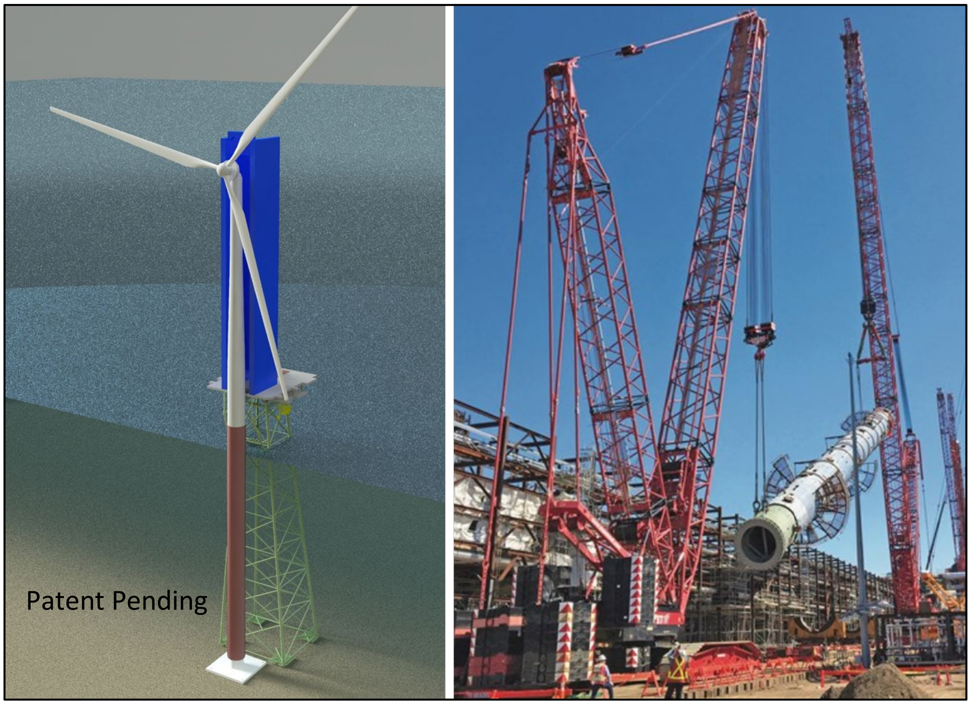

Figure 19 Spar Secured to Substation Tower for Turbine Installation (Source: Mammoet)

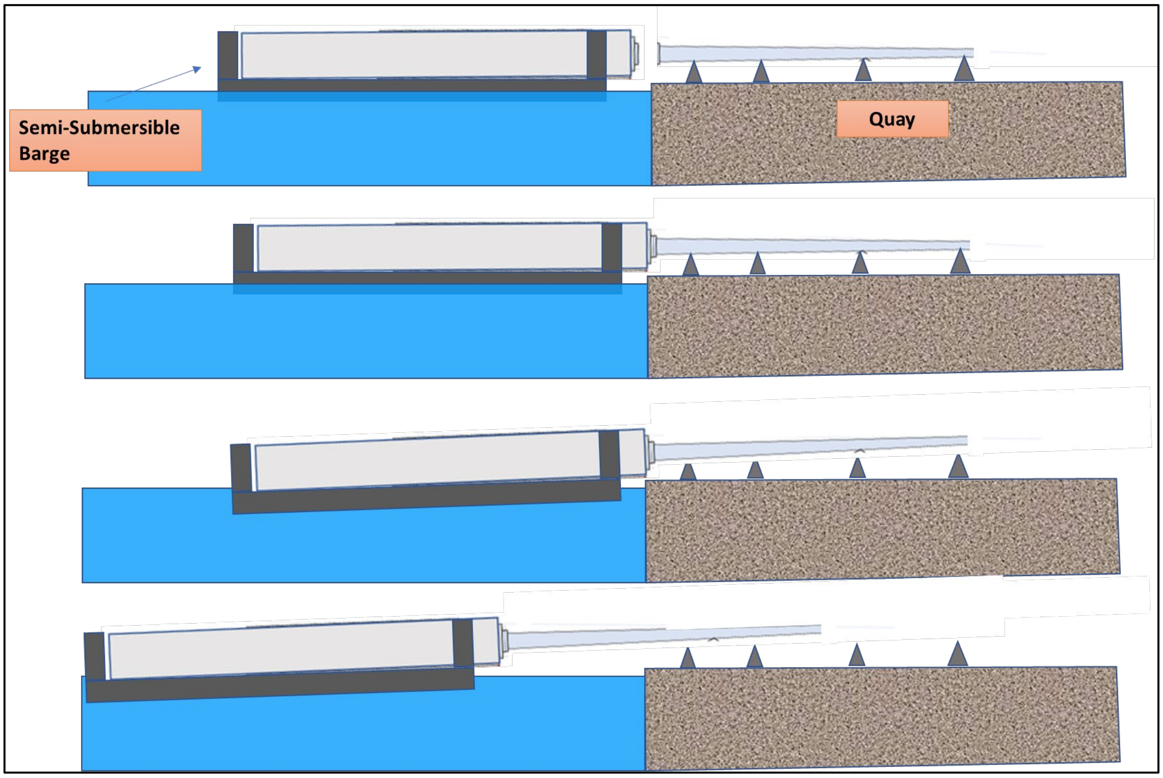

Figure 20 Horizontal Tower Installation

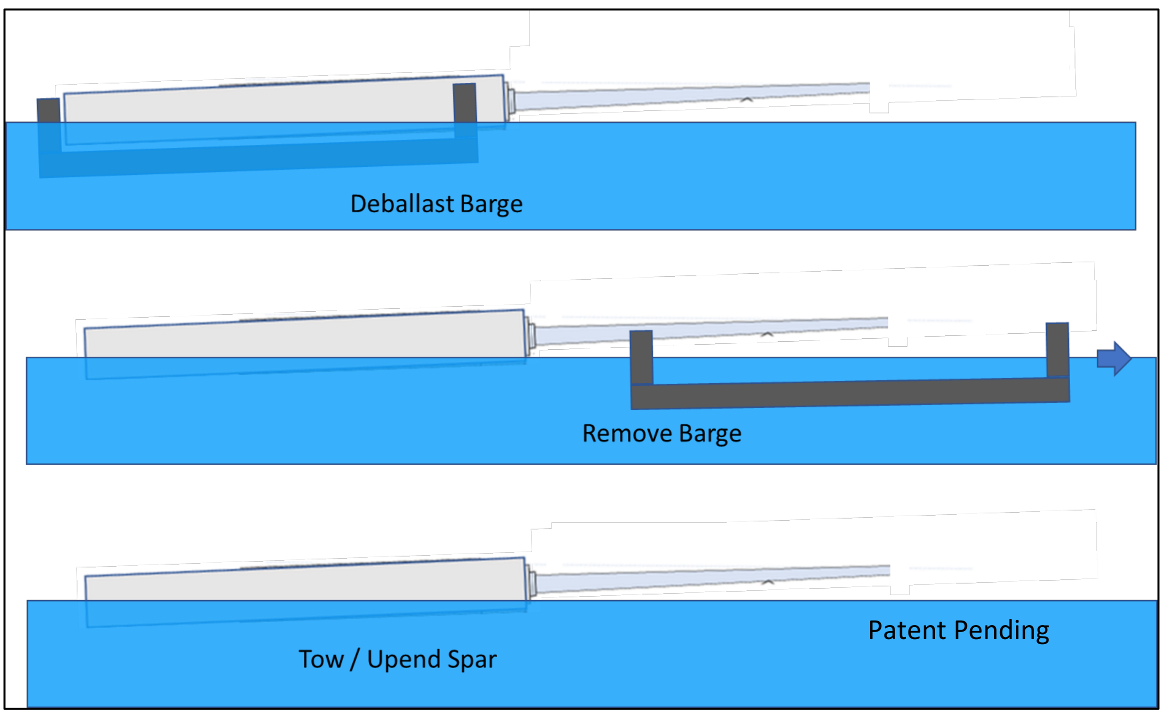

Figure 21 Float-Off Spar

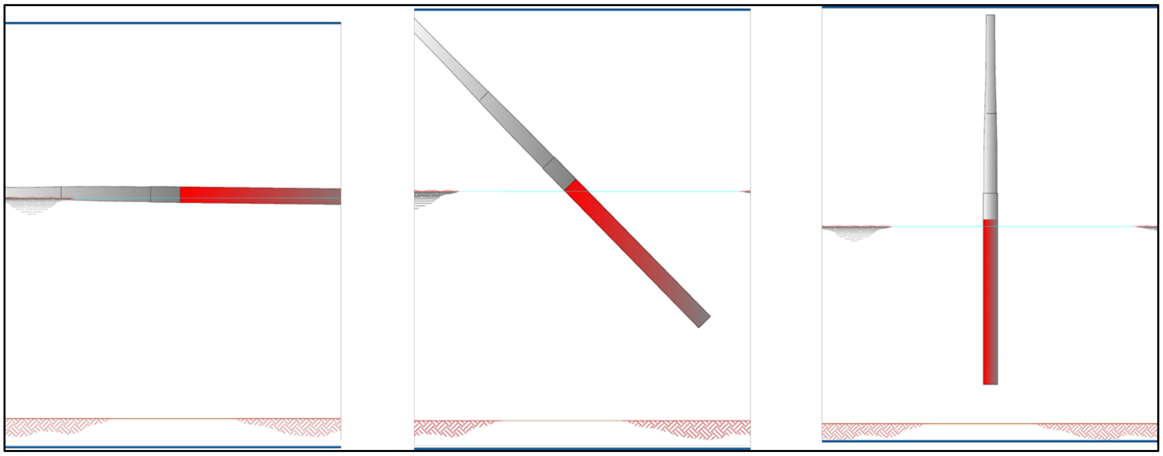

Figure 22 Spar Upending

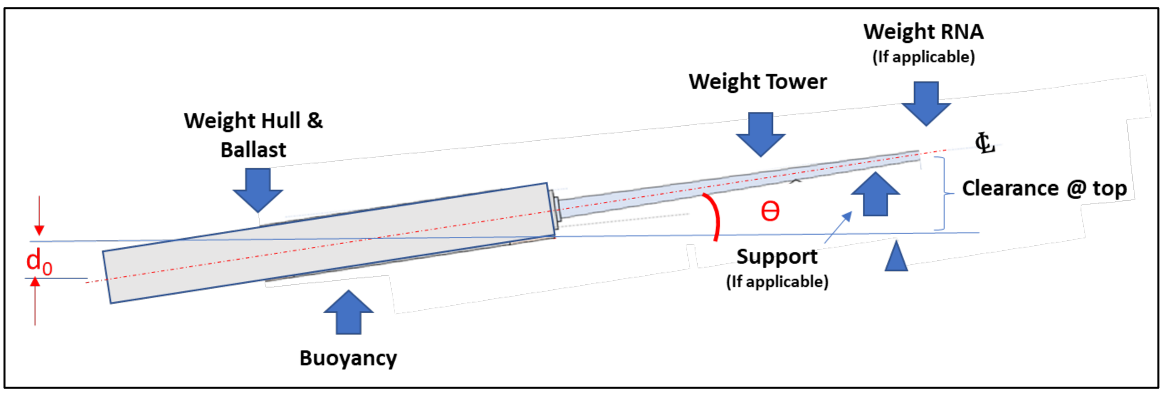

Figure 23 Definitions of Draft and Trim Angle of Horizontal Floating Spar

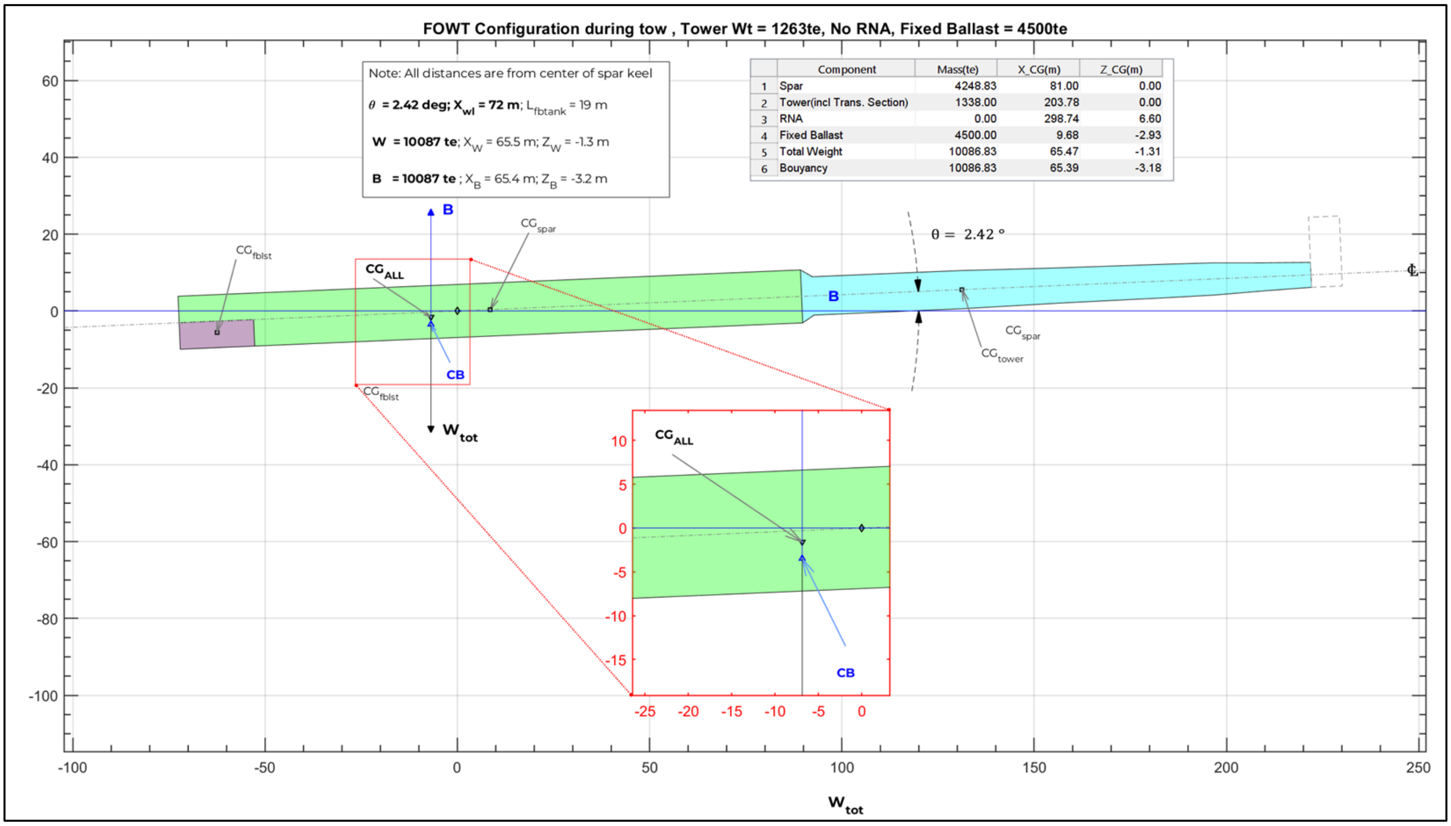

Figure 24 Static Tow Configuration with 4500 t Fixed Ballast

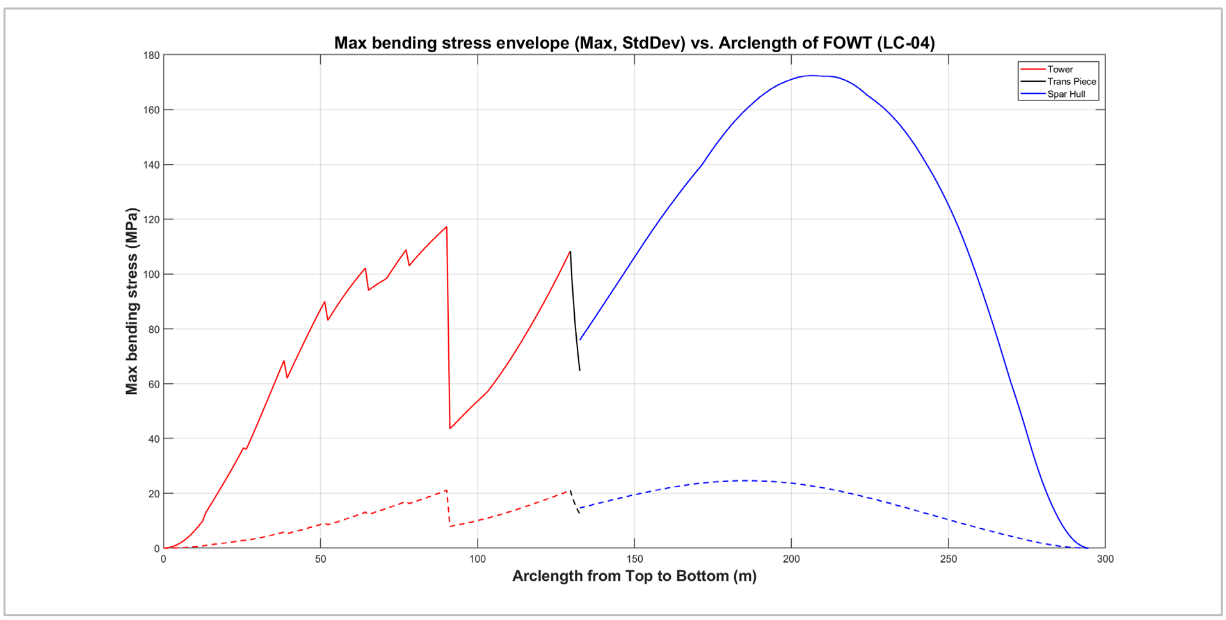

Figure 25 Maximum and Standard Deviation Bending Stress for Towing, 4500 t Ballast (semi tower)

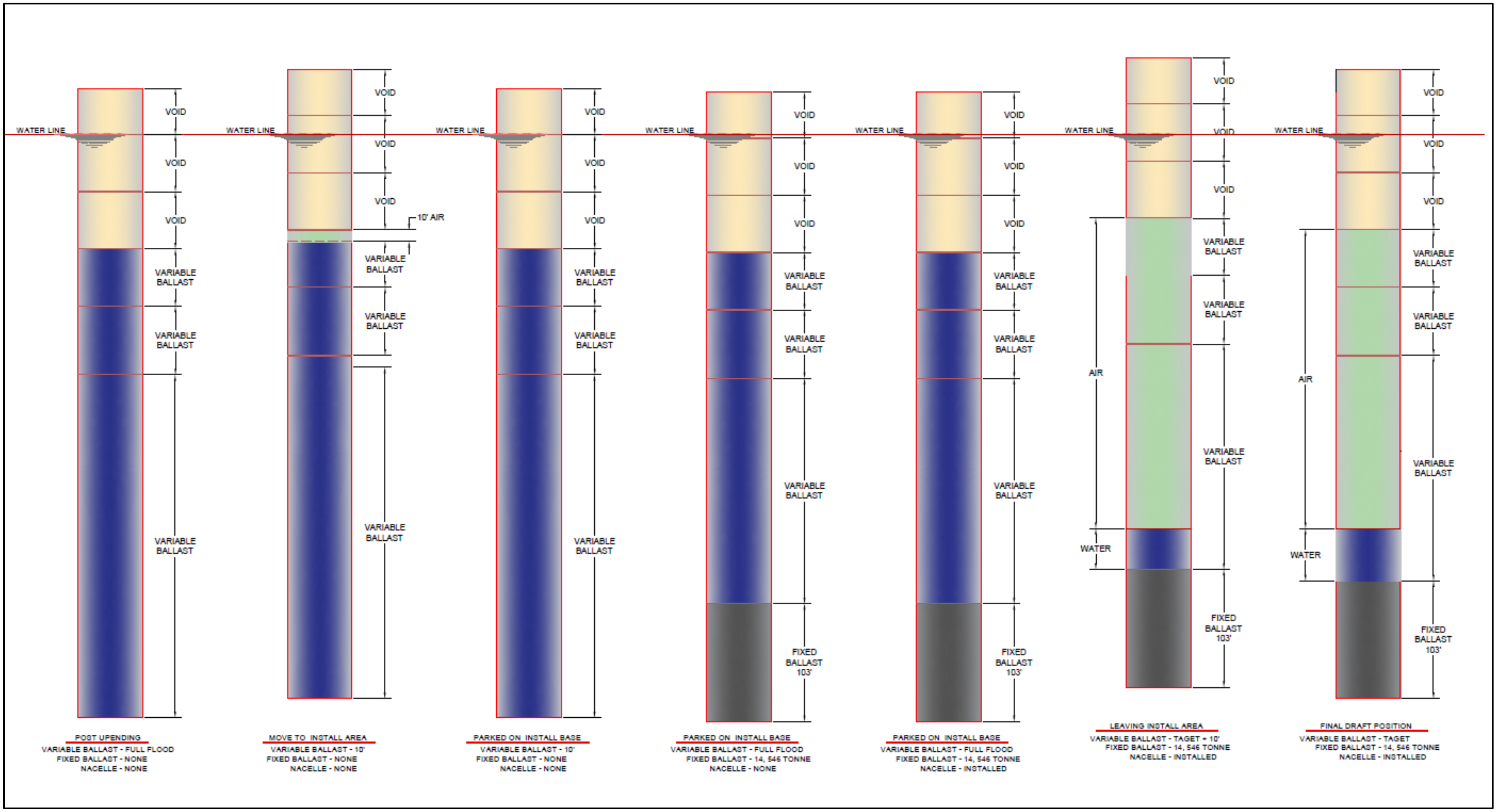

Figure 26 Ballast Conditions for Installation and Operations (Source: Trendsetter Vulcan Offshore)

Table 10 Results of Static Tow Analysis

Ballast, t	d0, m	Theta, deg	CL Above WL, Top of Tower, m	Max Stress, Mpa
0	-3.3	0.46	5.7	21
1000	-2.3	0.75	6.2	55
4500	2.5	2.4	10.0	160

7 COST SUMMARIES

7.1 BASIS OF THE CAPEX ESTIMATES

This Section presents cost estimates for the spar and TLP platforms for the Humboldt Bay site, and buoyant tower and TLP for the Gulf of Maine. CAPEX estimates are considered Class 4 AACE estimates (AACE International, 2020) with an accuracy of -30 +50%.

The estimates are based on a wind farm including 66 platforms, 15 MW turbines for a total capacity of 990 MW. US Fabrication of the platform is assumed, however the impact of foreign fabrication of modules is considered for the PelaStar® platform.

US procured raw steel prices are assumed $1500/t. This is an average American Steel Index value over the last three years.

Assumed Day rates for installation vessels are:

- Oceangoing tug for towing: $22,000
- Multipurpose Offshore Supply Vessel with Heave Compensated crane and ROV: $140,000
- Anchor Handling Tug: $100,000
- DP Heavy Lift Crane vessel $295,000
- Ocean going cargo barge: $5000
- OSV Equipped for Installing Subsea Micropile Anchors: $50,000

The costs are assumed the same for east and west coasts. For any positioning of barges offshore, or in harbor, two ocean going tugs are assumed to be required.

For the cell spar and buoyant tower, we assume construction is performed on a specially outfitted barge containing automated manufacturing capability similar to that used in current monopile fabrication (see next section). The spar is offloading to a semi-submersible barge to facilitate horizontal tower installation and offloading. The manufacturing barge is assumed foreign flag (non-Jones Act) while the semi-submersible barge is assumed Jones Act compliant (Wikipedia, 2022). Also, shuttle barges for turbine and blades and tugs employed in transportation are Jones Act compliant.

The manufacturing and submersible barges are considered fit-for-purpose new builds which are amortized over one wind farm installation, 66 platforms.

Base Case costs were prepared for the Cell Spar in Humboldt Bay. The Buoyant Tower costs were factored from these estimates.

7.2 Assumed Methods of Construction

7.2.1 Spar and Buoyant Tower

One goal in this project has been to introduce a new industrialized approach to manufacturing of multiple FOWT units which will reduce the cost/tonne to a fraction of costs typically associated with one-off floating platform construction.

The first spar concepts used traditional shipyard construction (Kuuri, Lehtinen, & Miettinen, 1999). Its fabrication costs, well in excess of $10,000/t, would not make this method of fabrication economic for offshore wind applications. The cell spar was introduced in the 2000s using a lower cost construction method based upon rolling steel plate (cells) in a fabrication yard (Hogan, Kuuri, & Maher, 2005). This same construction method was implemented for the buoyant tower (Crochet, Toll, Gommel, & Slider, 2013). It is this potential for reduction in hull fabrication costs which prompted the proposal to study these concepts for offshore wind.

Our current cost estimate for the cell spar and buoyant tower, described herein, utilizes automated manufacturing processes, Figure 27, to further lower the construction costs. For US applications studied here, a special manufacturing barge will be outfitted with robotic manufacturing equipment. Our estimate includes a quote for this equipment from the Dutch robotic equipment supplier Kranendonk (https://www.kranendonk.com/). The $/tonne costs in this case come closer to the material costs alone! The methods mirror, for example, those used in manufacturing of monopiles today.

We assume US steel plate is delivered to Humboldt Bay for fabrication. Purchased items include anodes and paint for protecting the hull.

Targeted is a fabrication of 50 or more units per year. A sample layout is provided in Figure 28. The main stations are the steel plate cutting and welding for the ring frame and deck fabrication (Figure 29). Ring sections will be rolled and assembled with stiffening rings (Figure 30 and Figure 31). In parallel, stiffened deck plates are fabricated.

Stiffened ring sections will be up righted and then welded together as shown in Figure 32. In a final step the joined sections will be completed and outfitted for final "Spar" deployment on to submersible installation barge (Figure 33).

Once the Cellular tube(s) are loaded on the submersible barge, it is towed to an onshore assembly yard where the tower is welded to the Spar, Figure 34. No flanges or grouted connections are required.

Figure 35 illustrates a possible utilization of the Port of Humboldt Bay for the manufacturing process. The spar construction barge would be moored adjacent to the port entrance outside of the channel in water of 20 ft (6 m) depth. The submersible barge would be lashed to the manufacturing barge for offloading of the cells. The submersible barge would then towed to a site for tower attachment, presumably the Fields Landing the designated Port of Entry for the wind tower and turbines (https://humboldtgov.org/2408/Humboldt-Wind-Energy-Project). Once the tower is welded to the Cell tube, the submerged barge towed offshore where it submerges and the cell spar with the wind tower welded in place, is floated off. A similar operation would be employed for the buoyant tower in the Atlantic at a designated port.

The load out methods on submersible barges/ships has been standard method for launching spars, and horizontal towing is typically performed to move the spar to the installation site, see Figure 36 and Figure 37.

After floatoff, the spar with tower is towed to the vicinity of a substation tower which is utilized for turbine installation and is upended. The installation methods were discussed in the previous section.

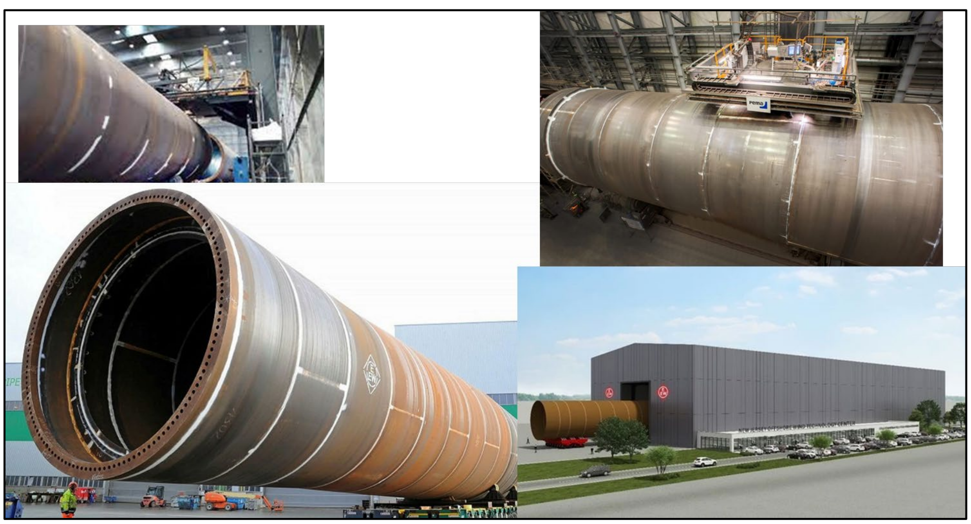

Figure 27 Spar Fabrication uses Proven Manufacturing Techniques for Monopiles (Source: EEW Group)

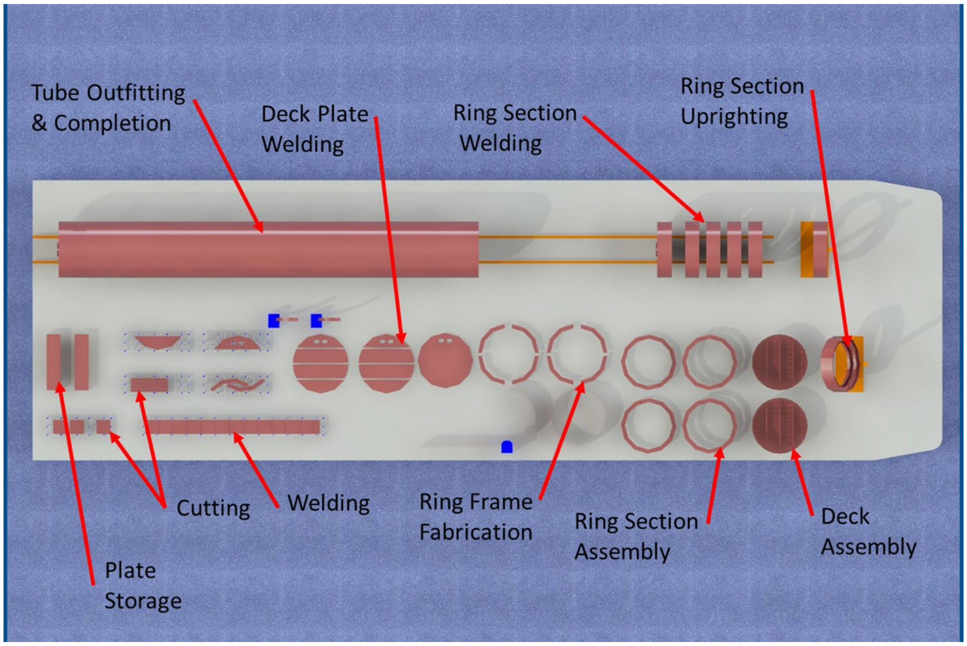

Figure 28 Layout of Manufacturing Equipment on Barge

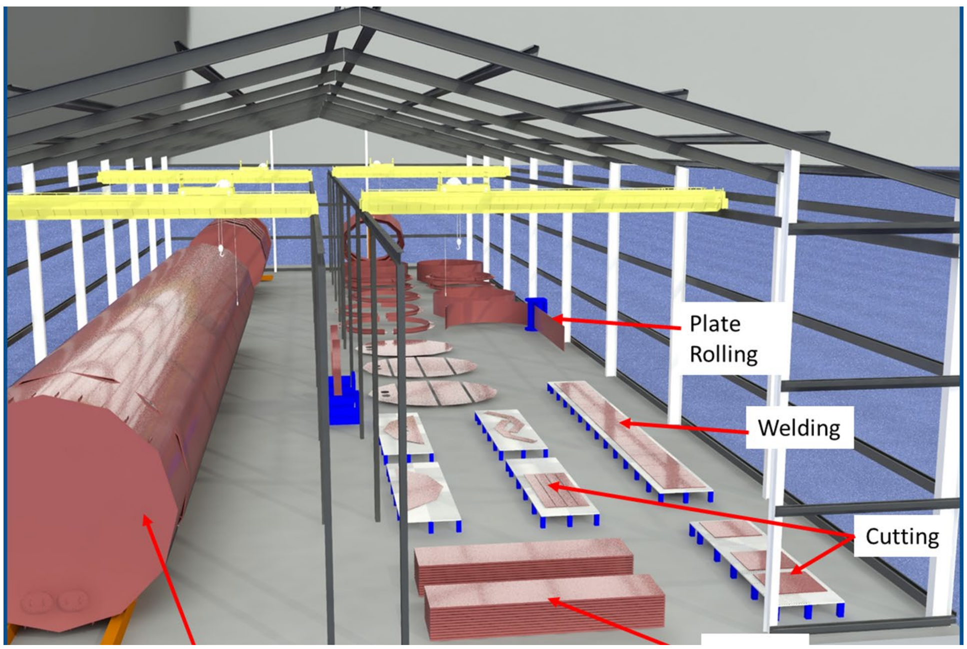

Figure 29 Manufacturing Barge

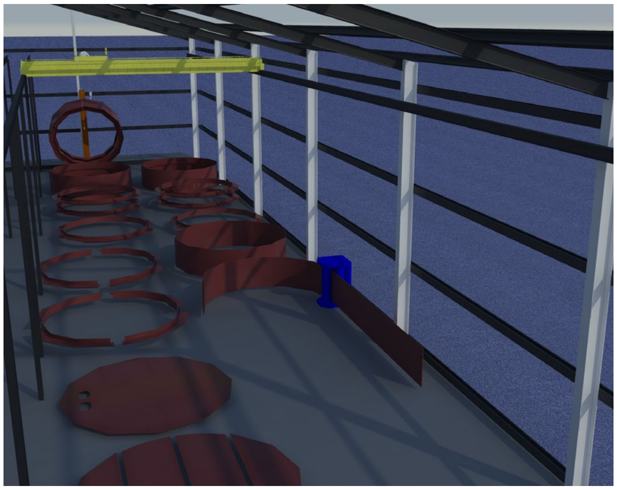

Figure 30 Steel Rolling for Tubular Sections

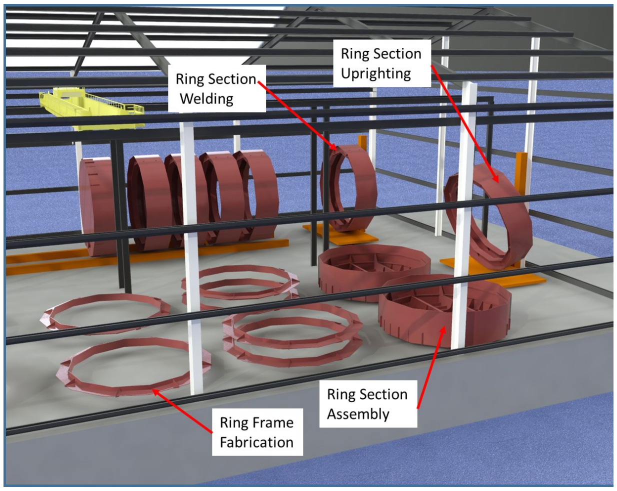

Figure 31 Ring Section Assembly

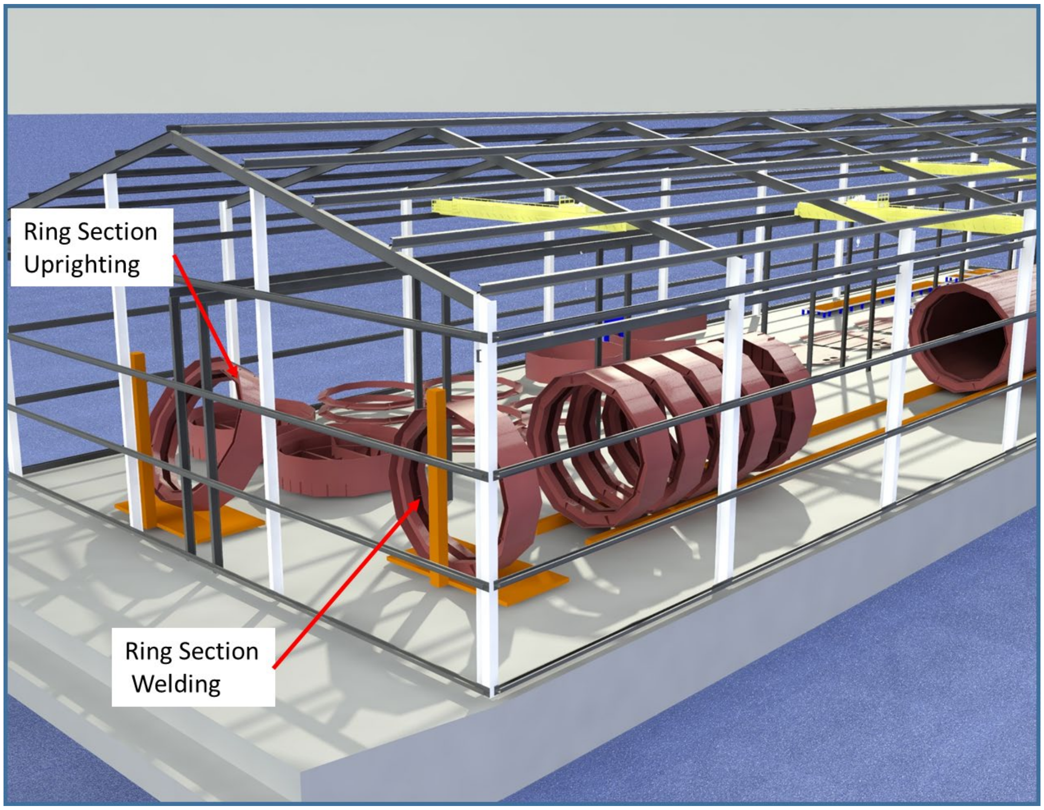

Figure 32 Ring Section Welding

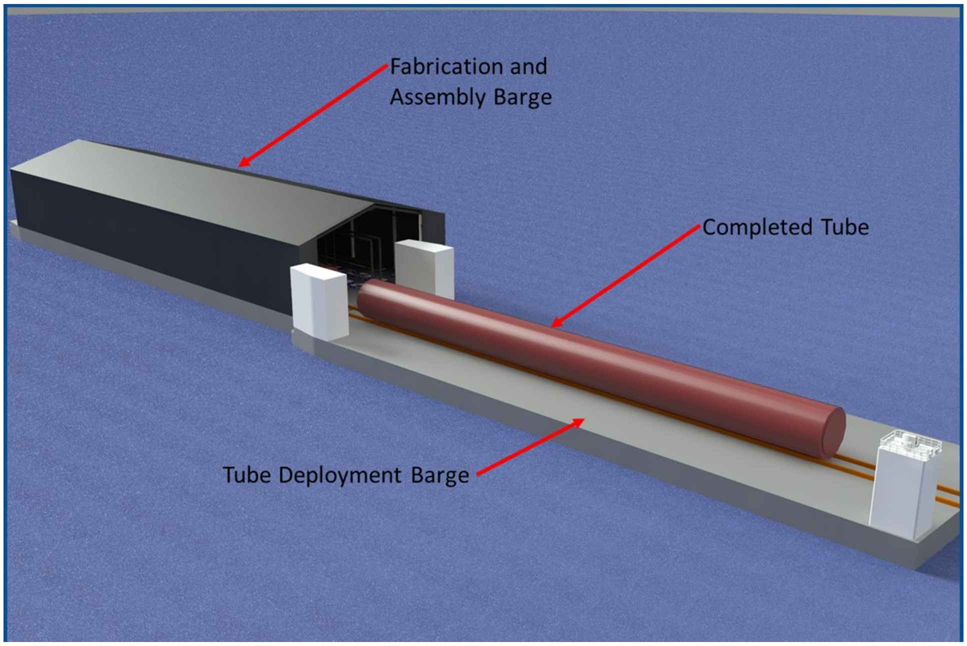

Figure 33 Loadout of Completed Cell (Tube) to Submersible Barge

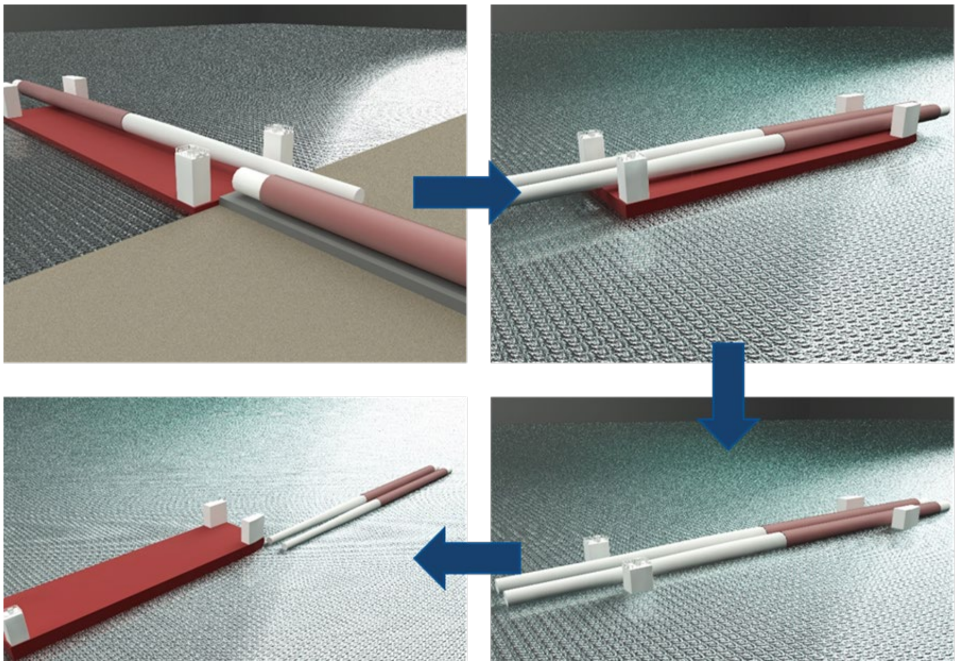

Figure 34 Tower is Welded to Cell Onshore, Skidded onto Barge and Towed Offshore for Float off

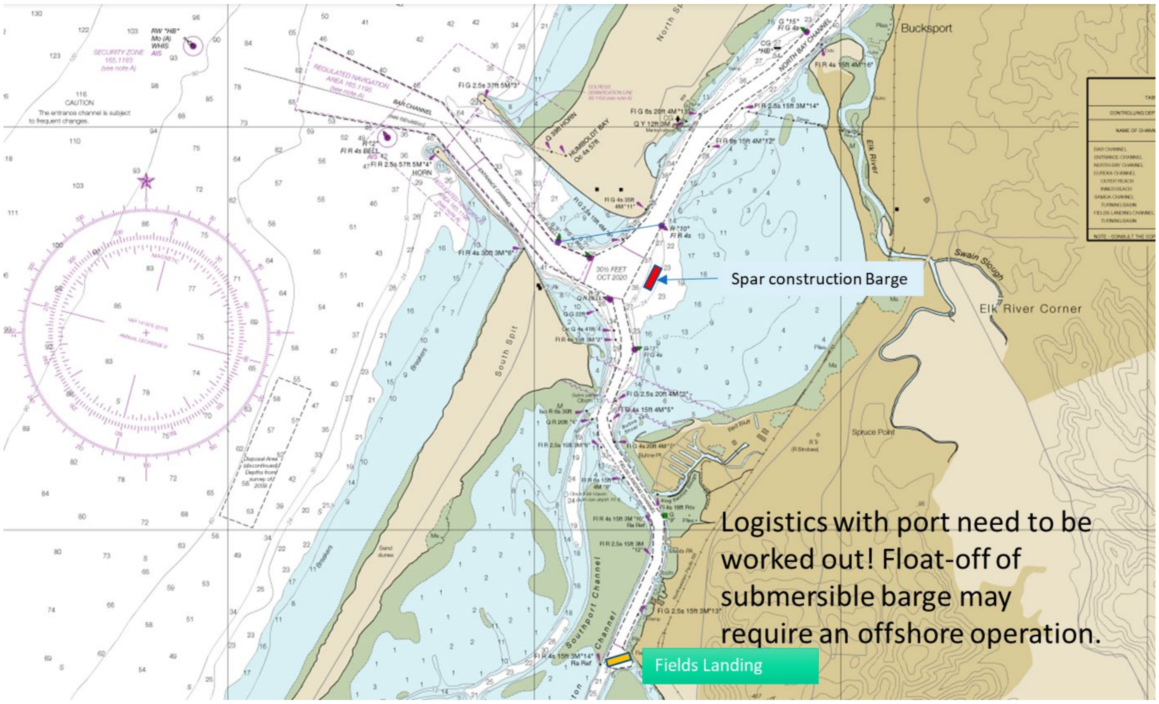

Figure 35 Humboldt Bay Port with Illustration of Spar Manufacturing

Figure 36 Floatoff of World's Largest Spar[5]

Figure 37 Red Hawk Cell Spar Being Towed after Loadout[6]

[5] Source: https://www.youtube.com/watch?v=SZkTlhvzUfw
[6] Source: https://jpt.spe.org/spar-platform-design-transformed-deepwater-development

7.2.2 PelaStar® Platform

Modules of the PelaStar ® TLP hull are fabricated in a fabrication yard and transported to a local logistics site for assembly. Two tower sections are preinstalled on the platform quayside and the TLP is towed to the installation site where the tendons are installed and hooked up to anchors. The turbine parts are delivered on a barge to the TLP location, and a heavy lift vessel is used to install the turbine and blades on stations.

Humboldt Bay manufacturing follows a similar method.

The Base Case assumes modules are built at an offshore fabrication yard on the U.S. Gulf of Mexico coast and barged to either the Maine or California sites. A variation in this estimate assumes Eastern Europe or Southeast Asia fabrication of the modules, respectively. Transportation costs account for longer transport distances.

The installation method used for this cost estimation is as follows:

1. Two tower sections erected quayside
2. Platform and tower towed to installation site
3. Tendons connected to platform and anchors and platform pulled down to installation draft for tendon lock-off
4. Installation tooling removed
5. Third tower section and RNA installed with floating crane vessel and commissioned offshore

7.3 CAPEX Breakdown

This Section includes costs for Platforms Construction & Loadout. A separate Report (DRT, 2022f) discusses the costs for mooring & installation. Figure 38 and Figure 39 show the cost breakdown for the Spar/Buoyant Tower and PelaSTar® Atlantic TLP's. The cost per platform is based on dividing all the project costs by the number of platforms (66).

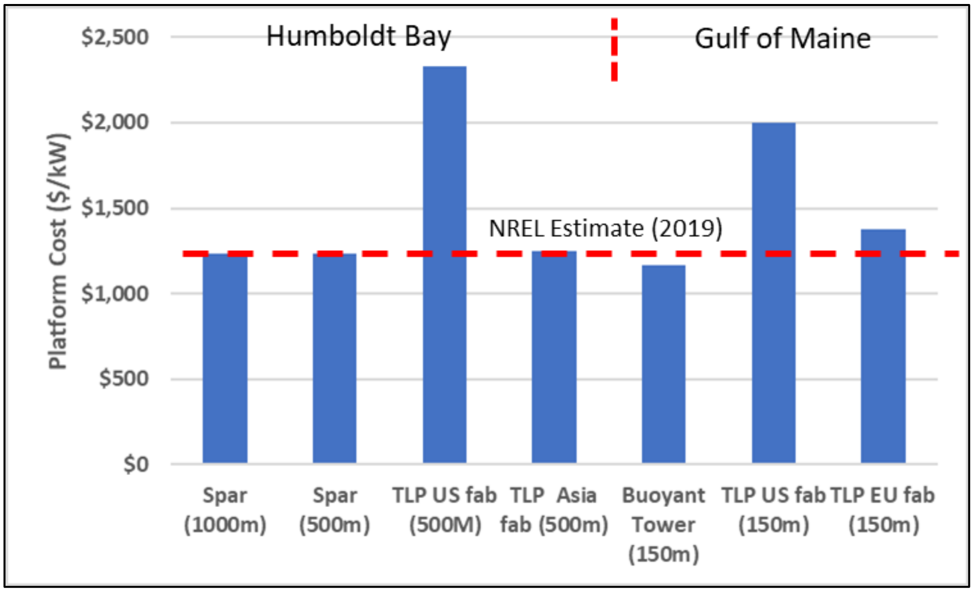

Figure 38 Comparison of Platforms Costs/kW

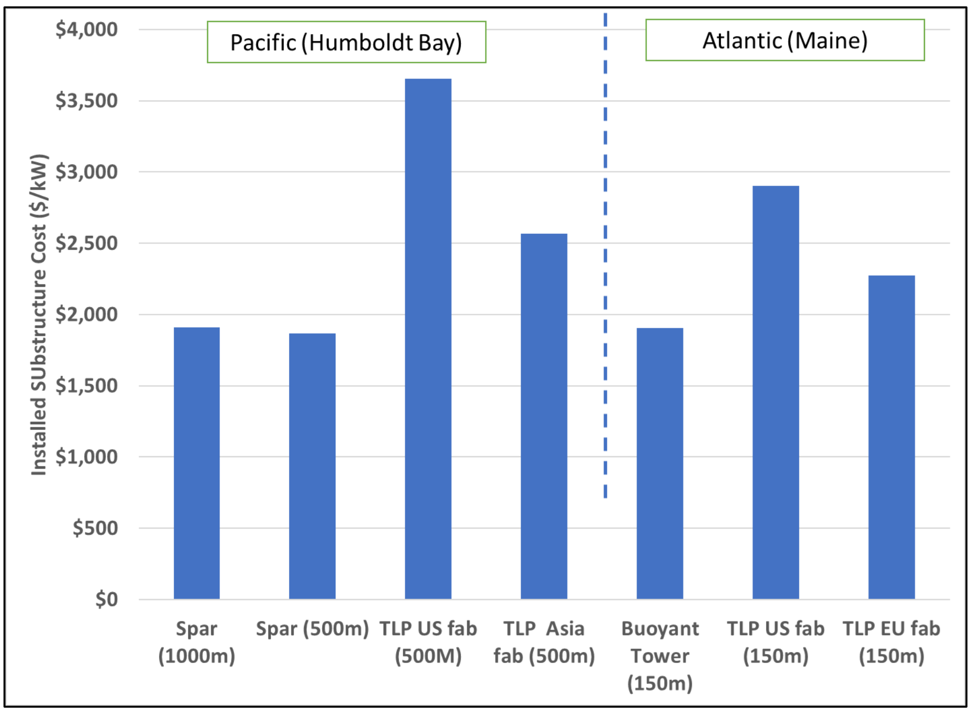

Figure 39 Total Installed Substructure Costs ($/kW)

Table 11 CAPEX Cost Breakdown (per platform)

Locations	Humboldt Bay				Gulf of Maine		
Platform	Spar (1000 m)	Spar (500 m)	TLP US fab (500 M)	TLP Asia fab (500 m)	Buoyant Tower (150m)	TLP US fab (150 m)	TLP EU fab (150 m)
Number of Platforms	66	66	66	66	66	66	66
Water Depth, m	1000	500	500	500		150	150
Platforms Costs ($MM)	**$18.4**	**$18.4**	**$35.0**	**$18.7**	**$17.4**	**$30.0**	**$20.6**
Project Management & Engineering	$1.5	$1.5	$2.8	$1.5	$1.4	$2.4	$1.6
Procurement	$8.7	$8.7	$25.1	$12.2	$7.9	$21.4	$14.7
Construction	$2.2	$2.2	$2.6	$2.6	$2.2	$2.4	$1.6
Loadout	$3.7	$3.7	$0.0	$0.0	$3.7	$0.0	$0.0
Contingency (15%)	$2.4	$2.4	$4.6	$2.4	$2.3	$3.9	$2.7
Mooring & Installation ($MM)	**$10.2**	**$9.6**	**$19.8**	**$19.8**	**$11.2**	**$13.5**	**$13.5**
Project Management & Engineering	$0.8	$0.8	$1.6	$1.6	$1.6	$1.1	$1.1
Survey & Boreholes	$1.1	$0.9	$2.0	$2.0	$0.8	$1.8	$1.8
Mooring Components	$4.5	4.2	$11.8	$11.8	$4.9	$7.1	$7.1
Platform & Mooring Installation	$0.9	$0.9	$1.0	$1.0	$0.9	$1.0	$1.0
Turbine installation	$1.4	$1.4	$0.9	$0.9	$1.4	$0.9	$0.9
Mob/DeMob	$0.2	$0.2	$0.0	$0.0	$0.2	$0.0	$0.0
Marine Surveyor	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Contingency (15%)	$1.3	$1.2	$2.6	$2.6	$1.5	$1.8	$1.8
Total Installed Platforms Cost/Platform ($MM)	**$28.6**	**$28.0**	**$54.8**	**$38.5**	**$28.6**	**$43.5**	**$34.1**
Total Cost/kW	**$1,909**	**$1,866**	**$3,654**	**$2,569**	**$1,904**	**$2,902**	**$2,275**

7.4 OPEX, BALANCE OF SYSTEM, FCR AND NCF

We have utilized published data for the OPEX as well as Balance of system costs, Fixed Charge Rate (FCR) and Net Capacity Factor (NCF), specifically

- Pacific Coast (Stehly & Duffy, 2022)
- California, specifically. Humboldt Bay (Beiter, et al., The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032 NREL/TP-5000-77384, 2020)
- Hawaii (for comparison) (Shields, et al., 2021)
- Gulf of Maine (Musial, Beiter, & Nunemaker, 2020)

This section covers these factors as they apply to the LCOE values presented in the following section.

Our “Balance of System” is defined as everything other than the cost of the installed substructure, i.e., Turbine, Tower, Electrical and other soft costs.

All the published costs for the Pacific and Hawaii are based upon an assumed semi-submersible floating platform. The reports considered turbine sizes from 8 – 15 MW based on various Commercial Operation Dates (COD) from 2019 (8 MW) to 2032 (15 MW). For example, Table 12 shows Technology Assumptions of (Beiter, et al., The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032 NREL/TP-5000-77384, 2020) for their assessments. Detailed capital expenditures were only presented for the 2019 8-MW turbine case. The costs (and LCOEs) of future installations were derived from theoretical “Experience Factors” derived from fixed bottom installations, and estimates scale effects due to reducing the number of platforms per kW.

For purpose of this study, we are assuming Balance of System and OPEX costs for the 2019 example (with costs escalated to 2022$) for the 8 MW turbine sizes, see Table 13. These Balance of System costs are assumed the same for all platform cases considered in this study. Since this does not account for any advantages in the Balance of System costs for the larger turbines, we have included below results based on scaling of the Balance of System costs as determined by (Beiter, et al., The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032 NREL/TP-5000-77384, 2020).

FCR factors were derived from the information in Table 14 and are assumed to be applicable to all the cases considered here. Also, NCR values for Humboldt Bay and Maine from the literature are used here.

Table 12 Technology Assumptions (Beiter, et al., 2020)

	Unit	COD Year			
		2019	**2022**	**2027**	**2032**
Turbine Rated Power	MW	8	10	12	15
Turbine Rotor Diameter	m	175	196	215	240
Turbine Hub Height	m	118	128	138	150
Turbine Specific Power	W/m^2	332	332	332	332
Waterline Clearance	m	30	30	30	30
Substructure Type	Name	Semisubmersible			
Minimum Water Depth	m	40			
Maximum Water Depth	m	1,300			
Wind Plant Rating	MW	1,000			
Turbine Spacing	D	7D by 7D			

Table 13 Assumed Balance of System Costs (Beiter, et al., 2020)

	Original	Inflated 15%
Rating (MW)	8	8
TOTAL Balance of System	**$2,999**	**$3,449**
Turbine	$1,297	$1,492
Electrical System	$800	$920
Dev, PM	$299	$344
Soft CAPEX	$603	$693
OPEX ($/kWh-Yr)	$118	$136

Table 14 Financing Assumptions (Beiter, et al., 2020)

Table 7. Commercial-scale floating offshore wind financing assumptions.

Parameter	Value
Nominal after-tax FCR, %	7.2
Real after-tax FCR, %	5.3
Nominal after-tax WACC, %	5.4
Real after-tax WACC, %	2.9
Capital recovery period, years	30
Share of debt, %	75
Nominal debt rate, %	4.4
Nominal return on equity, %	12.0
Tax rate, %	26
Inflation, %	2.5
Nominal after-tax capital recovery factor, %	6.8
Real after-tax capital recovery factor, %	6.0
Project finance factor,%	105
Depreciation basis, %	100
Depreciation schedule	5-year MACRS
Present value of depreciation, %	86

8 LCOE Analysis results and conclusions

8.1 LCOE Results

Table 15 shows the reported results from the references. The CAPEX has been parsed to show the substructure, including installation, separately from the Balance of System. Note that the FCR and NCF values used by (Stehly & Duffy, 2022) are inconsistent with the other references, although the net effect of a lower FCR and a lower NCF minimizes the effect on the LCOE! The FCR value used by (Stehly & Duffy, 2022) seems to be the "real" (adjusted for inflation) value as opposed to the nominal value used by others, hence we have used the nominal value in our calculations. We have used NCF values of (Beiter, et al., 2020) for California and (Musial, Beiter, & Nunemaker, 2020) for Maine.

For comparison purposes we have escalated the costs in Table 15 by inflation factors based upon the Producer Price Index.

The results of our LCOE calculations are shown in Table 16 and a comparison of the spar case with the published information (adjusted for inflation) is shown in

Table 17. Figure 40 shows the distribution of CAPEX costs. The Balance of System costs in and Figure 40 are derived from the 8 MW Case of (Beiter, et al., 2020). If we assume Balance of System costs reduce according to Turbine Size in accordance with (Beiter, et al., 2020) we get the LCOEs plotted in Figure 41.

Figure 42 shows a comparison of LCOEs of the 1000 m Spar case with the published results, all based upon the 8 MW Balance of System cost assumptions. LCOEs in all cases using the lower Balance of System and OPEX costs would be 30-40% lower.

8.2 Conclusions

Comparison of the options included in this study shows the lowest LCOEs for the spar in the Pacific and the Buoyant Tower in the Atlantic. This is due to the mass production strategy using automated processes for the hull construction.

TLP costs are driven by shipyard procurement of modules which obviously favors foreign fabrication. It is worth noting that the automated process proposed here could also be applied to semi-submersible and TLP hull construction, but that has not been considered in this study.

The savings is not in the tonnage of steel in the platform, but in the cost of fabricating a tonne of steel!

We believe that the supply chain issues involved in building large floating wind farms could overwhelm conventional fabrication facilities and that mass production such as that assumed for spars and buoyant towers in this study will have to be implemented.

Other issues are also worth considering when comparing different platforms. When comparing spars, semis and TLPs it is worth considering the impact of the mooring systems on the wind farm layout. (Cooperman, et al., Assessment of Offshore WInd Energy Leasing Areas for Humboldt and Morro Bay Wind Energy Areas, California NREL/TP-5000-82341, 2022) made a detailed assessment of the Humboldt Bay and Morro Bay leasing areas. They concluded that mooring design has a significant effect on the turbine layout, i. e. turbine spacing. One extreme is the TLP which allows turbines to be placed as close as possible considering wake effects, and the other extreme are catenary moorings which can require the turbines to be placed 2000 m or more apart.

While the CAPEX/kW and LCOE for various options may not be significantly different, the power generation capacity for a given wind farm area can be quite different. In the case of the spar, we assume taut moorings, and that the moorings can share a common anchor between platforms. The spacing is assumed to be 7 times the rotor diameter (7D), or 1.68 km. For a TLP, the prevailing winds at the Humboldt Bay site would suggest a rectangular spacing of 4D x 10D with the narrow spacing perpendicular to the prevailing wind. There is a complicated tradeoff in selecting platforms, moorings and turbine spacing for any site which is beyond the scope of this study.

Table 15 Published LCOE Data

Compare	Stehly & Duffy (2020)	Beiter et al (2019)	Shields et al (2021)	Musial et al (2020)
Location	Pacific Coast	Humboldt Bay	Hawaii	Maine
Year $$	2020	2019	2021	2018
Rating (MW)	8	8	8	10
Substructure ($/kW)	2298	1504	1679	1202
Balance of System ($/kW)	3030	2998	3585	2927
Total CAPEX ($/kW)	5328	4502	5264	4129
OPEX ($/kW/yr)	118	118	80	62
FCR	5.8%	7.2%	7.2%	7.2%
NCF	38.0%	49.9%	49.2%	46.6%
AEP MWh/yr/kW	3328.8	4371.24	4309.92	4082.16
LCOE $/MWh	$128.3	$101.1	$106.5	$88.0
LCOE Substructure ($/MWh)	$40.0	$24.8	$28.0	$21.2

Table 16 LCOEs for the Cases Studied

Locations	Humboldt Bay				Gulf of Maine		
Platform	Spar US fab (1000m)	Spar US fab (500m)	TLP US fab (500M)	TLP Asia fab (500m)	Buoyant Tower US fab (150m)	TLP US fab (150m)	TLP EU fab (150m)
Rating (MW)	15	15	15	15	15	15	15
TOTAL CAPEX	**$5,358**	**$5,315**	**$7,103**	**$6,018**	**$5,353**	**$6,351**	**$5,724**
Turbine	$1,492	$1,492	$1,492	$1,492	$1,492	$1,492	$1,492
Support Structurel w/ Inst	$1,909	$1,866	$3,654	$2,569	$1,904	$2,902	$2,275
Electrical System	$920	$920	$920	$920	$920	$920	$920
Dev, PM	$344	$344	$344	$344	$344	$344	$344
Soft CAPEX	$693	$693	$693	$693	$693	$693	$693
OPEX ($/kWh-Yr)	**$136**	**$136**	**$136**	**$136**	**$136**	**$136**	**$136**
FCR	7.2%	7.2%	7.2%	7.2%	7.2%	7.2%	7.2%
NCF	49.9%	49.9%	49.9%	49.9%	46.2%	46.2%	46.2%
AEP High (MWh/MW - yr)	4371	4371	4371	4371	4047	4047	4047
LCOE ($/MWh)	**$119.3**	**$118.6**	**$148.0**	**$130.2**	**$128.8**	**$146.5**	**$135.4**
LCOE Substructure ($/MWh)	$31.4	$30.7	$60.2	$42.3	$33.9	$51.6	$40.5

Table 17 Comparison with Published Cases (adjusted for inflation)

	Spar (1000 m)	Stehly & Duffy (2022$)	Beiter et al (2022$)	Shields et al (2022$)	Musial et al Maine (2022$)
Location	Humboldt Bay	Pacific Coast	Humboldt Bay	Hawaii	Maine
Year $$	2022	2022	2022	2022	2022
Rating (MW)	15	8	8	8	10
Substructure ($/kW)	$1,914.0	$2,527.8	$1,729.6	$1,813.3	$1,442.4
Balance of System ($/kW)	$3,447.0	$3,333.0	$3,447.7	$3,871.8	$3,512.4
Total CAPEX ($/kW)	$5,361.0	$5,860.8	$5,177.3	$5,685.1	$4,954.8
OPEX ($/kW/yr)	$135.7	$129.8	$135.7	$80.0	$62.0
FCR	7.2%	7.2%	7.2%	7.2%	7.2%
NCF	49.9%	49.9%	49.9%	49.2%	46.6%
AEP MWh/yr/kW	4371.24	4371.24	4371.24	4309.92	4082.16
LCOE $/MWh	$119.3	$126.2	$116.3	$113.5	$102.6
LCOE Substructure ($/MWh)	$31.5	$41.6	$28.5	$30.3	$25.4

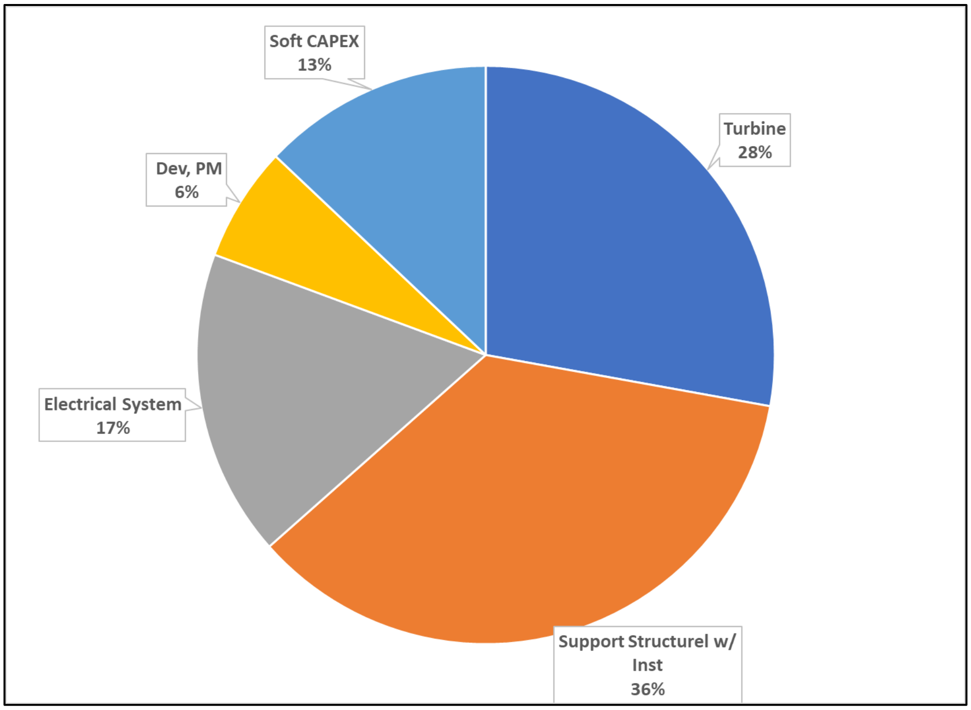

Figure 40 CAPEX Distribution – 1000 m Spar Case

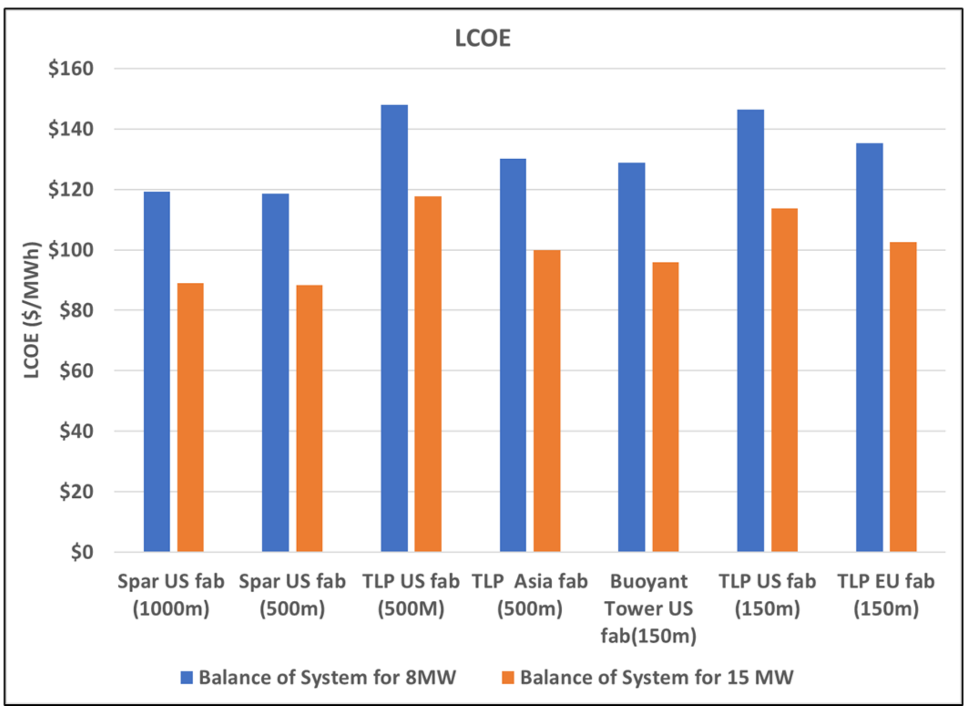

Figure 41 LCOE for Cases Studied Assuming Two Balance of System Bases

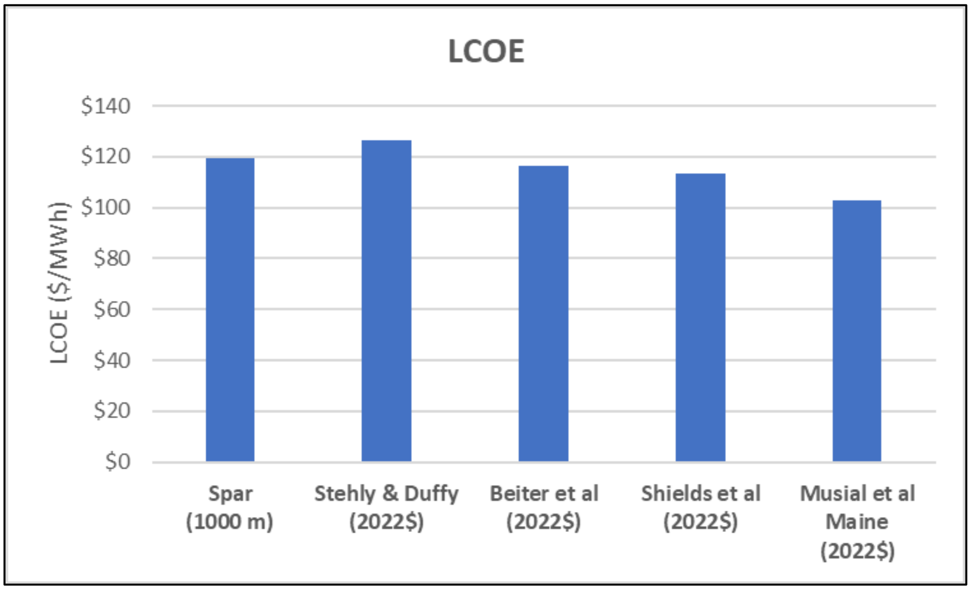

Figure 42 Comparison of Spar LCOE with Published Results (adjusted for inflation)

9 Discussion for Technical Risk Issues and Recommendations for Further Development

9.1 Summary of Observations and Recommendations

The floating offshore wind turbine market is expected to grow from 121MW in 2021 to around 26,000 MW and 2656 floating units by 2035 (Quest FWE, 2022). The inventory of floating offshore oil & gas platforms that have been built over the past 40 years includes (Offshore Magazine, 2019):

- 30 TLPs with average delivery times of 37 months (from project sanction to first oil),
- 21 Spars with average delivery times of 35 months
- 29 Semi-Submersibles with average delivery times of 38 months

Comparing 80 platforms built and installed over forty years with the projection of 2600 FOWTs over the next 14 years suggests that the current supply chain model would not be up to the task. We believe the method proposed here or a similar approach is required to meet this challenge. Even our proposed mobile barge manufacturing method producing one spar platform per week, if implemented by 2024, could “only” produce around 500 platforms by 2035! There would need to be several such facilities, on land or floating, to meet the expected demand!

The main observation is thus that there needs to be a paradigm shift in the model for supplying FOWTs like that proposed here to meet the expectations for floating wind.

The other observation is that this paradigm shift will remove the focus on minimizing steel weight for these platforms. This, and the proposed turbine installation methods, places the spar concept, including the buoyant tower, in a very competitive position relative to semi-submersible and other floating concepts.

Maybe more importantly, developing a local automated manufacturing method will reduce the environmental footprint of the project by eliminating transportation of large modules long distances. Manufacturing on a barge eliminates local temporary land use requirements and generally results in a more sustainable supply chain for FOWTs in different locations.

Recommended activities focus on vetting the manufacturing and installation methods. This will involve finalization of platform scantlings and design of the appropriate fabrication equipment to meet these requirements. If there is a manufacturing or structural limit the platform design may need to be modified. For example, monopiles are manufactured using similar methods up to 12 m diameter (EEW Group, 2016). If there is a practical limit to the diameter or the thickness for manufacturing this needs to be considered in the platform sizing. It is necessary to work with the providers of this equipment.

Similarly, the assumption that the substation platform may be used for turbine installation needs to be verified with operators. The substation has historically been in the lease area, however for example in the case of California the lease area water depths are too great for a fixed platform. If a floating substation is required, it would not be useable for the method proposed here. If the substation could be located in shallower water (e.g. 150 m) it may be impractical or uneconomic to run the power cable individually form each FOWT to the substation. This must be evaluated.

Finally, the control co-design method (ARPA-E, 2019a) should be considered to optimize the platform and turbine for final design. This is already being implemented for the PelaStar® design in order to reduce platform weight (GE Research, 2022). It should be noted that if the manufacturing methods are automated, hull weight does not necessarily have a significant impact on project cost and optimization on weight is not as important. Also, the manufacturing methods proposed here could be adapted for efficient local manufacturing of semi-submersibles and TLPs. The TLP has the advantage over other floating concepts of not requiring lateral mooring lines. This reduces obstacles to a local fishing industry, and allows optimum spacing of platforms.

9.2 Risks

The concepts proposed here have a history of application in the oil & gas industry, hence technical risks are somewhat mitigated or understood in the context of those applications. The requirements for supporting a wind turbine present unique challenges including, e.g.

- Platform, Tower, and Turbine Dynamics
- Platform size limitations (for the proposed manufacturing method)
- Installation of tower and turbine

9.2.1 Dynamics

The dynamics involve fatigue and strength issues and are complicated by the fact that the platform (including tower) have natural periods that may fall within the periods of design waves and the turbine periods. It has been recognized that designing cost effective FOWTs traditionally requires reducing steel weight, and this in turn introduces these risks. To mitigate this, considerable research has been directed at design methodologies that introduce features in the turbine control algorithms to dampen or filter the excitations of the dynamic loads. This technology, referred to as "control co-design" (CCD) is the subject of a major effort by the Department of Energy, Advanced Research Project Agency – Energy, or ARPA-E (IEC, 2019). To apply this technology, turbine designers and platform designers need to consolidate their efforts and design the platform and turbine, particularly the turbine controllers, synchronistically. It is particularly important in the case of the spar that the tower and spar are designed as an integral unit.

While control co-design is an important consideration, it is worth noting that the novel manufacturing method introduced here makes the cost of adding additional steel to the structure less significant and facilitates more flexibility to the designer. Also, the experience in designing, installing, and operating these platforms in the oil & gas industry with sophisticated Asset Integrity Management (AIM) systems in place has generated high confidence in the analytical methods for assessing the behavior of these platforms in service. Thus, there is confidence in the tools and methods that need to be employed in the final design of these platforms which mitigates the risk. Nevertheless, there is a need to be rigorous in this analysis as is laid out in the IEC standards (IEC, 2019).

9.2.2 Cell Diameter Limitations

The diameters selected for the single-cell spar in this project are considered the outer limit of what can be fabricated by the proposed method. Buckling is also a criterion which depends on the cell diameter. If further work determines the diameters are too large for manufacturing or buckling consideration multi-cell spars would be required. This is also the case if the overall performance criteria re increased, e.g. larger turbines. This will increase the cost and complexity of the proposed methods, albeit we believe effect will be small.

9.2.3 Installation

Installation of wind turbines on floating platforms is typically a risk because of the dynamics of two floating vessels (the foundation and a crane vessel) operating side-by-side in a seaway, and the relative motions of the turbine suspended from a crane and the tower under these conditions. The method(s) proposed for installing the turbine in this study circumvent these risks by employing a fixed crane on a fixed tower with the substructure (spar) secured to the tower and not subject to movement. The operations utilized in achieving this have been carried out previously for other projects, spars and buoyant towers, the risks are mitigated. The spar – tower mating still requires consideration of swell, particularly in the Pacific, and this requires further study.

9.3 Further Development and Improvement

9.3.1 Design update

The following Tasks are required to finalize a design for a specific project.

- Update of metocean and geotechnical conditions in accordance with IEC 61400 standards. This includes climatology for transport and installation.
- Resizing of the spar based on the stiffer, and heavier, tower design using DLC 1.6 and 6.1 as in this report.
- Further simulations in accordance with IEC 61400, and the subvariants of this standard, especially for the towout and installation cases, see (Jiang, Feng, Jiang, & Jiang, 2016), (GE, 2022).
- Global structural analysis and code checks of the spar and tower structure.

9.3.2 Manufacturing Study

Aside for further design and analysis to mitigate the risks discussed above, the key development required is the manufacturing method. Trendsetter Vulcan Offshore has already commissioned an investigation by the robotic equipment manufacturer, Kranendonk (https://www.kranendonk.com/), into the feasibility of outfitting a barge with the equipment discussed in Section 7.2 for spar construction. This work is not part of the current NOWRDC study. The principal concern is with the maximum diameter the spar, for example current monopile manufacturing using similar technology is limited to about 12 m (EEW Group, 2022) compared to 13.8m for the spar sizes proposed in this report. Previous similar designs have been limited to less than 8.5m.

9.3.3 Turbine Installation

The proposed installation method depends on the availability of a fixed platform in suitable water depth. The feasibility of using the substation for this purpose needs to be investigated with operators. In some instances the substation must be in the lease area. If this is the case for California the depths may be too great, > 500 m, for a fixed platform and a floating substation may be required (DNV, 2021). Our proposal assumes a fixed platform in a water depth close to the draft of the spar (no less). If it is not feasible or practical to do this for deep water floating wind farms like California we have two options:

a) Investigate the feasibility and cost of a bespoke fixed platform for this purpose. Costs would have to include construction and demobilization and would have to be amortized over regional wind farms.
b) Further develop the horizontal turbine installation method originally proposed for this study.

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