Evolved spar concrete substructure for floating offshore wind (WHEEL technology)

U.S. based design for large scale turbines.

D. 5.2

FINAL REPORT

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#119 – Evolved spar concrete substructure for floating offshore wind (TELWIND Technology). U.S. based design for large scale turbines: novel approach for WTG/Substructure interaction.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ALS	Accidental Limit State
BM	Metacentric Radius
COB	Center of Buoyancy
COG	Center of Gravity
CM	Center of Mass
CTO	Chief Technology Officer
DOE	Department of Energy
EU	European Union
FLOWIN	Floating Offshore Wind Readiness
ft	feet
GA	Grant Agreement
GBS	Gravity Based Structure
GM	Metacentric Height
Hs	Significant Wave Height
KB	Keel-COB vertical distance
KG	Keel-COG vertical distance
kWh	kilowatt hours
LCoE	Leverized Cost of Energy
LT	Lower tank
MSL	Mean Sea Level
m/s	meters per second
MW	megawatts
NREL	National Renewable Energy Laboratory
NOWRDC	National Offshore Wind Research and Development Consortium
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
SoW	Statement of work
Tp	Wave Peak period
ULS	Ultimate Limit State
UT	Upper tank
W	watts

WEIS	Wind Energy with Integrated Servo-control
WETO	Wind Energy Technologies Office
WTG	Wind Turbine Generator

EXECUTIVE SUMMARY

Most of the present designs for floating wind, either built or under development, are concepts inherited and adapted from other sectors, particularly Oil&Gas. While it is certainly wise and convenient to profit from the valuable experience gained in other sectors, the wind sector should at the same time be capable of developing wind-specific dedicated concepts that are novel precisely because they address new specific requirements of offshore wind, which can qualitatively differ from the ones present in Oil&Gas, such as the need for fast and industrialized serial production of a large number of repetitive units and need to reduce the cost of each unit in order for floating wind to be competitive with other energy sources.

WHEEL is a disruptive wind-dedicated technology based on an evolved spar configuration, in which a lower stabilizing ballast tank is suspended from an upper buoyancy tank. The suspension tendons are kept in tension by the lower tank's self-weight, and their triangular configuration of ensures both bodies move in a solidary manner. The upper hull is submerged for convenient transparency, with a modular steel tripod emerging as transition piece. The solution delivers the excellent sea-keeping performance of a spar solution, while allowing for a very efficient and industrialisable manufacturing strategy.

FIGURE 1. GENERAL VIEW OF THE WHEEL FLOATING CONCEPT

Both tanks can be built together one inside the other as one single concrete caisson, which will act as a barge during temporary harbor and tow-out operations. This delivers unparalleled compacity on harbor (26m radius and 5m draft for 15MW units) which shall allow for fast concrete caisson construction on floating barges, qualitatively reducing the port infrastructure requirements for large scale serial production.

FIGURE 2. GENERAL LAY-OUT FOR FLOATER SERIAL PRODUCTION BASED ON FLOATING BARGES. THE SAMPLE YARD SHOWN INCLUDES THE FLOATER PRODUCTION AREA (LEFT) AND A TRIPOD&TURBINE INTEGRATION AREA (RIGHT), ALTHOUGH THESE TWO AREAS DON'T HAVE TO BE NECESSARILY INCLUDED IN THE SAME YARD.

WHEEL's distinct attributes decisively widen the range of suitable harbor infrastructure, even opening possibilities for mass production of 15MW+ floaters based only on currently existing harbor infrastructure in the West Coast.

Specifically, a key aspect of the WHEEL floater is its unparalleled compacity, with a width and draft in harbor which halve those required by an equivalent semisubmersible solution. Combined with the simple geometry and vertical wall configuration of the floater concrete tanks, this makes it possible to effectively build WHEEL tanks directly on floating barges, with no need for very large yards, yard upgrading, or specialized shipyard facilities. This can prove a key advantage to overcoming one of the major challenges that the industry is facing for large-scale deployment in the West Coast.

Such strategy emulates the very successful and cost-efficient construction techniques that have been extensively used for the mass production of large concrete caissons for marine structures (Figure 31). These have serial production rates of 1 unit per week with only one construction barge, despite caissons often having weights, heights and drafts that may triple those of the 15MW WHEEL floater.

Note that the upper and lower ring-shaped tanks are built together, one inside the other, as if they were one single caisson. They are configured with flat bottom slabs and vertical walls, which allows mimicking the low-cost concrete construction techniques used for concrete caissons, with fully pre-assembled rebar cages for the lower slab and slipforming techniques for the vertical walls.

WHEEL tanks do include some elements which increase construction time as compared to caissons, such as prestressing elements intended to ensure a fully watertight behavior of the concrete walls or the suspension tendons connecting the upper and lower tanks, which are pre-assembled on the barge. In any case, the same high production rates (1unit/week) conventionally achieved for concrete caissons can be delivered using two floating barges instead of one. A low acreage yard with two working barges can produce 40-50units/year, enough to meet or even exceed the most optimistic expectations from the industry.

The steel tripod transition piece is assembled in parallel and installed onto the concrete floaters (Figure 2) after these have been floated-off, with no effect on the barge unit cycle time. Its modular configuration allows for a fast assembly rate.

The project has delivered a complete design of the WHEEL floater suited for supporting the IEA 15MW wind turbine in Pacific Ocean conditions characteristic of the US West Coast. This designed has been generated and validated jointly by ESTEYCO and NREL, including detailed coupled simulations of the operative condition of the floater, as well as advanced hydrodynamic modelling of the critical temporary conditions for the floater installation.

The project has also delivered a feasibility pathway for large scale deployment of WHEEL floaters in southern California, providing a cost-effective solution that supports large turbines, enhances local supply chain and can be produced based solely in existing harbor infrastructure, establishing a breakthrough advantage as compared to practically all state-of-the-art solutions. Specifically, the project has included the assessment of:

- How WHEEL can be manufactured in series with full US supply chain and overcoming current challenges in terms of available and suitable harbor infrastructures in the West Coast.
- How WHEEL can be installed with US vessels, without imported `ad-hoc means´.
- How WHEEL is suited to deliver reduction in cost and carbon footprint.
- How to enhance in general the interaction between platform and turbine designers

PURPOSE AND SCOPE

This document aims to gather non-proprietary/non-confidential information, covering key aspects of the Work performed under this Agreement #165431.

CONCEPTUAL DESCRIPTION OF THE WHEEL TECHNOLOGY

The WHEEL technology is an evolved spar concept. Spars deliver the required floating stability with a large bottom ballast weight which brings the center of gravity sufficiently below the center of buoyancy. If the structure tilts, downward weight on the bottom and upward buoyancy on the top deliver the needed righting moment (Figure 3). Floating stability is therefore not dependent on a large floating plane, as opposed to ships or other platform solutions such as semisubmersibles or barges.

This concept is well known in both oil&gas and wind (Figure 3-left) and is characterized by long vertical structures that bring the ballast weight down and keep it moving along with the upper buoyancy hull. However, these long vertical structures have critical drawbacks for construction and installation (Figure 3-center), since they prevent the possibility to integrate the floater and the wind turbine generator (WTG) in harbor, which is crucial for an industrialized solution.

FIGURE 3. SPAR PRECEDENTS AND WHEEL technology CONCEPT. (LEFT) SPAR PRECEDENTS FROM THE OIL&GAS AND WIND SECTORS; (CENTER) WTG INTEGRATION CHALLENGE FOR CONVENTIONAL SPARS; (RIGHT) WHEEL TECHNOLOGY CONCEPT.

WHEEL uses instead a lowerable weight suspended from the upper structure with tendons. Once in deeper waters, the weight is lowered, and the tensioned cables will behave as triangularised rigid bars which make the ballast weight solidary with the whole system (Figure 3-right).

The floater therefore comprises two tanks, an upper one which provides the required buoyancy, and a lower one which houses the ballast weight (Figure 4-right). The upper buoyancy tank is conveniently submerged in operation, keeping it away from the concentrated wave energy on the surface. A steel tripod structure will act as transition piece between the upper tank and the wind tower.

The WHEEL floater evolved spar concept is disruptive with regards to the construction and installation process. The upper and lower tanks can be positioned together, one inside the other, acting as one barge-type platform which provides adequate stability during temporary construction and installation stages.

Thus, WHEEL capitalizes on the transparency and stability characteristics of a spar while allowing for quayside turbine integration, much like semisubmersibles or barge solutions, but with a much more compact width and reduced draft in harbor.

Specifically, for the 15MW design developed in the present project, such “barge” has 26m radius and 5.3m draft, roughly half of an equivalent semisubmersible alternative. These key aspects, together with a concrete-based hull, decisively widen the range of suitable harbors and thus open options to pursue local manufacturing strategies that may overcome the harbor infrastructure constraints faced in the West Coast.

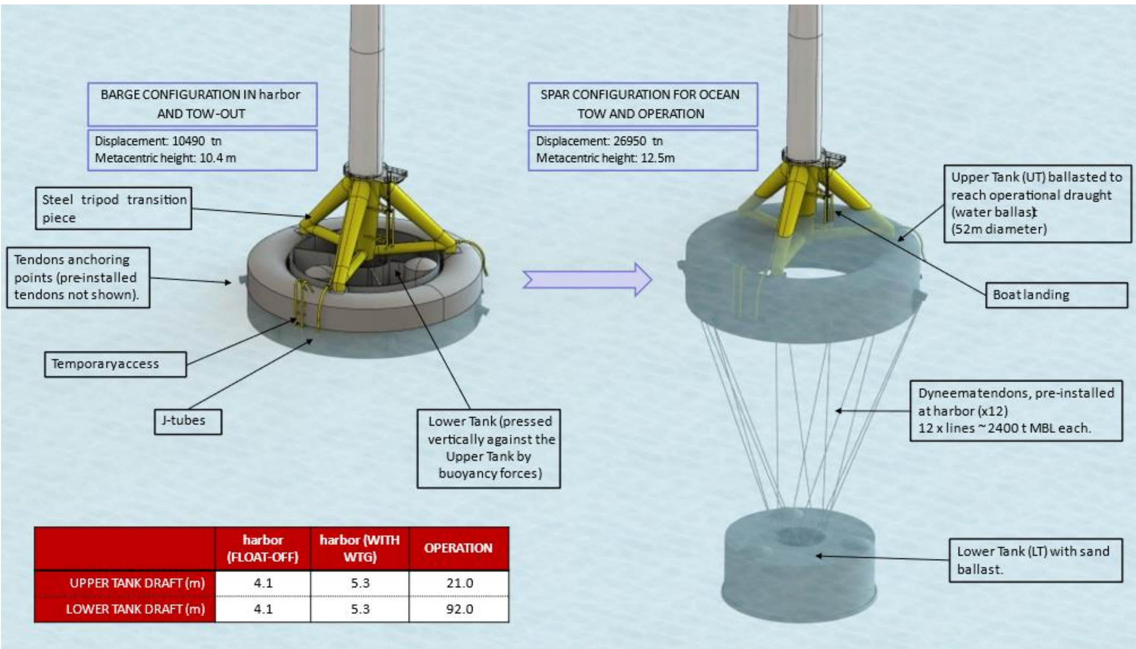


FIGURE 4. WHEEL FLOATER SIZED FOR 15MW WTG IN MORRO BAY (CA). LEFT: COMPACT LOW-DRAFT BARGE CONFIGURATION FOR HARBOR ASSEMBLY AND TOW-OUT. RIGHT: ULTRA-STABLE AND TRANSPARENT SPAR CONFIGURATION FOR OPERATION.

In the “barge” configuration (Figure 4-left), buoyancy keeps the upper and lower tanks pressed against each other, behaving as one single solidary hull. Once in sufficiently deep waters, the lower tank can be deployed in a controlled manner and WHEEL will achieve an ultra-stable transparent configuration for operation (Figure 4-right).

It worth mentioning that, on its path of development and deployment WHEEL technology, Esteyco is leading the WHEEL project.

The overall objective of the WHEEL project is to fully demonstrate and bring to a precommercial Technology Readiness Level (TRL) a revolutionary floating wind technology excellently suited for deep water locations, effective industrialization strategies, breakthrough cost reduction and minimized carbon footprint. This shall enable a radical step forward for LCoE reduction, whilst also addressing scalability, harbour infrastructure suitability and availability, and the sustainability & circularity of floating offshore wind.

Development and demonstration will be achieved through the design, installation, certification and testing of a fully operative pilot unit, which will showcase and demonstrate the breakthrough advantages that the WHEEL technology can deliver to the floating wind industry. A 6 MW two-bladed downwind wind turbine on a WHEEL float will be installed in a deep-water location in the PLOCAN testing area (Canary Islands, Spain) at the end of 2025, where it will be thoroughly monitored along a period sufficient to underpin the commercialization and bankability of the technology.

In the framework of the Horizon Europe Programme, WHEEL project has been awarded with EU funds (GA nº 101084409). It will impulse the demonstration of the WHEEL technology as feasible very competitive player in the floating offshore wind market.

The awarded Consortium is composed by renowned European companies and research institutions with extensive experience and a spearhead position in the renewables and marine industry. This multidisciplinary team joins forces to complete the full demonstration (including the engineering and manufacturing works) of such a disruptive technology by integrating complementary expertise fields and capabilities which effectively cover all key areas of floating wind systems in pursuit of the ambitious objectives of the project.

Partner name	Short name	Country	Expertise	Role in the project
ESTEYCO	EST	SP	Civil Engineering	Coordinator / Engineering / Floater Technology & systems supplier / Dedicated Construction Means / D&C
2B ENERGY	2BE	NL	Wind Turbine Generators	Wind Turbine and steel tower supply, commissioning and operation
ROVER MARITIME	RVM	SP	Marine Construction Works	Concrete Floater Construction works
REPNAVAL	RNC	SP	Shipyard and Harbor Infrastructure	Construction&Assembly yard & means. Steel Structure Supplier
BRIDON-BEKAERT	BBRG	BE	Cables and Ropes	Synthetic Ropes for suspension tendons and mooring
VICINAY	VIC	SP	Station Keeping System	Mooring line Design and Supply
FIHAC	FIH	SP	R&D and Laboratory testing	Tank testing campaign
PLOCAN	PLO	SP	Marine Energies & Blue Economy	Testing Site and Energy Evacuation provider / SSH and Public Acceptance
EnBW	EBW	GE	Renewable Energy Developer	Technology Business Case and Commercialization
CEMEX	CEM	SZ	Cement and Concrete	Supplier of Advanced Lightweight Concrete / Sustainable and circular materials
BOSKALIS	BOS	NL	Marine services	Marine operations and means

TABLE 1. WHEEL PARTNERS

Likewise, it must be announced that WHEEL technology has been selected as one of the nine Phase One winners of the Floating Offshore Wind Readiness (FLOWIN) Prize. Launched by the U.S. Department of Energy's (DOE) Wind Energy Technologies Office (WETO) in September 2022 and administered by the National Renewable Energy Laboratory (NREL), this prize aims to unlock the potential of U.S. offshore wind energy by promoting the manufacturing and deployment of floating offshore wind energy technologies. Moreover, it supports the Biden administration's goal of decarbonizing the U.S. electricity grid by 2035 and achieving a net-zero economy by 2050.

Esteyco, together with a consortium composed of renowned companies in the field of wind energy, including TotalEnergies, SSA Marine, Infrastructure and Energy Alternatives (IEA), Sarens USA, and Rover Maritime which also participates in the HE project, has demonstrated in Phase One that the WHEEL technology is ready for mass manufacturing.

As Phase One winners, Esteyco has also been invited to participate in Phase Two, where a plan for the mass manufacturing and deployment of gigawatt-scale floating offshore wind energy farms using the WHEEL technology will be developed.

PERFORMED WORK

This project started on December 13th, 2021, Administrative Kick of Meeting date. The work performed has had a duration of approximately 12 months and has been organized in 4 different Tasks as described in the following sections:

1. TASK 0 - PROJECT MANAGEMENT AND PROGRESS REPORTING

Within this task ESTEYCO has timely coordinated its own employees and subcontracting agents in order to complete tasks described in the Statement of Work.

All project reporting has been provided to the NOWRDC Consortium.

Likewise, control over the project budget and adherence to the Milestone Payment Schedule and Detailed Budget Justification has been ensured.

Next, some information regarding the project schedule, advisory board meeting and periodic project reports.

1.1 Project Organization

1.1.1 GO/NO GO evaluation

As a multi-phase project, it included a Go/No-Go decision point at the conclusion of Phase I. The Project Manager notified that the decision from DOE and NYSERDA was a “Go” and that ESTEYCO could move forward on May 16th, 2022.

TITLE: EVOLVED SPAR CONCRETE SUBSTRUCTURE FOR FLOATING OFFSHORE WIND (TELWIND TECHNOLOGY). U.S. BASED DESIGN FOR LARGE SCALE TURBINES: NOVEL APPROACH FOR WTG/SUBSTRUCTURE INTERACTION IN THE U.S.

TASK O	PROJECT MANAGEMENT AND PROGRESS REPORTING
	D0.1.1: Written periodic Progress Reports 1
	D0.1.2: Written periodic Progress Report 2
	D0.1.3: Written periodic Progress Report 3
	D0.1.4: Written periodic Progress Report 4
	D0.2: Brief report summarizing the Kick-off Meeting and Minutes.
	D0.3: List of members of the Advisory Board
	D0.4: Brief report summarizing the Completion Meeting and Minutes.
	D0.5: Annual metrics Report
	D0.6: Team Member Contact List
	D0.7: Project Gantt Chart
	D0.8: NREL´s upfront payment Budget Period 3
TASK 1	DEVELOPMENT OF A CONCEPTUAL DESIGN (INCLUDING MOORING) FOR THE 15 MW REFERENCE TURBINE AND REPRESENTATIVE METOCEAN CONDITIONS OFF THE US EAST COAST
	D1.1 Platform Design Report for the IEA-15 MW WTG
TASK 2	COUPLED MODEL DEVELOPMENT
	D2.1 Detailed Analysis of Marine Performance of the IEA-15 MW Floating Wind Turbine
TASK 3	DESIGN UPDATE TOWARDS INDUSTRIAL MANUFACTURING WITH LOCAL SUPPLY CHAIN
	D3.1 Industrially deployable design report.
	D3.1 Technical report that assesses whether the tow-out of a 15-MW turbine stays within expected OEM warranty limits
TASK 4	INNOVATIVE MOORING AND ANCHORING SYSTEMS
	D4.1 Moring and anchoring design report.
TASK 5	Development of a specific methodology to enhance OEM and platform designer interaction in commercial projects.
	D5.1 Draft Final Report
	D5.2 Final Final Report
	D5.3 DOE required closeout reporting per Exhibit F
	D5.4 Market Engagement Report

FIGURE 5. PROJECT TASKS AND LINKED DELIVERABLES

1.2 Progress reporting

Although within the contract signed between NOWRDC and ESTEYCO there were two written periodic reports included, it was verbally agreed to submit a report per quarter but only invoicing two of them.

Quartely Report	Months included	Date of submission	Total cost
Q1	M1 (December 2021)	01/25/2022	$1,200
Q2	M2-M3-M4	04/20/2022	$1,200
Q3	M5-M6-M7	08/08/2022	$0
Q4	M8-M9-M10	10/15/2022	$0

TABLE 2. QUARTERLY REPORTS LENGTH AND SUBMISSION. (DELIVERABLES D0.1.1 TO D0.1.4 QX PROGRESS REPORT).

1.3 Advisory Board

The Project Advisory Board has been formed by of offshore wind developers and other industry partners from the Consortium's membership who provided technical and commercial advice to the project team throughout the duration of the project.

Meetings have been held online quarterly.

Advisory Board	Date	Minutes
AB1	01/19/2022	D0.3 Advisory Board
AB2	04/27/2022	D0.1.3 Q3 Progress Report
AB3	09/15/2022	D0.1.4 Q4 Progress Report
AB4	12/13/2022	N/A

TABLE 3. ADVISORY BOARD MEETINGS DATES. (DELIVERABLE D0.3 ADVISORY BOARD.)

2. TASK 1 - DEVELOPMENT OF A CONCEPTUAL DESIGN FOR THE 15MW REFERENCE TURBINE AND REPRESENTATIVE METOCEAN CONDITIONS OFF THE US WEST COAST

This task aimed to describe and define the design for the WHEEL floating technology for the reference IEA 15MW offshore wind turbine as applicable in representative conditions of the US West Coast.

The general strategy for construction and assembly of the floater and the advantages pursued with its design regarding both operative performance, constructability and suitability for industrialization were also outlined.

In addition to the geometrical and mass properties of the floater, hydrodynamic properties and damping parameters were provided which serve for the detailed coupled simulations of the floater in operating conditions, to be performed in following tasks.

2.1 The WHEEL technology

2.1.1 Basic description of the WHEEL technology

The WHEEL technology is an Evolved Spar Floating Solution based on the solidary suspended ballast tank concept, patented by Esteyco in 2014.

The floater comprises two concrete tanks: an upper tank, which provides buoyancy, and a lower tank, which provides stabilizing ballast weight lowering the center of gravity of the overall system.

FIGURE 6. WHEEL TECHNOLOGY: TOW-OUT CONFIGURATION (LEFT), OPERATION CONFIGURATION (RIGHT).

The lower tank is suspended from the upper tank with suspension lines in a triangularised configuration; the selfweight of the lower tank keeps all suspension lines in tension for all operational conditions, so that they behave as rigid bars ensuring that both tanks move solidarily.

Finally, the floater comprises a transition piece configured as a steel tripod analogous to those used for bottom-fixed offshore wind foundations.

WHEEL stands for Wind Hybrid ESTEYCO Evolution for Low-carbon solutions. WHEEL is considered hybrid not only because it uses both steel and concrete where each material is deemed more suitable and competitive, but also because it allows for two configurations (see previous figure), each one particularly suited for the Construction&Assembly stage on one side and the operational stage on the other:

- A barge type configuration in harbor, which allows full onshore assembly of the floater and WTG just like semisubmersible floaters, but with much lower width, draft and material usage, and a simpler caisson configuration for a more cost-effective construction.
- An ultra-stable spar configuration in operation, which as compared to semisub or barge solutions minimizes the exposed area on the surface, providing a much convenient transparency to sea loading and lowering mooring costs; this configuration delivers excellent sea-keeping performance, with large mass inertia and very high natural periods in both heave and pitch which result in very slow motions.

2.1.2 Main components of the WHEEL floater

Figure 7 next depicts the main components of the WHEEL floating structure:

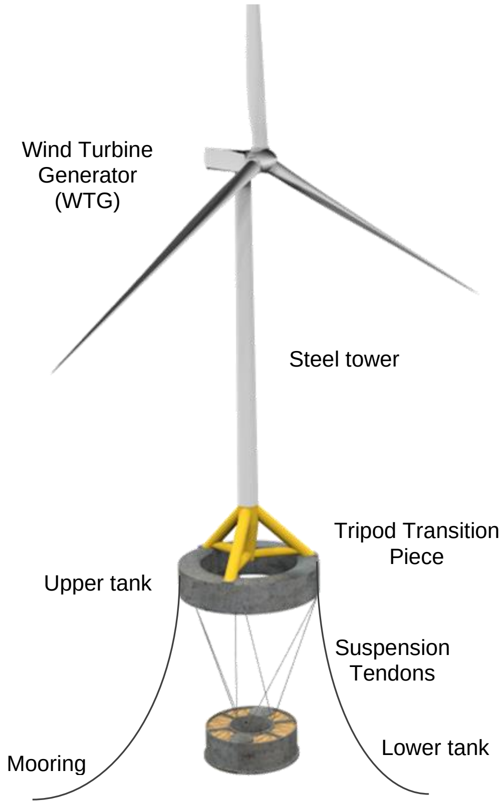


FIGURE 7. WHEEL GEOMETRY AND COMPONENTS. MAIN COMPONENTS OF THE WHEEL FLOATER.

The concrete structure is formed by two tanks, upper tank and lower tank. They have a simple ring-shaped geometry that makes it possible to build and transport both tanks together, one inside the other. This allows for a simpler and cheaper construction by significantly reducing the size and draft in harbor.

The upper tank shall hold water ballast for draft control, no active ballast system (ABS) is required for operation. The lower tank is divided in open sand chambers to be filled with sand solid ballast to provide low-cost weight and closed cylindrical tanks which allow for controlled deployment and descent of lower tank. The large mass of the lower tank which lowers the Centre of Gravity (CoG) while the upper tank is mostly void and provides the buoyancy raising the Centre of Buoyancy (CoB). By maintaining the CoB sufficiently above the CoG high stability is generated in a so-called SPAR floater configuration.

Both tanks are connected to each other by suspension tendons in a triangularised manner. Triangularised suspension tendons, prestressed by the weight of the lower tank, ensure that both tanks move along in a solidary manner.

2.1.3 Construction strategy and suitability for industrialization

Manufacturing strategy and simplification has been a key driver in the conception of the WHEEL technology and its selected configuration.

A key aspect of the WHEEL floater is its compact size and low-draft which is crucial to widen the range of suitable harbor infrastructure and existing construction and float-out means. Combined with the simple geometry and vertical wall configuration of the floater tanks, this makes it possible to apply very proven and cost-efficient construction techniques that have been extensively used for the industrialized mass production of very large concrete caissons for marine structures (see

Figure 8). These make use of floating dock or barges, so that the concrete structure can be built on the barge and directly floated-off. Such construction strategy has been proven as very suitable for serial production of repetitive units, delivering very competitive unitary cost-rates per m3 of concrete.

Production rates of 1 unit per week are conventionally achieved for caisson construction, which matches well with the expectable demand of commercial offshore wind farms. Note that this production rates are achieved for caissons with weights and drafts that often more than triple the expected characteristics of a WHEEL floater with 8000tn weight and 5m draft (for 15MW).

Production rates can in any case be multiplied by using more construction barges with very little additional demand on the required harbor infrastructure. This is deemed a key advantage for deployment in the US west coast, where availability of suitable and available harbor infrastructure is acknowledged by the industry as one of the key challenges for industrial deployment of giga scale floating wind.

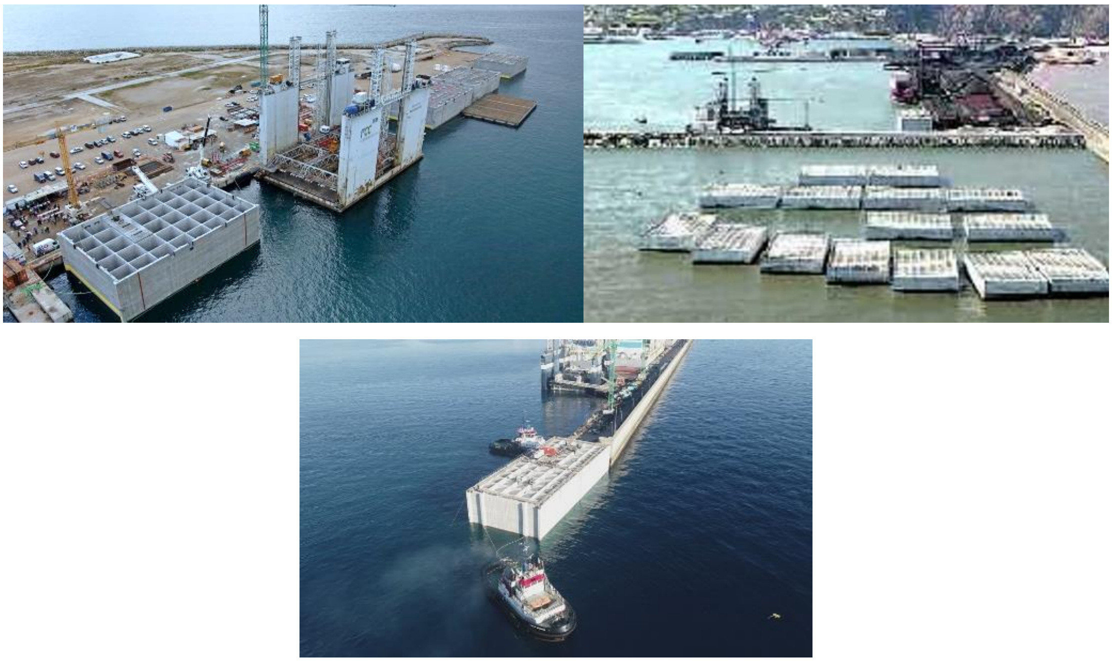


FIGURE 8. INDUSTRIALIZED MASS PRODUCTION OF CONCRETE CAISSONS BUILT ON FLOATING DOCKS/BARGES WITH LIMITED USE OF QUAY AREA (UP LEFT), WET STOCKED AS REQUIRED (UP RIGHT) AND INSTALLED WITH TUG-BOATS (DOWN).

Figure 9 next depicts a reference lay-out for the construction of WHEEL floaters. A construction barge with two positions (or two construction barges with one position) are planned to deliver 1 unit/week production rates. It is noted in any case that the WHEEL floater can also be suited for on-yard construction strategies accompanied by the corresponding load-out and float-off operations and means. However, it is expected that yard area requirements and harbour upgrade upfront investments would increase considerably with such a construction strategy.

The steel tripod is configured by 7 different tower-like tubular elements, 6 of which are transportable on road and may be supplied by onshore tower manufacturers. No need for a specialized or large capacity shipyard. These elements are then pre-assembled on harbour, with simple automated welds in the underwater connections and conventional flange and bolts for the above water connections.

Figure 9 shows an example configuration in which the same harbor would be used for floater construction and for WTG assembly and integration. It is however clarified that this may not always be the selected strategy and it is indeed also possible to build the floater on a different harbor and transport them to another WTG marshalling harbor where turbine assembly and integration works would take place before tow-out for offshore installation.

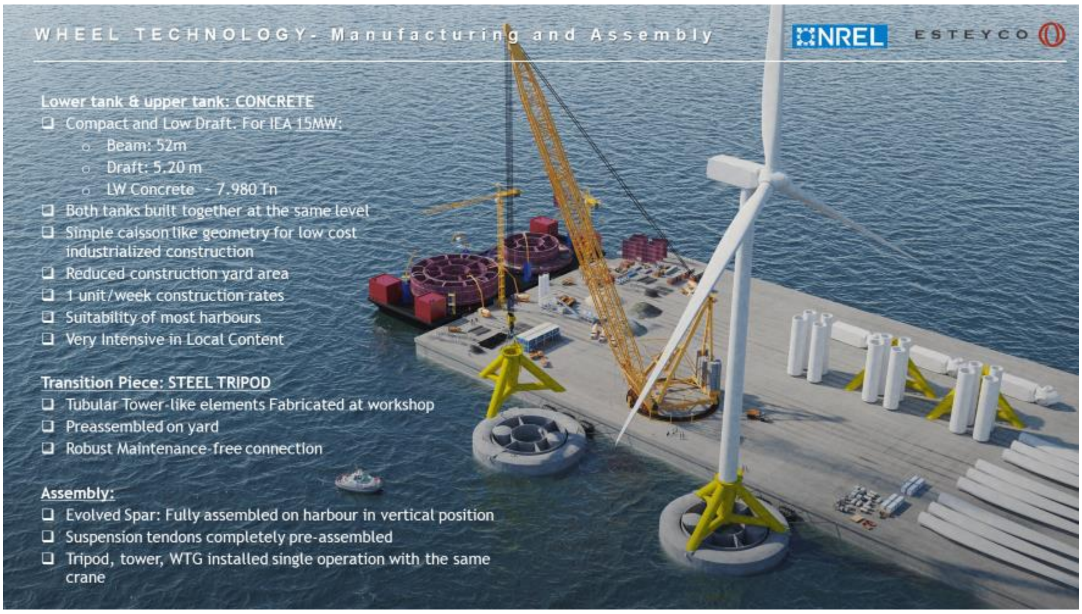


FIGURE 9. OVERVIEW OF MANUFACTURING AND ASSEMBLY (TURBINE INTEGRATION) STRATEGIES.

The installation process, temporary conditions and marine operations for the installation of the WHEEL technology have obviously been a critical factor in the analysis and design. These have been reviewed and coordinated specifically with specialist contractors for marine operations and include the tow-out, the deployment of the lower tank with controlled water ballast (the LT comprises closed column tanks to control the lowering process), the solid ballast infill or the mooring pre-lay and hook-up.

Base case considered for the US west coast is that deployment of the lower tank (LT) and ballast infill will happen in a near-coast location with sufficient water depth, and once the LT is deployed the tow can continue to the final location. However, depending on the wind farm location or project size, it is also possible to two units directly to the site and perform the deployment of the Lower Tank after mooring hook-up.

A general overview of the installation process is given in Figure 10 next:

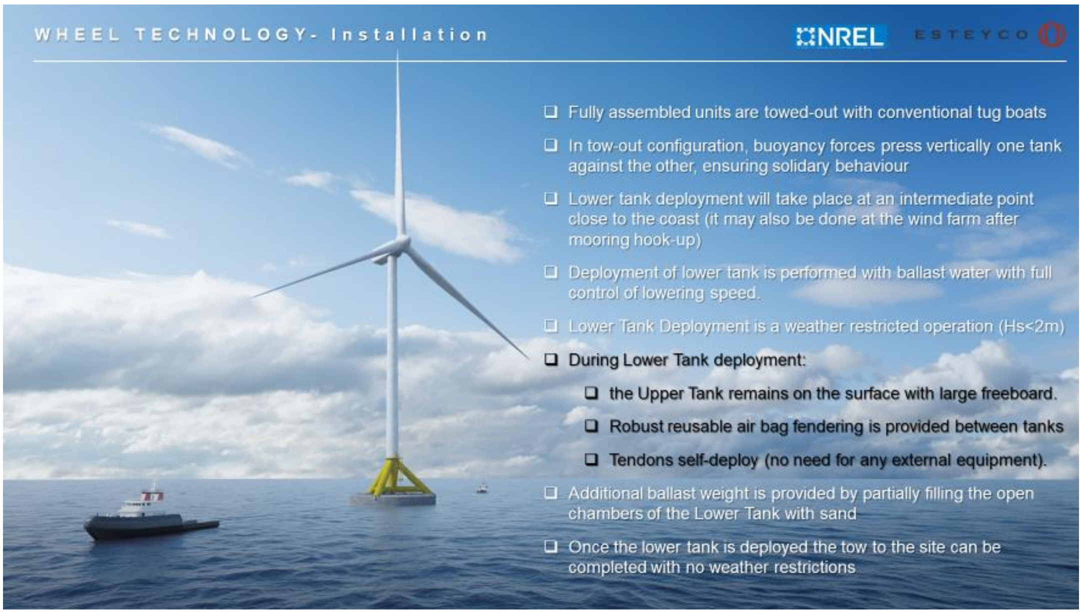


FIGURE 10. OVERVIEW OF THE INSTALLATION PROCESS.

2.2 WHEEL reference location and meteocean conditions

The selected location for design and analysis of the WHEEL floater is Morro Bay area in California (Figure 11), around 40 NM off Morro Bay. Average water depth considered is 900 m LAT.

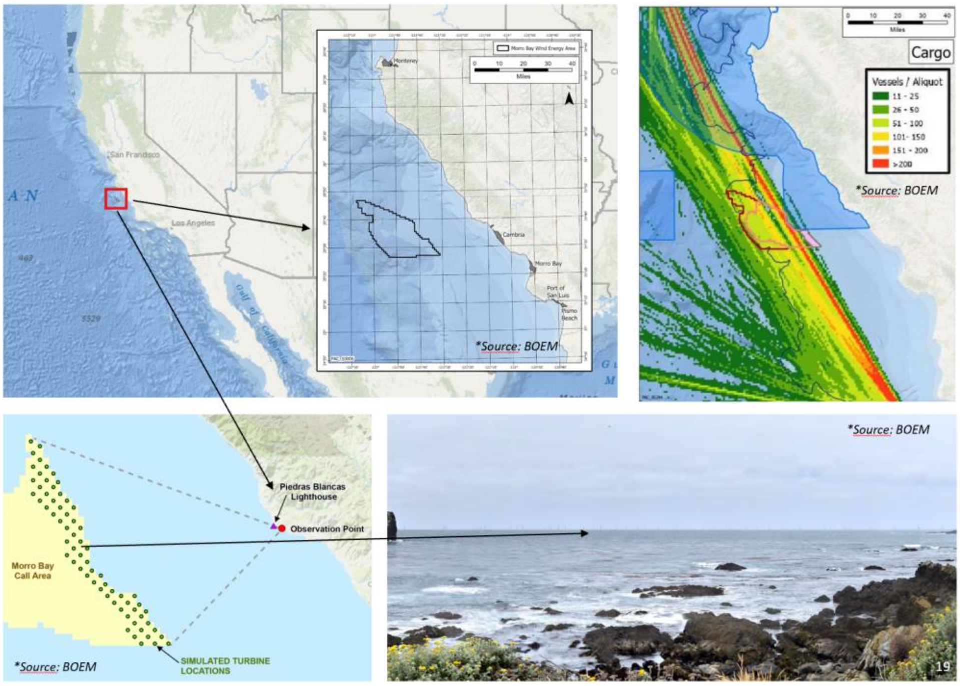


FIGURE 11. SELECTED REFERENCE LOCATION AT MORO BAY AREA (CA)

800m water depth has been considered representative of the Morro Bay area. The Station Keeping System has been designed at a conceptual level and for the costing and supply chain analysis.

The corresponding metocean conditions considered for the analysis were provided within document ID-21I9-TN-002. Some relevant aspects worth commenting for design of the 15MW floater and are summarized below:

- With regards to waves:

In general, the site has not the best mean regime weather conditions for marine operations. Long swells are common, with average significant wave height over 2 m. Most of the marine operations to be carried out, as for instance, mooring pre-lay or anchors deployment, have weather limits close or below the average wave in the area, which limits the operability of the marine spread. This should also be considered regarding O&M accessibility during the project's service life.

Substantial directional waves coming from NWW.

On the other hand, extreme conditions, defined as per 50-yr return period waves, are not very demanding (below 10 m) as compared to other locations. It is worth stressing that further data is required for the final assessment of the survival conditions. Slightly larger waves will not modify the floater design but will potentially have an impact on mooring sizing that will need to be reassessed in future project stages.

- With regards to currents:

In general, they seem to be mild, even for 50-yr return period where they are slightly above 2 knots.

Return period	Hs [m]	Tp [s]
50	9.9	14 – 18
20	9.0	
10	8.3	
1	6.0	

Average current	0.2 m/s
1-yr current	0.8 m/s
50-yr current	1.1 m/s

TABLE 4. METEOCEAN CONDITIONS IN THE MORRO BAY AREA. EXTREME WAVE (LEFT) AND CURRENT REGIME (RIGHT).

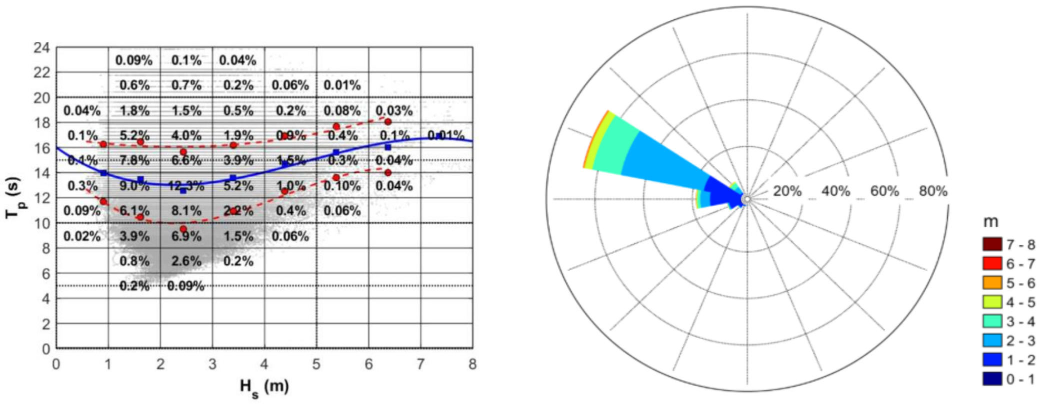


FIGURE 12. MORRO BAY'S WAVE SCATTER DIAGRAM AND ROSE.

- With regards to wind:

Wind speed seems to be on average around 5.9 m/s hourly averaged, which means around 6.2 m/s 10-min mean at 10 m height. At the hub height that means on average around 9 m/s.

Quite directional wind, but not perfectly aligned with waves (which are predominantly swells) coming mainly from NW and NNW.

Extreme wind speed at hub height is, as for waves, are not extremely high, reaching 36 m/s at hub height.

The most typical wave-wind combinations are waves between 1-3 m combined with winds between 4 and 8 m/s (1-h @ 10 m), which means that most of the time the turbine will be operating just below rated with waves around 2 m high.

Sig. Wave height	Wind speed (1-h at 10 m)										
	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	>20
0-1	0.084	0.27	0.28	0.084	0.004						
1-2	3.103	9.247	10.896	8.021	3.621	0.55	0.017	0.002			
2-3	2.453	7.425	9.817	9.54	8.452	4.282	0.781	0.037	0.006	0.001	
3-4	0.665	2.201	3.296	3.293	2.911	2.227	0.897	0.118	0.014	0.003	0.001
4-5	0.215	0.529	0.779	0.857	0.818	0.619	0.302	0.088	0.014	0.002	0.003
5-6	0.047	0.127	0.165	0.171	0.169	0.104	0.082	0.037	0.014	0.003	0.002
6-7	0.008	0.023	0.033	0.041	0.036	0.028	0.025	0.017	0.005	0.001	0.001
>7	0.004	0.005	0.004	0.002	0.005	0.007	0.004	0.002			

TABLE 5. WIND-WAVE RELATION FOR THE MORRO BAY AREA

Extreme Wind Profile 50 yr	
Height [m]	Speed [m/s]
10	26.9
20	29.0
50	32.1
100	34.7
119	35.3
150	36.2

TABLE 6. WIND EXTREME REGIME IN THE MORRO BAY AREA

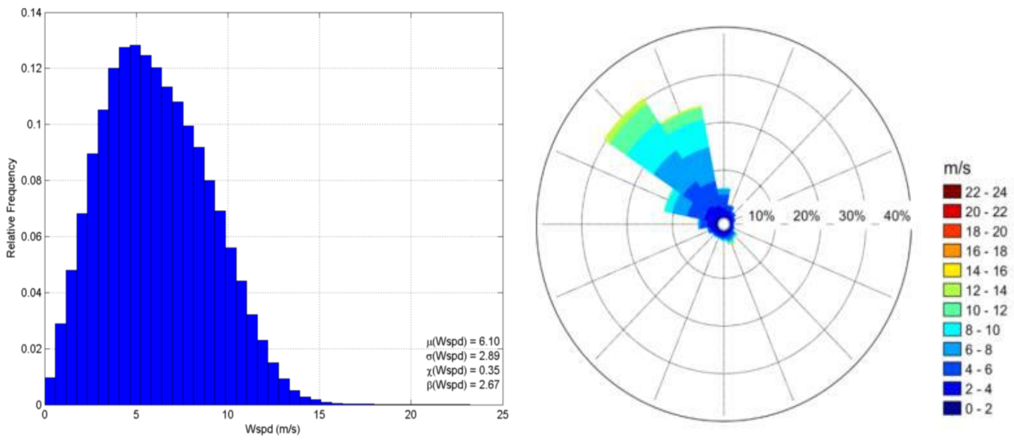


FIGURE 13. WIND DISTRIBUTION DIAGRAM AND WIND ROSE IN THE MORRO BAY AREA

2.3 WHEEL geometry for the IEA 15MW WTG

Next figure depicts the installed condition of the WHEEL floater and summarizes the main design figures, which are further detailed in the following sections:

FIGURE 14. WHEEL FLOATER FOR IEA 15MW WTG IN INSTALLED CONDITION AND SUMMARY OF KEY DESIGN FIGURES

2.3.1 Axis system and sign convention

The axis system adopted is as follows:

- The center of coordinates (point O) is located at the geometric center at UT keel level (Figure 15).
- X axis is positive upwind.
- Z axis is pointing upwards, to tower top.
- Y axis is pointing towards portside.

Motions shall be given as:

- Positive surge when movement goes parallel to X-axis towards its positive direction.
- Positive sway when movement goes parallel to Y-axis, towards its positive direction.
- Positive heave when movement goes upwards.
- Positive roll when the WHEEL rotates around X-axis and the turbine goes towards negative Y-direction.
- Positive pitch when the WHEEL rotates around Y-axis and the turbine goes towards positive X- direction.
- Positive yaw when WHEEL rotates counterclockwise in plan view.

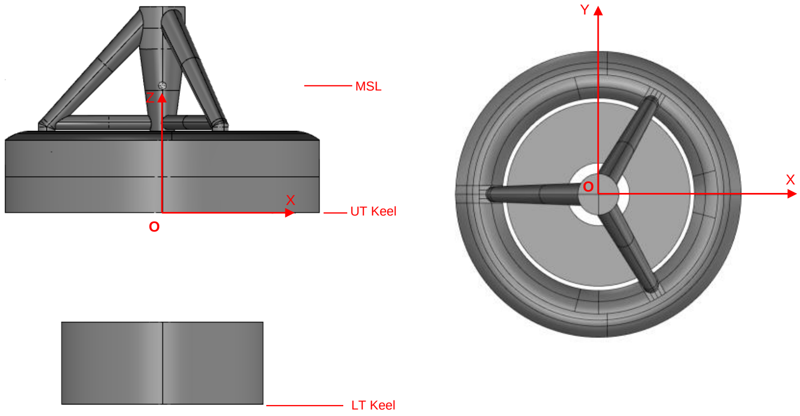


FIGURE 15. WHEEL AXIS SYSTEM

2.3.2 Geometrical definition in operating condition

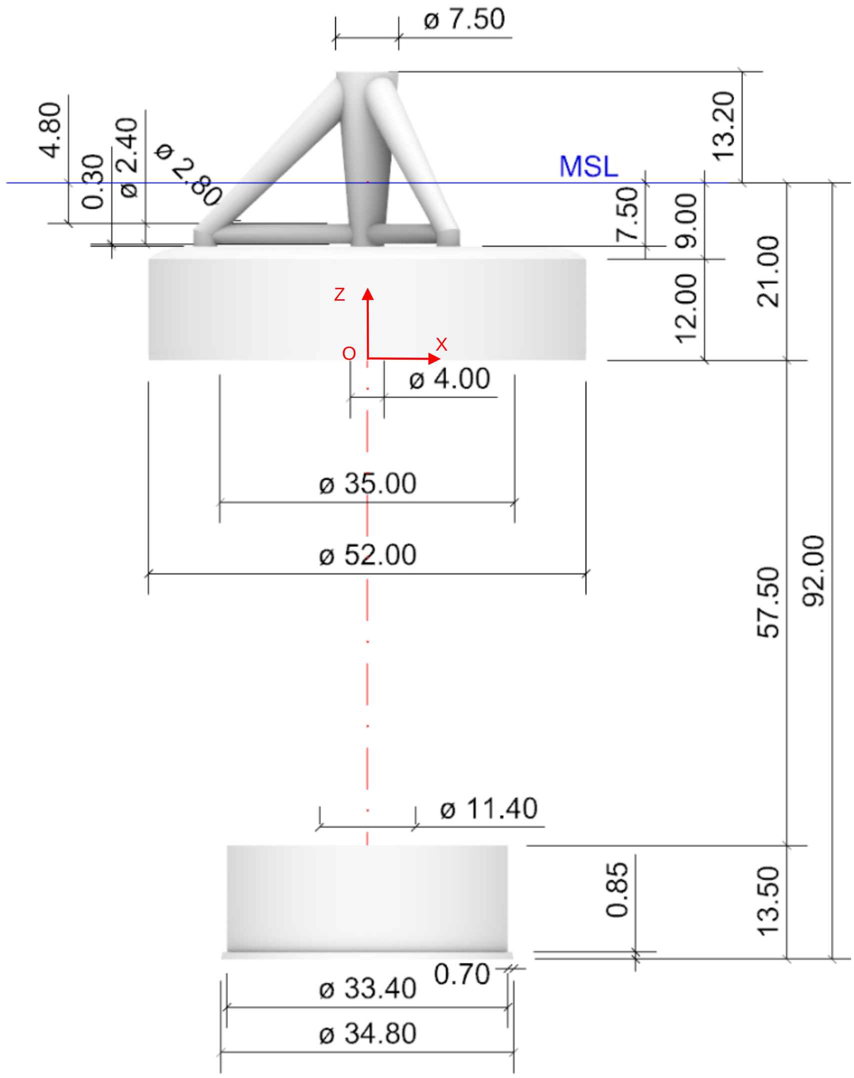


FIGURE 16. WHEEL PRINCIPAL DIMENSIONS FOR 15MW TURBINE (IN METERS)

2.4 WHEEL sizing information

In these chapter all the relevant information for shaping the WHEEL prototype for a 15MW turbine is described. It includes information about the upper tank, the lower tank and the steel tripod transition piece, as well as the global characteristics of the floater as whole. Information about the mooring and tendon systems is also included.

2.4.1 Tower

The following table presents the data used to define the steel tower.

Parameter	Value	Unit
Tower length	121.15	m
Height of tower base above MSL	13.00	m
Overall tower mass	920442	kg
Diameter of the tower base	7.5	m
Diameter of the tower top	5.6	m

TABLE 7. STEEL TOWER GENERAL DATA

2.4.2 Wind turbine

The turbine chosen is developed by NREL for the IEA. It has 15 MW of nominal power output and a rotor diameter of 240 m. The following tables give an overview of the WTG characteristics, while NREL/TP-5000-75698 document provides further information (* The RNA mass value differs from NREL document because an updated value provided NREL has been used).

Parameter	Value	Unit
Output power	15	MW
Rotor diameter	242	m
Hub diameter	7.94	m
Hub height above MSL	139.5	m
Nacelle mass including rotor *	950	t
Cut-in wind speed	3.0	m/s
Rated wind speed	10.59	m/s
Cut-out wind speed	25.0	m/s
Minimum rotor speed	5.0	rpm
Maximum rotor speed	7.56	rpm

TABLE 8. WIND TURBINE

Parameter	Value	Unit
Height of Nacelle COG above MSL	134.4	m
Height of Hub COG above MSL	139.9	m
Height of Blades COG above MSL	139.9	m
Weight horizontal eccentricity	6.5	m

TABLE 9. COG POSITION OF THE WTG AND ITS MAIN COMPONENTS.

2.4.3 Platform

The following table present general data of the whole structure including WTG and tower. Keel (K) is considered at the UT keel and the GM was calculated considering the free surfaces effect. All data is given for the barge transport condition (LC03).

Parameter	Mass (tn)	COGz (m)
Tripod	410	23.77
UT	5122	5.96
Water Ballast in UT	915	1.24
LT	18621	-64.79

TABLE 10. PLATFORM MASS PROPERTIES

Parameter	Value	Unit
Total Draft	92.0	m
UT Draft	21	m
KG (with mooring)	-34.64	m
KB	-21.8	m
BM	0.1	m
GM corrected	12.81	m
Floating plane area	60.9	m2

TABLE 11. PLATFORM GENERAL DATA.

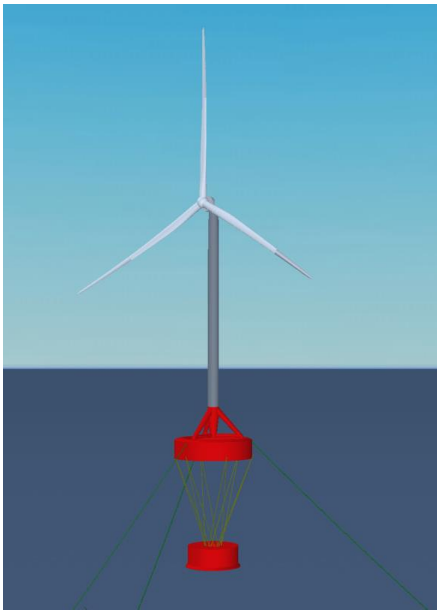


FIGURE 17. VIEW OF WHEEL'S MODEL FOR ADVANCED HYDRODYNAMIC SIMULATIONS

Other information provided was:

- The mass properties and inertias of each part of the structure.
- The mass, COG position, inertia and hydrodynamics characteristics of the upper structure, which includes upper tank, tripod, tower and WTG.
- The mass, COG position, inertia and hydrodynamics characteristics of the lower structure, which includes lower tank.
- The natural periods of the floater.

2.4.4 Mooring system

The mooring system is defined by the following criteria:

70%-80% utilization ratio of the ULS and ALS strength design criteria described in chapter 8.2 of "DNVGL-ST-0119" document, under metocean conditions for a parked turbine in 50-years extreme wind and waves (DLC 6.1).

Maximum floating structure excursion 20% of water depth obtained from previous experiences (COREWIND), under metocean conditions for a parked turbine in 50-years extreme wind and waves (DLC 6.1), see Table 12

Waves	Wind	Current
Irregular Jonswap Spectrum Hs=9.9m, Tp=17s	Turbulent EWM50 50 m/s (at hub height)	0.77 m/s (10 years max, not 50y)

TABLE 12. MOORING SYSTEM ENVIRONMENTAL CONDITIONS.

Following these criteria, the mooring system parameters are shown below.

2.4.5 Tendons system

The following table shows the position of the connections of the tendons in both upper and lower tank, along with the pretension of the lines.

It is noted that while this specific design considered the suspension tendons connected to the inner wall of the lower tank, tendons may also be connected to the outer wall of the Lower Tank delivering equivalent performance. The chosen material for the tendon system is Dyneema,

Tendons #	Position						
	UT			LT			Pre-tension
	x [m]	y [m]	z [m]	x [m]	y [m]	z [m]	[kN]
TA2	4.5	2.6	-59.95	0	27.1	2.55	6579
TA6	-4.5	2.6	-59.95	0	27.1	2.55	6817
TB1	0	5.2	-59.95	23.47	13.55	2.55	7321
TB3	4.5	-2.6	-59.95	23.47	13.55	2.55	7234
TC2	4.5	2.6	-59.95	23.47	-13.55	2.55	7234
TC4	0	-5.2	-59.95	23.47	-13.55	2.55	7321
TD3	4.5	-2.6	-59.95	0	-27.1	2.55	6579
TD5	-4.5	-2.6	-59.95	0	-27.1	2.55	6817
TE4	0	-5.2	-59.95	-23.47	-13.55	2.55	6109
TE6	-4.5	2.6	-59.95	-23.47	-13.55	2.55	6260
TF5	-4.5	-2.6	-59.95	-23.47	13.55	2.55	6260
TF1	0	5.2	-59.95	-23.47	13.55	2.55	6109

TABLE 13. TENDONS SYSTEM: POSITION AT UT & LT

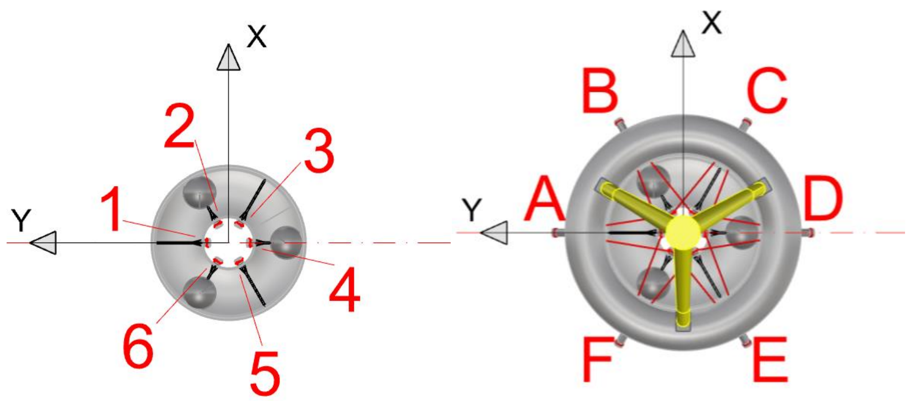


FIGURE 18. GENERAL ARRANGEMENT OF THE WHEEL OFFSHORE PLATFORM TENDONS.

2.4.6 Tripod geometry and weight

The following table shows the geometry and weight of the tripod components:

Tripod geometry & weight	Diameter max. (m)	Diameter min. (m)	Length (m)	Thickness (avg.)(mm)	Extra weight (%)	Weight (tn)	Zg (m)
Central Column	7.5	4.0	20.5	45	30	169	26.8
Inclined braces	4.3	2.8	24.3	25	12	177	23.6
Horizontal bottom braces	2.4	2.4	15.7	18	12	56	15.0
					TOTAL	402	23.7

TABLE 14. GEOMETRY AND DESIGN OF THE TRIPOD COMPONENT

3. TASK 2 - COUPLED MODEL DEVELOPMENT

This task aimed to describe the results of fully coupled simulations of the WHEEL floating platform supporting the IEA-15MW turbine, aimed to demonstrate that the WTG meets the desired load and motion constraints and to verify that loading on the main components of the floating platform remains with the admissible design loads.

A model of the complete floating wind system was built in NREL's Wind Energy with Integrated Servo-control (WEIS) using the proven and renowned OpenFast simulation software package. This enables coupled simulations of the wind and waves while considering the control interactions and structural dynamics. A selection of the most representative and critical load cases was performed for a variety of operational and environmental conditions, considering the reference international standard IEC TS 61400-3-2:2019). With WEIS, a baseline controller was also tuned using the ROSCO toolbox at NREL, with care to avoid any controller-induced instabilities.

In addition to the base complete coupled simulations performed by NREL, Esteyco also performed in-house coupled simulations with OpenFast and Orcaflex software packages that have served for contrast and effective collaboration between NREL and Esteyco in the setting up of the models and processing and interpretation of the results. Contrast of different simulation models have shown good results.

3.1 Coupled analysis

Design cases analyzed include DLC1.1 (for fatigue analysis), DLC1.3 (extreme turbulent wind), DLC1.6 (operation with severe sea states – Hs=6m), DLC 5.1 (emergency stop) and DLC 6.1 (extreme 50-y storm).

In the present section some of the key results and design considerations are summarized.

3.1.1 General approach and NREL-Esteyco collaboration

NREL and Esteyco have collaborated in the development, calibration and interpretation of coupled simulations. The final complete results of the coupled analysis are those resulting from NREL's detailed simulations with do incorporate the specific tuning of the WTG controller.

Along the process, Esteyco also performed coupled simulations with varying levels of simplification in both Orcaflex and OpenFast, as a complement and contrast of NREL's detailed coupled simulations. In this way, NREL and Esteyco collaborated in confirming together the general performance and results of the models before thousands and different simulations were run and final results were obtained. Results of different models and software tools proved to be well aligned contributing to the reliability of the results obtained.

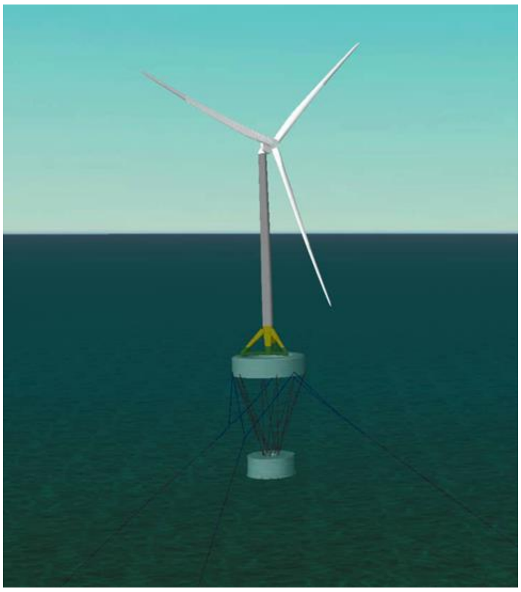


FIGURE 19. GENERAL VIEW OF CONTRAST COUPLED SIMULATIONS IN ORCAFLEX.

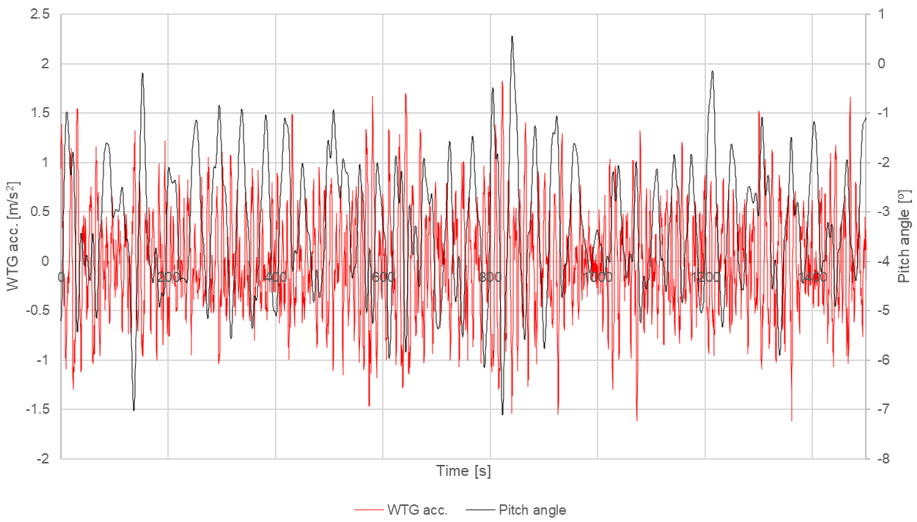


FIGURE 20. RESULTS OBTAINED FROM ORCAFLEX CONTRAST COUPLED MODELS: TIME SERIES OF PLATFORM TILT AND RNA ACCELERATION FOR DLC 1.6 FOR TURBINE OPERATION AT RATED WIND SPEED (MAX THRUST) AND SEVERE SEA STATE (HS=6M).

3.1.2 Reference design thresholds

The WHEEL platform has been designed to comfortably remain within reference design thresholds commonly considered for the design of floating wind turbines in the industry in terms of admissible motions (platform tilt and accelerations in the nacelle which provide a direct measure of the force levels generated in the wind turbine components). Specifically, the design thresholds provided in ref. 12 (DNVGL-RP-0286) have been considered as given in Table 15 next:

Control Parameter	Design Threshold
max. tilt during operational load cases (e.g. DLC 1.2, 1.6)	mean value in the time series: 5 degrees max. value in the time series: 10 degrees
max. tilt during non-operational load cases (e.g. DLC 6.1, 6.2)	15 degrees
max. acceleration at tower top during operational load cases (e.g. DLC 1.2, 1.6)	0.3 g (2.95 m/s2)
max. acceleration at tower top during non-operational load cases (e.g. DLC 6.1, 6.2)	0.6 g (5.9 m/s2)

TABLE 15. REFERENCE DESIGN THRESHOLDS AS PER DNVGL-RP-0286

In addition, NREL's analysis will monitor force levels in multiple key components of the wind turbine and floating platform to verify that they remain within reasonable and expectable load levels.

3.1.3 Main results

Thousands of coupled simulations have been carried out. The following table gathers the results of different simulations covering Design Load Cases DLC1.1 (for fatigue analysis), DLC1.3 (extreme turbulent wind), DLC1.6 (operation with severe sea states – Hs=6m), DLC 5.1 (emergency stop) and DLC 6.1 (extreme 50-y storm)

Control Parameter	Design Threshold (Dnvgl-Rp-0286)	Result
tilt during operational load cases (mean value)	5 degrees	3.5 deg (DLC1.6)
tilt during operational load cases (max value)	10 degrees	5.9 deg (DLC1.6)
max. tilt during non-operational load cases	15 degrees	8.2 deg (DLC5.1)
max. acceleration at tower top during operational load cases	0.3 g (2.95 m/s2)	2.3 m/s2 (DLC1.6)
max. acceleration at tower top during non-operational load	0.6 g (5.9 m/s2)	3.3 m/s2 (DLC6.1)

TABLE 16. SIMULATIONS RESULTS: MAIN RESULTS AND COMPARISON WITH DESIGN THRESHOLDS

As it can be observed design thresholds have been met comfortably. Margin for avoidance of snap loads in suspension tendons is also large. Results therefore suggest that there may be some room for optimization in the sizing (and cost) of the WHEEL floater.

3.1.4 Design considerations

Task 1 provided a detailed description of the WHEEL platform design and the main drivers and characteristics linked with both the operational conditions and the intermediate construction and installation stages.

The present section reviews some of the key design considerations as linked to the operational performance of the floater analyzed in the advanced couples simulations performed.

Hydrostatic stiffness

Hydrostatic stiffness governs the inclination that the floater undergoes under a given permanent acting moment. It is directly dependent on the factoring of the floaters displacement (27 ktn) and its metacentric height (12.5m).

This is the characteristic governing the average inclination of the turbine in operation. It must be noted that in addition to an adequate hydrostatic stiffness, average tilt may also be regulating by use of an Active Ballast System (ABS), which can be used to move ballast water in the upper tank to compensate for average acting moments, thus reducing or even nulling the average tilt in the turbine.

Conservatively, the present WHEEL platform has been sized to deliver high hydrostatic stiffness and thus avoid the necessity of an active ballast system, achieving limited mean tilt angles (3.5deg at rated wind speed) with no need to control moving water ballast. This way, there is no need for a permanent control system and a ballast system to be relied on and must always work during the structure lifecycle, thus reducing maintenance costs. Nonetheless, WHEEL is indeed directly compatible with an ABS which could be used to optimize floater sizing.

RAOs and natural periods

A high hydrostatic stiffness of a floating body, as described in the previous section, will tend to lower its pitch and roll natural periods. If these periods become too low and close to the acting periods of the largest waves (in the 20s range), dynamic amplifications will result and the seakeeping performance of the system in high seas shall be severely affected.

A key characteristic of the WHEEL platform is the fact that it delivers extremely high mass inertia, thanks to be big masses siting at the very top and very bottom of the system, separated by a distance of more than 250m. This huge inertia intuitively results in low tilting speeds and naturally increases the systems natural periods in pitch/roll, conveniently keeping them way above the periods of the acting waves.

In addition, the reduced water plane area of WHEEL results in very high heave periods. Overall, this results in low excitation from wave forces and slow motions, as indicated in the Response Amplitude Operators (RAOs) for pitch/roll and heave shown in the next figure:

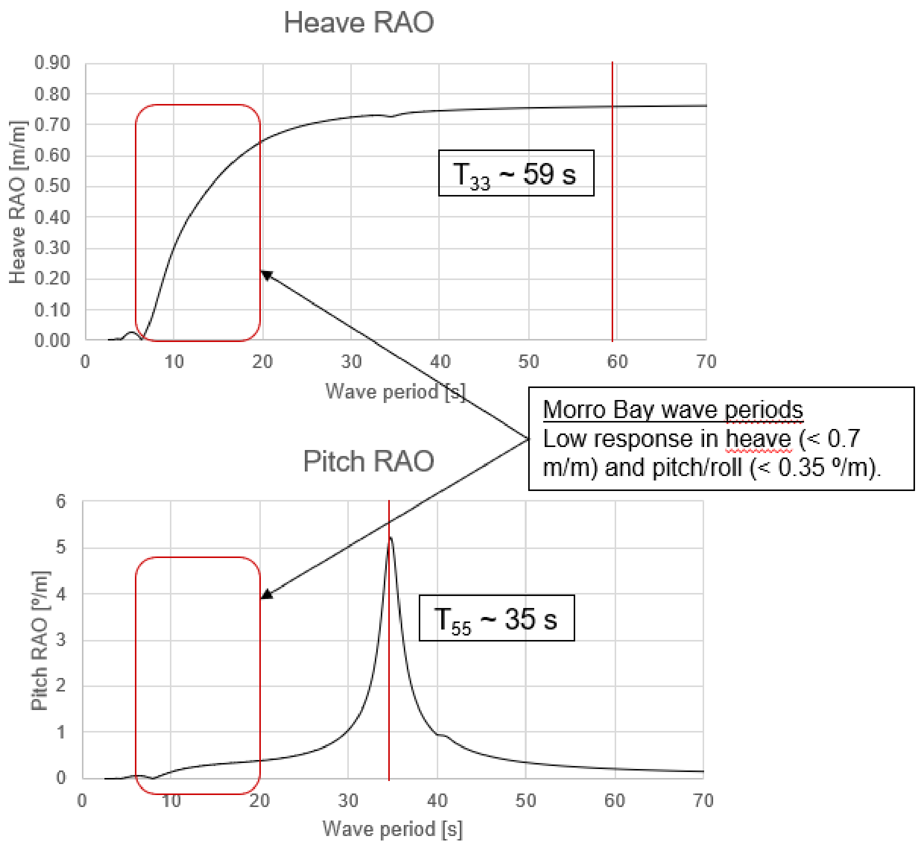


FIGURE 21. RAOS OF THE WHEEL PLATFORM

Yaw stiffness

Yaw stiffness is essentially provided by the Mooring or Station Keeping System (SKS). Such yaw stiffness is mainly dependent on the length of the crowfoots provided in each of the three mooring lines (see Figure 22). The mooring system is conceived so that the yaw natural period is conveniently apart from the roll/pitch natural periods of the floater.

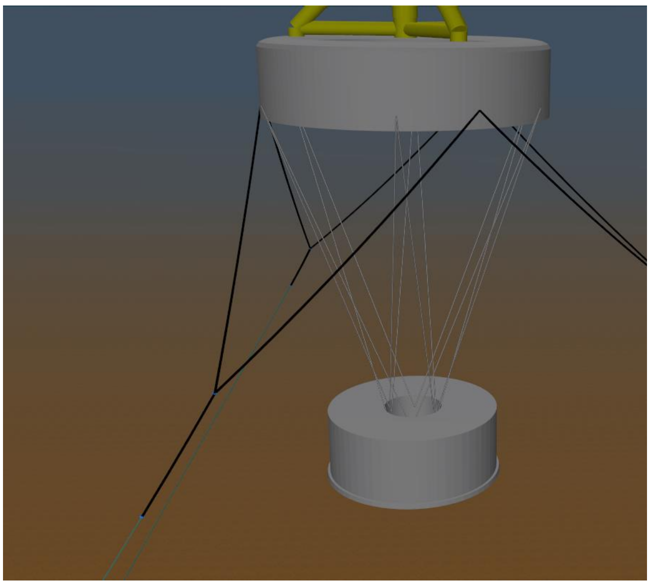


FIGURE 22. GENERAL ARRANGEMENT OF THE MOORING SYSTEM.

Avoidance of snap loading in suspension tendons

The WHEEL platform is designed to carefully ensure that no snap loading may happen in the suspension tendons.

In this regard, a clear distinction must be made between presence of tendon slacking (zero tension force in a tendon) and presence of snap loads. Absence of tendon slacking indeed ensures absence of snap loads. But presence of tendon slacking in a highly redundant 12 tendon system does not necessarily imply risk of snap loads as long as a sufficient number of tendons remain in tension.

Snap loads can only happen if tendon slacking leads to the loss of the solidary behavior between upper and lower tanks. If such solidary behavior is lost and relevant relative speed between both bodies develops, the recovery of tension load in tendons that have temporarily gone slack may involve high accelerations to restore equal speed of both bodies, and such high accelerations lead to high forces. That is the definition of a snap load in a cable or line. The design of the platform ensures that this will never happen, neither in operational nor in extreme conditions.

However, it is important to clarify that slacking in a limited number of tendons does not imply losing the solidary behavior between upper and lower tanks. Not at all. This is because the tendon system used for the WHEEL platform is highly redundant and the solidary behavior is ensured even with some slack tendons. It can be shown by simple analysis that solidary behavior will not be lost until more than 4 tendons have gone slack. If solidary behavior is maintained, snap loads on the tendons cannot happen.

Given the symmetry of the system, forces in the tendons tend to develop in pairs (pairs of tendons will show similar force levels) so in practice solidary behavior will not be lost until 3 tendon pairs (6 tendons) have gone slack. This is graphically represented in the following figures:

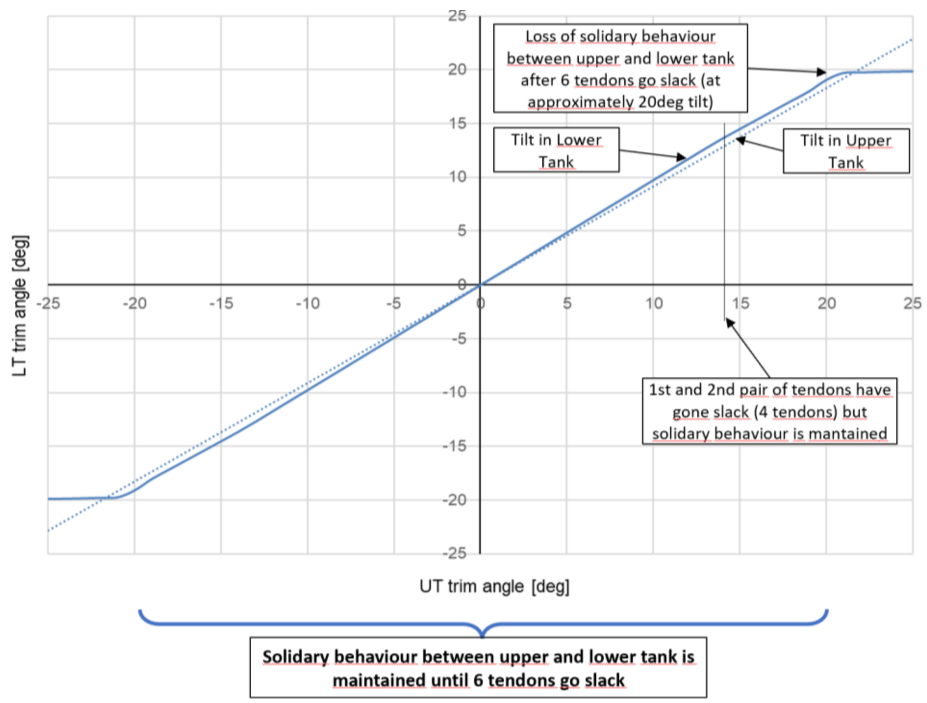


FIGURE 23. QUASISTATIC PLATFORM TILT OF UPPER AND LOWER TANKS.

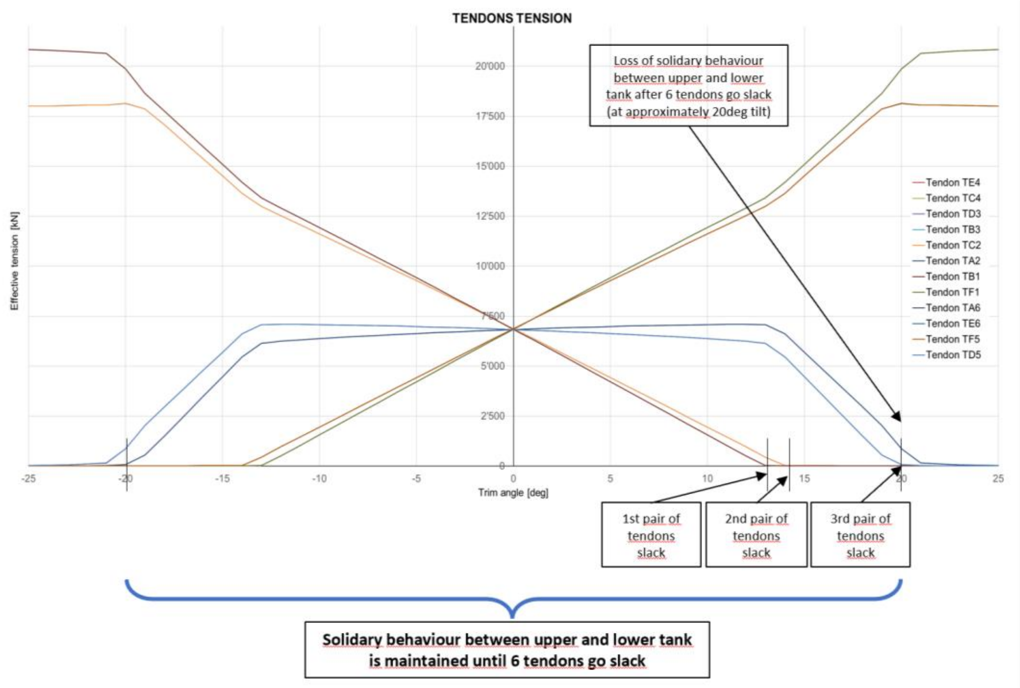


FIGURE 24. VARIATION OF FORCE IN SUSPENSION TENDONS AS A FUNCTION OF QUASISTATIC PLATFORM TILT.

While it is important to clarify that slack in no more than 4 tendons cannot lead to snap loads, it is also important to emphasize that tendon slacking is by no means a frequent condition in the WHEEL platform, but rather a very exceptional circumstance that can only happen in very rare and singular conditions, if any. In fact, in order to carefully assess the effect of tendon slacking, advanced hydrodynamic simulations have been performed in which the WHEEL design and/or the loading conditions had to be modified unrealistically to artificially force and increase the appearance of tendon slacking so that its effects may be better analyzed (with the real platform design and loading conditions slacking did not occur). Through this analysis, which does incorporate the non-linear behavior of tension-only tendons, it has been indeed verified that even with 4 slack tendons solidary behavior is maintained and no snap loads can be generated.

3.2 Task 2 conclusions

A detailed fully coupled analysis of the WHEEL floater platform supporting the IEA-15MW turbine has been completed with positive results. Complete simulations with specific tuning of the control system have been developed and run by NREL with OpenFast software. Results of contrast models developed by Esteyco in Orcaflex and OpenFast have been well aligned.

A good seakeeping performance has been verified, with values for the key control parameters used to monitor motions and forces in the wind turbine comfortably below the pre-established reference design thresholds. The large safety margin with respect to such design thresholds suggests that there may be room for optimization in the sizing of the platform. Key design considerations and lessons learned have been obtained and outlined to be duly considered in further detailed design stages of the WHEEL platform.

To ensure that the scaled-up WHEEL design for the IEA-15 MW turbine meets the desired load and motion constraints, a loads analysis of the system was performed. A model of the complete floating wind system has been built in NREL's Wind Energy with Integrated Servo-control (WEIS), to enable coupled simulations of the wind and waves while considering the control interactions and structural dynamics. A select set of load cases were performed for a variety of operational and environmental conditions, considering the most relevant standards (main reference can be sought in the IEC TS 61400-3-2:2019). With WEIS, a baseline controller was also tuned using the ROSCO toolbox at NREL, with care to avoid any controller-induced instabilities.

4. TASK 3 - DESIGN UPDATE TOWARDS INDUSTRIAL MANUFACTURING WITH LOCAL SUPPLY CHAIN

This task delivered a suitable strategy for industrial deployment of the WHEEL technology in the U.S. West Coast.

The assessment performed pursued verifying whether the WHEEL platform can be:

a) Industrially manufactured, in existing East coast port facilities and with conventional onshore local means and workforce. This means, among others, that: yard occupation is reasonable, required draft is compatible with US ports, weight and size of the pieces allows handling with local means, and material used are standard.
b) Installed offshore with US flag marine capabilities, and no 'ad-hoc' means. This will rely on a simulation of the assembled turbine with the WHEEL platform in the tow-out configuration.

Indeed, one of the key challenges for large scale development of floating wind the U.S. West Coast is linked to the availability and selection of suitable harbor infrastructure for the multiple tasks that such a project would involve. The present exercise has been based on the use only of existing harbor infrastructure for the local manufacturing of floaters and WTG integration works, which is something that the specific attributes of the WHEEL platform make possible but may not be feasible in the west coast for many floater designs.

4.1 Industrial implementation strategy

4.1.1 US-built floaters based only on existing harbor infrastructure.

The WHEEL technology is well suited for execution strategies with a high share of local content and reduced requirements on harbor infrastructure.

Thanks to its compact dimension and reduced draft, WHEEL can be directly manufactured on floating barges, which qualitatively reduces the quay area needed. This emulates the large successful experience with serial manufacturing of concrete caissons.

High fabrication rates can be achieved for the WHEEL technology despite of the small harbor area used.

The upper tank and the lower tank are built together at the same level as if they were a single caisson. Construction rate for the concrete works has been established together with companies specialized in the fabrication of concrete caissons. Output rate, when using two fabrication barges plus one quay position for tripod assembly and finishing purposes, is 1 unit/week.

The tendon system is completely pre-assembled during the concrete fabrication phase.

Assembly of the steel tripod takes place in an additional working station after float-off of the concrete caissons. The tripod comprises 7 modules: central column, diagonal braces (which include the outer nodes) and horizontal braces. The tripod is preassembled on the yard and installed onto the floater in one single lift.

Tripod can be assembled with a specific crawler crane. If the floater is fabricated in the same port used for WTG integration, the ringer crane used for WTG assembly could also be used for tripod assembly (as in the example figure shown). Use of the WTG ringer crane for tripod assembly is an opportunity, not a need.

Completed floaters with the tripod transition pieces shall be moved to a wet storage area.

During the offshore installation season, floaters are moved from the wet storage to the quay for turbine integration works. Once the tower and the WTG have been installed and pre-commissioned, the floater is towed-out to a nearshore location for deployment and ballasting of the lower tank.

After LT deployment, the ocean towing to the wind farm site is carried out by medium-sized tugboats. Towing operations can be set up as weather unrestricted once the LT is deployed.

Pre-installation of anchors, mooring pre-lay, mooring hook-up and IAC installation follow already established methods in the offshore industry, not essentially different to other floater designs.

FIGURE 25. CONSTRUCTION BASED ON FLOATING BARGES.

4.1.2 Potential ports and logistics

Five harbors have been identified and grouped as per different activities of interest for the project. From North to South the harbors are:

- Port of Humboldt Bay: In Samoa. Not ready at present but plans have been announced to upgrade it into a future offshore wind hub. Closer to potential projects in Oregon or northern California, but very far from West Coast OWF (around 350 NM). In the present exercise it has been considered as potential WTG marshalling harbor, but not as a harbor for floater construction or WTG integration with the floater.
- Port of Richmond: Industrial harbor around 160 NM off WCOW. Bridge air gap restrictions discards it as potential harbor for WTG integration. It could be suitable for manufacturing of WHEEL floaters, but these would then need to be moved to another location for WTG installation increasing the number of tows and marine operation, so this option has not been preferred for the present exercise. Useful as base harbor for large vessels operating only in the wind farm (Anchor handling vessels, offshore supply vessels, etc) and as marshalling harbor for mooring equipment.
- Morro Bay harbor: The closest harbor to the wind energy area but with limited facilities and space. Potential use as base harbor for small vessels operating only in the wind farm (guard vessels, CTVs).
- Los Angeles harbor (Long Beach): Very large and busy harbor 230 NM off the wind farm. Given its activity and occupation it has not been proposed as an offshore wind hub, since it offers no available area for a large WTG marshalling harbor or for the kind of shipyard facilities that would be required for manufacturing large semisub floaters. However, given the distinctive manufacturing strategy for WHEEL and the low yard area it requires, Long Beach has been considered a feasible location for WHEEL floater construction and wet storage, as well as for WTG integration. This is the assumption made for the present exercise. Selected yard location is specifically berth 46.
- (Hueneme harbor -50 NM north of LA- could be an alternative for the activities planned at Long Beach, but quay and area availability are lower unless some existing activity or facility was displaced. Room for wet storage is also more restrictive)
- Ensenada harbor: In Mexico. Selected as potential supplier of ballast sand required for the LT ballasting. Around 140 NM off Los Angeles harbor where sand ballasting would take place. Suitable for agile feeding of bulk material in towed barges, fall pipe vessels, hopper dredgers or similar. Being outside the US it could be compatible the US of foreign vessels (not restricted by the Jones Act)

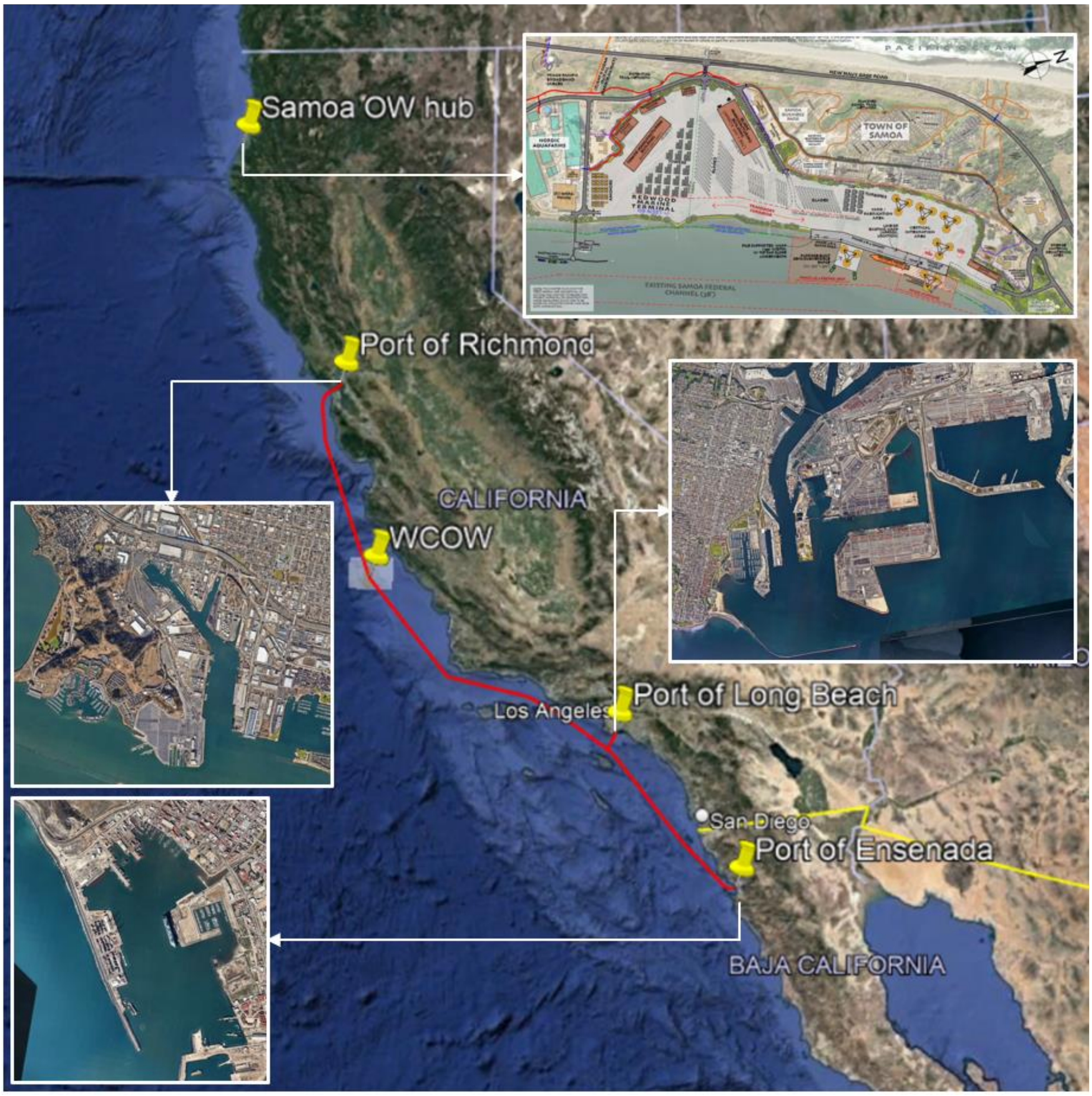


FIGURE 26. CONSIDERED HARBORS FOR THE CONSTRUCTION OF THE WHEEL SYSTEM

4.1.3 General coreography proposed

As previously described, the execution strategy considered aims to deliver US-built floaters which can be manufactured and assembled on existing harbor infrastructure, including WTG integration.

The key aspects of the proposed execution strategy are summarized below:

- Fabrication of upper tank and lower tank takes place at Berth 46 inside Port of Long Beach. This process is carried out onboard two floating barges. Materials and workforce will be sourced locally.
- Assembly of the tripod also takes place at Berth 46 in Port of Long Beach. The tripod central column is assumed to be shipped from a specialized yard in Mexico with sea

access. The tripod braces (x6) are assumed to be sourced from an onshore wind tower factory in Mexico (they can be transported to shipping port by road).

- The installation of tower and WTG is assumed to take place also at Berth 46 in Port of Long Beach. It is assumed that WTG will be shipped to Long Beach from an unspecified WTG marshalling harbor. The yard currently considered may provide area to stock the components of 6-8 WTG units which has been considered enough buffer so that feeding of WTG units during the installation season will not affect the floater installation schedule.
- The lower tank is deployed and filled with solid ballast at a dedicated location between Long Beach and Santa Catalina Island. It is assumed that the solid ballast is brought from Port of Ensenada, Mexico.
- Fully-assembled units are towed to WCOW (210 NM). This ocean two is not weather restricted
- Mooring hook-up operation takes place once a WHEEL unit arrives at the OWF and proper environmental conditions are met. This has been identified as a key driver of the offshore installation schedule and thus of the marine spread sizing.
- Port of Richmond is selected as base port for mooring and subsea operations (160 NM from the OWF).
- Construction and installation means assumed in the present exercise have been sized so that all 50 units in the wind farm can be installed along a single 9-month campaign.

Concrete fabrication starts Q3 2031. T&I operations take place in a 9-month campaign during 2032. Installation of suction anchors is assumed to take place during summer 2031. Mooring pre-lay is assumed to take place in summer 2031 and summer 2032. IAC installation is assumed to take place during 2032, simultaneously with the T&I.

The proposed execution strategy could be adapted to other fabrication location (i.e. Humboldt Bay). However, Port of Long Beach has been selected as it is closer to the OWF and provides a feasible example where both local content and reduced area requirements are highlighted.

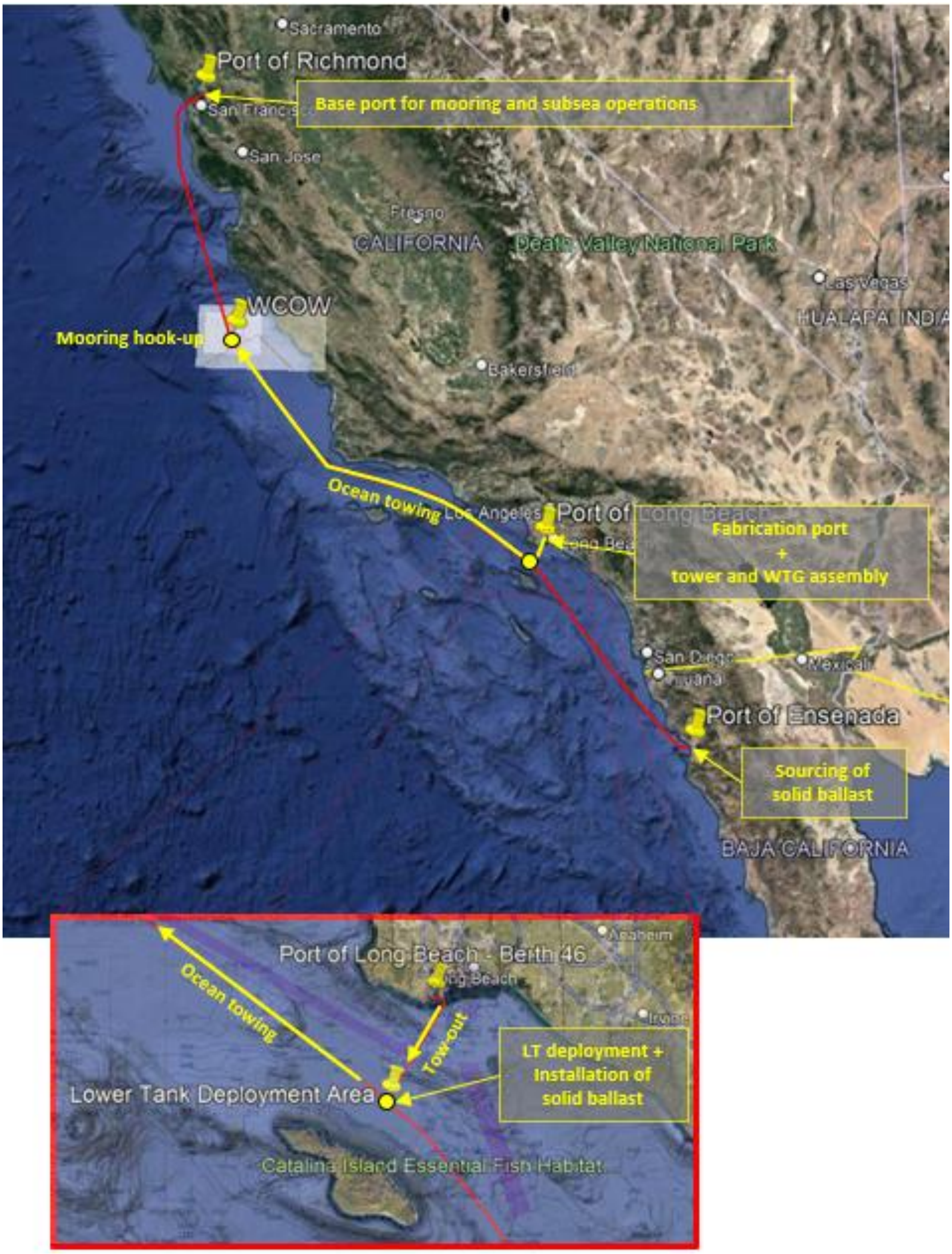


FIGURE 27. GENERAL COREOGRAPHY

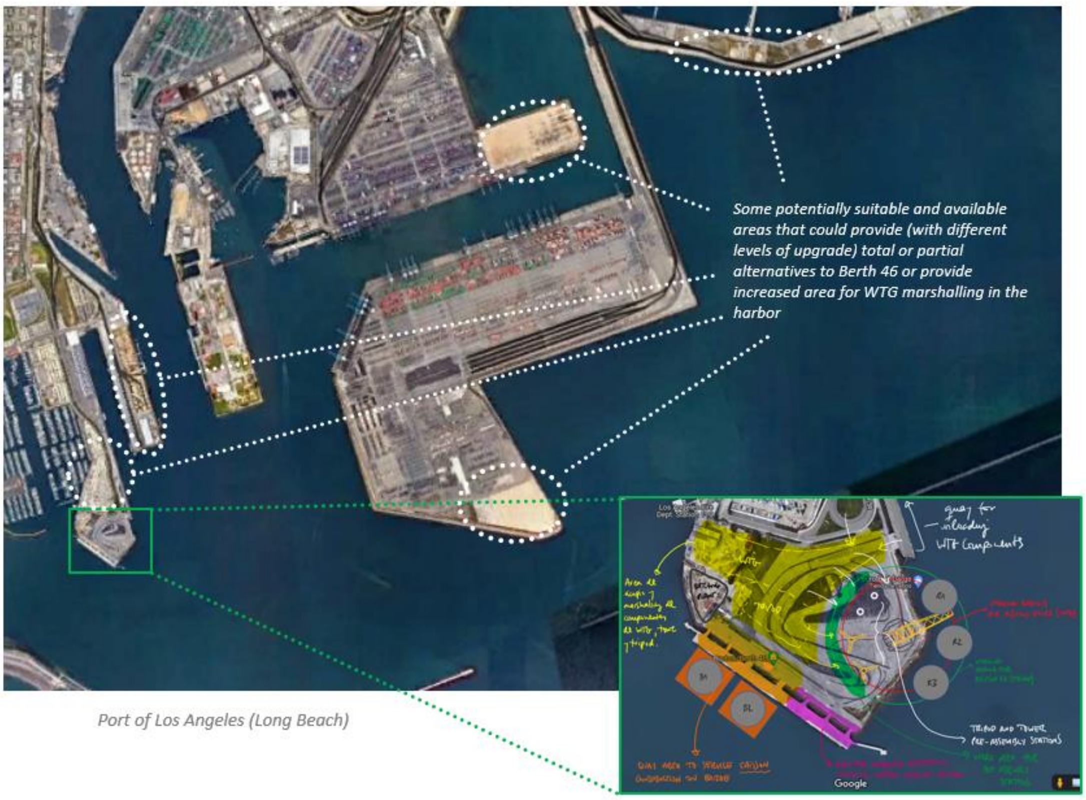
4.1.4 Port selection

The WHEEL Technology benefits from its reduced dimensions and its shallow draft, enabling its construction onto commercial barges. Therefore, the required yard space for fabricating the floaters, is substantially reduced compared to other solutions. These characteristics are of key importance as they enlarge the possibilities when searching for local yards for constructing the floaters.

In is estimated that 7-8 Ha of yard area will suffice for floater construction and WTG integration activities, including a small WTG marshalling area for 6-8 WTG units that may provide sufficient buffer for the WTG feeding process to the yard. It is noted that floater construction and WTG integration activities do not need to be located in the same yard area, so the above-mentioned total area may be divided in two separate yards if convenient (preferably within the same harbor). The construction of floaters on board floating barges will require a minimum draft of 7-8m which is comfortably met in LA.

In addition, the harbor must provide sufficient sheltered area for wet storage of floater's winter production (during the installation season floaters will be installed faster than they are manufactured, so a sufficient number of units must be produced in advance and stored before the installation season begins)

Several potentially suitable areas have been identified which may be currently unused or available. For this RFI, Berth 46 at Port of Los Angeles has been preliminarily selected since it provides sufficient area both for construction of the concrete floaters and for WTG integration. This is a seldomly used area which is not close to the main ship traffic routes in the harbor. It is emphasized that no check on the availability of this area or any other has been performed for the present feasibility exercise, which is only intended to illustrate the general strategy that may be pursued, and the main harbor requirements linked to the WHEEL technology.



Port of Los Angeles (Long Beach)

First sketch of the possible lay-out for floater construction and WTG assembly

FIGURE 28. POTENTIAL LOCATIONS IN THE PORT OF LOS ANGELES (LONG BEACH)

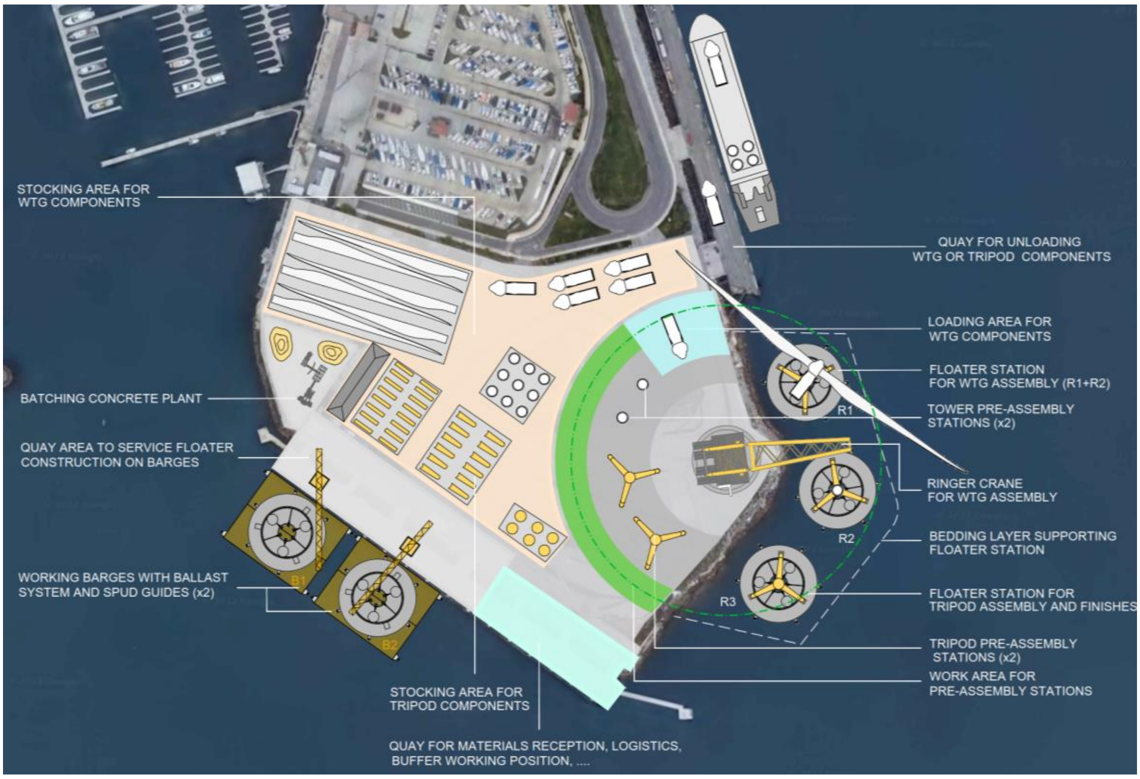


FIGURE 29. EXAMPLE OF POTENTIAL YARD LAY-OUT (PORT OF LA – BERTH 46)

Key features of a potential yard in the Port of L.A. (Berth 46)

- Distance to site: 16NM+210NM=226NM
- Total Yard Area 7.5 Ha
- Yard area for floater construction and tripod assembly: 4 Ha
- Quay length for construction: 150 m
- Concrete construction stations: 2
- Tripod pre-assembly stations: 2
- Tripod assembly & Finishes station: 1
- Quay length for WTG supply vessels: 200m
- WTG marshalling area: 3.5 Ha
- WTG integration stations: 2
- WTG integration stations are assumed to have a gravel bed where the floater will be ballasted and sit (upgrade required). This is needed in Berth 46 given the absence of quay on the east side of the yard, but it is not strictly required if a quay is available (the use of a gravel bed does ease and speed up WTG integration works since it removes all motions from the floater)

4.2 Works organisation

4.2.1 Fabrication of concrete floaters

The construction of the concrete floaters onto barges follows the usual fabrication methodology when constructing port caissons.

Both the upper and the lower tank are constructed simultaneously onto the barge.

Depending on the required production rhythm and available quay space, the number of barges is selected. For an output rhythm of aprox 3.5 floaters/month (40 floaters/year aprox.), 2 barges are foreseen.

The time span for constructing lower slab and walls, is two weeks. At this moment, the floater is put afloat and transferred to the finalization position where the tripod will be assembled and other equipment and finishing tasks will be performed.

The unit cycle is therefore estimated in 3 weeks/floater (multiple work shifts considered).

FIGURE 30. CONCRETE CAISSON CONSTRUCTION

FIGURE 31. CONCRETE CAISSON CONSTRUCTION (WITH SEMISUB BARGE).

4.2.2 Tripod transition piece. Marshalling and pre-assembly

The Tripod transition piece has been conceived as a modular element suited for industrialized manufacturing and assembly strategies.

The Tripod will be shipped to the construction yard in modules whose size, handling and stocking are analogous to those of the steel wind tower sections and can be based on essentially the same means and processes.

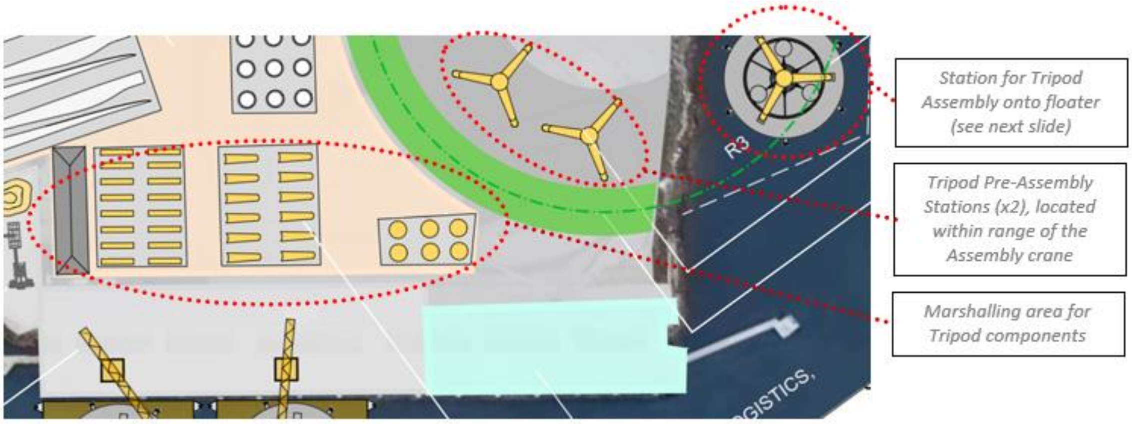


FIGURE 32. TRIPOD MARSHALLING STRATEGY AND PRE-ASSEMBLY STATIONS

As shown in the following figure, specifically, each tripod is formed by 7 modules: 3 horizontal tubes (piece C), 3 inclined braces (piece B) and 1 central tube (piece A)

Six of the 7 modules (pieces B and C) are sized so that they can be transported by road (max. dimension below 4.3m), which largely widens the potential supply chain and in particular opens it to industrialized steel wind tower manufacturers whose cost per kg ratios are significantly lower than those of shipyards.

Tripods will be stocked in modules and pre-assembled in specifically conceived Tripod Pre-Assembly Stations. These pre-assembly stations are located within the range of the Tripod Assembly Crane, so once the Tripod is preassembled it can be directly lifted on top of the concrete tanks.

Tripod pre-assembly requires 9 connections:

- 3 Type-1 connections at height. These connections remain emerged at all times and are bolted with L-flanges just like the standard emerged connection between floater and steel tower. These connections are accessible through adequate working platforms within the steel tubes.
- 3x2 Type-2 connections at ground level. These connections will be underwater and shall be welded. Given their favorable ground level location and equal circular shape, they are perfectly suited for the use of welding robots (see figure) which will operate always in the same welding stations and deliver, with increased speed, low-cost high-quality repetitive welds (6x50=300 identical circular welds for WCOW). Automated painting process at fixed locations can similarly be applied.

To deliver the pursued Tripod pre-assembly ratio of 1 unit/week, a single Tripod pre-assembly station might suffice. Two have been considered in the present exercise for redundancy and buffer. They are equipped with all the required means (fixed template bases, robot welding stations, painting tents, positioning struts, etc.)

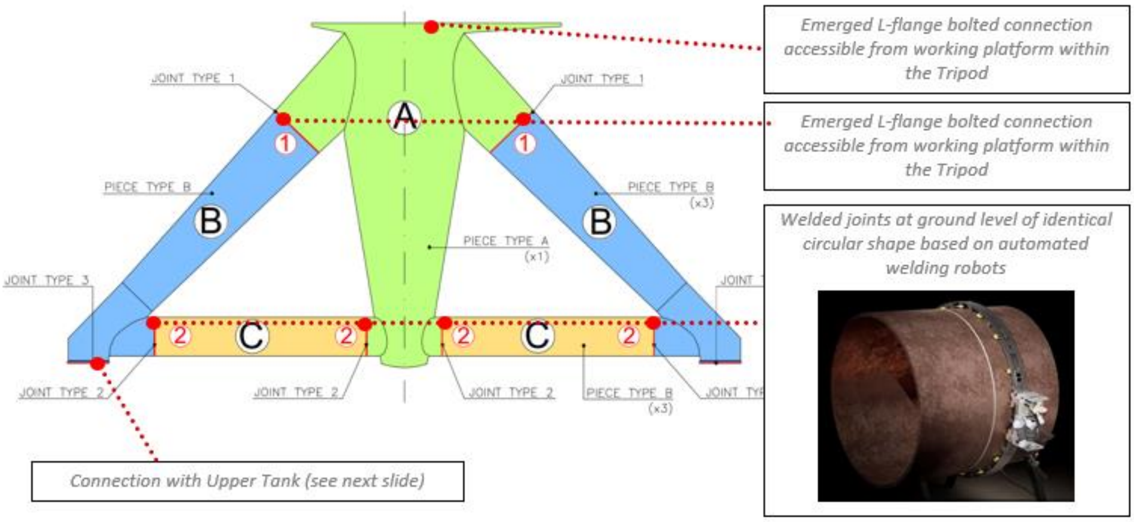


FIGURE 33. TRIPOD MODULAR CONFIGURATION AND PRE-ASSEMBLY STRATEGY

4.2.3 Wet storage

Once the substructure is completed, floater+tripod, it will be transferred to the wet storage.

The wet storage is a sheltered area where the floaters can stay afloat until the WTG assembly and subsequent T&I offshore take place. The area will be selected in accordance with the Port Authorities avoiding any interference with the usual traffic.

The floaters will stay moored on a prelaid mooring spread, as it is commonly done with concrete caissons (see pictures). As an alternative, the floaters can be moored to a quay/dolphin or positioned onto the sea/port bed.

The number of floaters at the wet storage will depend on the fabrication and installation schedules and the availability at sheltered waters.

FIGURE 34. POSSIBLE WET STORAGE LOCATIONS IN LONG BEACH HARBOR (

FIGURE 35. WET STORAGE OF CONCRETE CAISSONS

4.2.4 Tower and WTG assembly (integration)

The WTG assembly requires a ringer crane, SGC120 type, and two assembling stations (the same ringer crane covers both station with no reduction in the maximum lift capacity or height).

The floaters will be positioned onto gravel beds which will avoid any movement during the assembling operations making them faster, safer and less weather dependent (WTG integration afloat is also possible). Positioning of the tanks onto the gravel bed is done with its integrated ballast system and is no issue for the robust concrete tanks.

The steel tower, prior being lifted onto the tripod, will be preassembled on the yard. Hence allowing for only one lift to mount it onto the tripod. This is the typical practice with offshore wind turbines in order to reduce turbine integration time. However, in this case installation schedule is driven by marine operations and the ringer crane will operate only at a fraction of its maximum speed, so it may be preferred not to pre-assemble the steel towers.

The nacelle is the heaviest component and therefore determines the ringer crane selection. Normally, offshore WTGs, have the nacelle and the hub already connected prior the lift. Some OEMs, due to the substantial increase in size and weight of the forecasted WTGs, are assessing the possibility of splitting the nacelle and hub in several lifts which would reduce the requirements for the ringer crane.

Once the WTG is assembled, the completed unit is ready for T&I.

FIGURE 36. WTG INTEGRATION STATION: ASSEMBLY OF PREASSEMBLED STEEL TOWER (LEFT); COMPLETE FLOATER AND WTG ASSEMBLY READY FOR TOW-OUT (RIGHT).

4.3 Marine operations

The key features of the WHEEL technology regarding marine operations are summarized next:

- Fully assembled units are towed by means of conventional tugboats.
- During tow-out, before deploying the lower tank, buoyancy forces press vertically this tank against the upper tank, ensuring solidary behavior.
- LT deployment takes place at an intermediate point close to the coast. Deployment of lower tank is performed with ballast water with full control of lowering speed.
- During lower tank deployment, the upper tank remains on the surface with large freeboard and pre-assembled tendons self-deploy (no need for any external equipment).
- Robust fendering is provided between both tanks which guides the lowering of the LT in its initial stages (potentially reusable)
- The lower tank is filled with solid ballast once it is deployed reaching the floater's operational conditions. From that point towing operations may be considered weather unrestricted.

This section describes the marine operations required for the offshore installation of the WHEEL FWTGs:

1. Towing from Port of Long Beach to the lower tank deployment area (16 NM).
2. Lower tank deployment.
3. Installation of solid ballast.
4. Ocean towing to WCOW (210 NM).
5. Mooring hook-up.

Planning and engineering of marine operations follow the weather restricted / weather unrestricted philosophy from DNVGL-ST-N001.

FIGURE 37. WHEEL FLOATER TOW-OUT IN BARGE-TYPE CONFIGURATION

4.3.1 Summary of required marine spread

Required marine means have been detailed for towing operations, lower tank operations including solid ballast installation and mooring hook-up.

The marine spread described next has been sized to allow for the complete installation of the 50-unit wind farm in a single 9-month installation season, despite the limitations linked to availability of weather windows for mooring hook-up.

The proposed marine spread is found to be available in the USA market.

Note that other minor vessels such as guard vessels, CTVs or small workboats shall also be required. Marine spread for pre-installation and post-installation activities has not been detailed in this presentation (i.e., installation of suction anchors, mooring pre-lay and IAC installation).

Vessel group	Vessel type	Units required	USA flag required
Mooring hook-up	Anchor handling vessel	2	Yes
Towing and positioning	Team 1 - Tugboat 80 TBP	3	Yes
	Team 2 - Tugboat 80 TBP	3	Yes
LT sand ballasting	Sand carrying barge	2	No*
	Tugboat 60 TBP	4	No*
	Multicat with camera ROV	1	Yes

*Assuming that solid ballast is sourced in Mexico.




TABLE 17. MARINE SPREAD

4.3.2 Workability assessment

NOAA buoys database has been consulted and historical data from relevant buoys has been gathered and preliminary filtered to get useful data. This has allowed for preliminary time series useful for a first approach to workability/downtime assessment of the marine operations the WHEEL will undergo.

Buoy data generally shows good agreement with the preliminary metocean conditions used for this preliminary design. Some examples of the data gathered from the buoys are shown below:

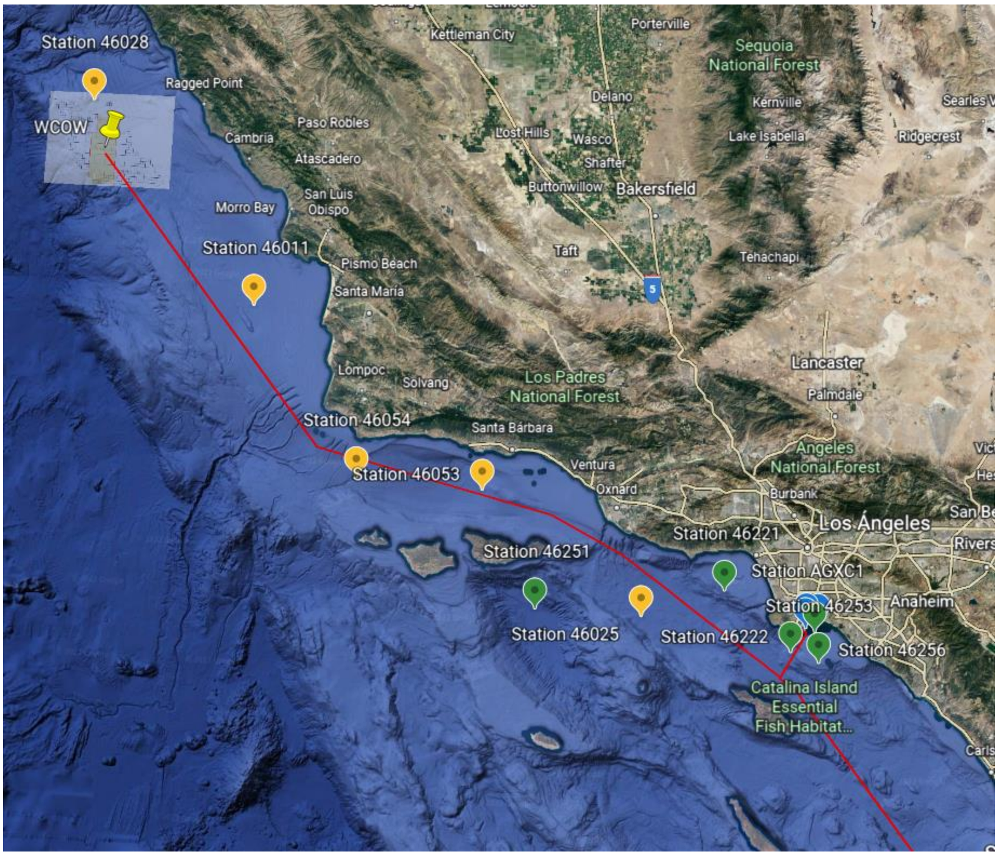


FIGURE 38. NOAA BUOYS CONSULTED FOR WORKABILITY ASSESSMENT

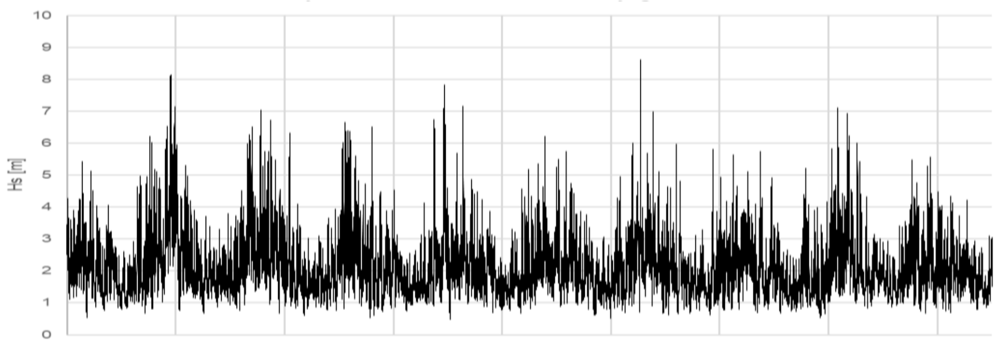


FIGURE 39. WAVE TIME HISTORY

Based on this historic information an analysis of the statistically available installation windows for the different operations is performed, based on which the required marine spread is sized in order to meet the pursued project installation schedule.

Two separated workability assessments have been carried out for the two following sets of marine operations:

- Set 1: Tow-out + LT deployment + LT sand ballasting
- Set 2: Mooring hook-up

For these analyses, wave data has been extracted from NOAA-NDBC website (buoys 46222 and 46011 respectively). Results from the workability assessment show that mooring hook-up operation could be highly restricted by the environmental conditions at the OWF, where average Hs above 2m. This restriction has therefore been the main driver in the sizing of the required marine spread. Note that this potential bottleneck would affect any type of floater design as the related Hs limiting criteria considered correspond to typical HSE limitations for deck activities onboard anchor handling vessels.

On the other hand, high workability rates have been obtained for the tow-out and the lower tank deployment operations, which are carried out in an area with more benign conditions, both in terms of average wave height and wave height variability.

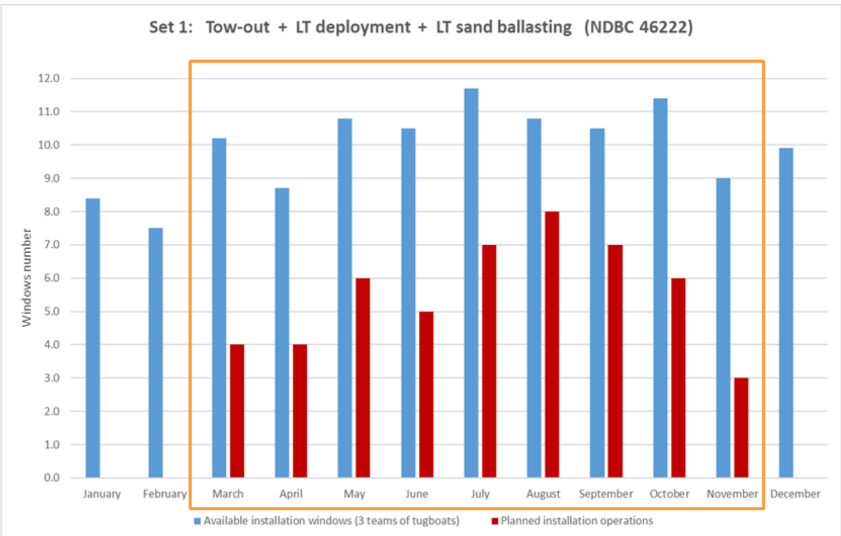


FIGURE 40. WORKABILITY ASSESMENT FOR THE TOW-OUT & LOWER TANK DEPLOYMENT OPERATION IN LONG BEACH.

4.3.3 Motions and load analysis

4.3.3.1 Openfast simulations

Detailed simulations of the seakeeping performance of the WHEEL platform on its temporary barge-type configuration for tow-out and towed transport have been performed by NREL.

It has been a thorough and detailed analysis which has generated very positive results on the performance of the platform. See key figures and conclusion in the next section.

4.3.3.2 Orcaflex simulations

In addition to the complete analysis performed by NREL in OpenFast, additional contrast simulations have been performed by ESTEYCO with an alternative software package, to confirm alignment between both sets of simulations performed independently and thus increase confidence on the reliability of the results obtained.

Orcaflex models, simulations and results have shown good coincidence with OpenFast simulations by NREL. See key figures and conclusion in the next section.

4.4 Task 3 conclusions

The exercise performed in Task 3 contributed to a good understanding of the WHEEL suitability for floating wind projects in the US West Coast. The following key aspects can be highlighted:

- WHEEL floaters are suited to be built locally in California, based only on existing harbors (including WTG and floater integration).
- Compact beam and low draft allow for constructive strategies that largely reduce the requirements on harbor infrastructure. These emulate the extensive experience in cost-effective serial production of concrete caissons built on floating barges.
- Fast production rates of 1 unit per week can be met (using two floating barges for construction).
- Being based on conventional concrete construction processes and means, WHEEL may be sourced using a strong and available local supply chain (no need for a large shipyard)
- Fabricating close to the site not only increases local content qualitatively but also contributes to overcoming logistical challenges, allowing for a lean Marine Spread with no need for heavy transport vessels.
- Mooring hook-up at WCOW has been identified as a key driver for the floater installation schedule. The marine spread can however be sized to allow for the complete installation of a 50-unit wind farm in a single 9-month installation season.
- The use of concrete, the reduced transport needs thanks to local manufacturing and the low material usage (between one third and one half of the weight of a concrete semisub) results in a very low carbon-footprint as compared to other solutions and particularly steel semisubs.

- WHEEL has excellent scalability and the implementation strategy and global conclusions described in the present exercise may as a rule be extrapolated for the use of even larger wind turbines.

Looking at the motions, accelerations, and forces between the tanks, which are the most critical parameters to be monitored in the current assessment, the following conclusions can be highlighted:

- Inclinations: The maximum inclinations obtained with Orcaflex (with maximums of 5.1º) and by NREL in OpenFast (with a maximum of 4.7º) are well aligned and comfortably within recommended thresholds. Stability criteria is met with very large safety margins and a large 7.5m freeboard also minimizes probability of green waters.
- Nacelle accelerations: Maximum accelerations at the nacelle obtained in Orcaflex (0.9 m/s2) and OpenFast (1 m/s2) are well aligned and well below the maximum accelerations recommended for non-operating conditions by DNVGL-RP-0286 (0.6g). This results in low forces far from the design driving forces obtained in the operative condition.
- Vertical contact forces between Upper Tank (UT) and Lower Tank (LT): Minimum vertical force between upper and lower tank (meaning the lowest force between bodies) is again very well aligned, with a value of -15704 kN in Orcaflex and -14900 kN in Openfast, very far from decompression. This confirms that the prestressing force that pushes one body against the other is enough to ensure that both bodies will remain together and in permanent contact in any towed transport condition, thus behaving in practice like one single body.

In summary, it can be concluded that the seakeeping performance of the WHEEL platform in its barge-type transport configuration can be considered very good. Accelerations at the WTG of only circa 1 m/s2 results in moderate forces (i.e. forces at tower top or tower bottom during towed transport are as a reference around one third of the design driving forces which are governed by the operative and extreme conditions.

While the weather restrictions assumed for the tow-out operation (Hs<2.5m and 10-min average wind speed at 10m height <12m/s) are deemed suitable to allow for a large enough number of weather windows in most cases, the very positive results suggest that even less restrictive limits might be set if convenient in project-specific circumstances.

The good alignment between Orcaflex and OpenFast simulations contribute to the confidence and reliability of the above-mentioned results and conclusions.

5. TASK 4 - INNOVATIVE MOORING AND ANCHORING SYSTEMS

This task covers the design of the station keeping system (SKS) for operation the 15MW WHEEL floater in the Morro Bay Area (California).

In addition, ESTEYCO has developed an innovative solution of self-installing gravity anchors, which may prove a cost-effective and competitive solution, particularly when hard or rocky soil conditions make it more complicated to used conventional anchoring methods such as drag anchors or suction piles.

This was a cost-sharing task which has been developed with ESTEYCO's own funds.

5.1 General description of the station keeping system for Morro Bay

5.1.1 Mooring design criteria

The mooring system consist in three main lines that are linked to the UT by a bridle, each having two lines that start from a fairlead and are linked to a main line via a delta plate.

The mooring system analysis is defined by the following criteria:

- Utilization ratio of the ULS and ALS strength design criteria described in chapter 8.2 of "DNVGL-ST-0119" document, under DLC 6.1 and 1.6 for ULS and 6.2 and 6.6 for ALS. The utilization ratio is calculated following the guidelines included in section 8.2 of ID-21I9-TN-002.
- Maximum floating structure excursion 30%-40% of water depth (31-42m for 105m water depth), pending of permitting and power cable limitations, among others.
- Simplified fatigue damage verification under FLS criteria, see section 8.2 of DNVGL-ST-0119.
- Consequence class 2 is assumed in all criteria.

It is worth stressing that metocean conditions analyzed are preliminary and need to be confirmed. Sufficient margin in ULS and FLS have been considered for future definition.

5.1.2 WTG modelling

As the inclusion of the turbine in the dynamic simulations has a very high computational cost, different methods to implement the turbine have been considered:

- For the simulations in which the turbine is operating, a series of forces is applied at the tower top. The series is obtained from dynamic simulations performed with the turbine isolated and its controller. This is made in the FLS simulations, and in the ULS DLC 1.6 simulations.

- For the simulations in which the turbine is idling with a constant pitch angle at its blades, the drag coefficient is calculated and applied to an equivalent element placed in the same position. Simulations corresponding to ULS DLC 6.1 and ALS DLCs 6.6.1, 6.6.2 and 6.6.3.

- Simulations in which the turbine is idling but with a non-linear force over it (mainly due to potential misalignments due to yaw motions) have the turbine directly included. This is given in the ALS DLC 6.2.

5.1.3 Mooring design description

Figure 41 shows the general arrangement of the SKS for the pre-design developed for the Morro Bay Area. It is taut-mooring design based on polyester lines supported by chain crowfoots on top. This mooring configuration can be adapted for sharing anchor points with suction piles (see Figure 42). Do note it is a preliminary design pending full ULS and FLS mooring analyses, subject to farm lay-out and excursion restrictions (site specific permits, power cable, …)

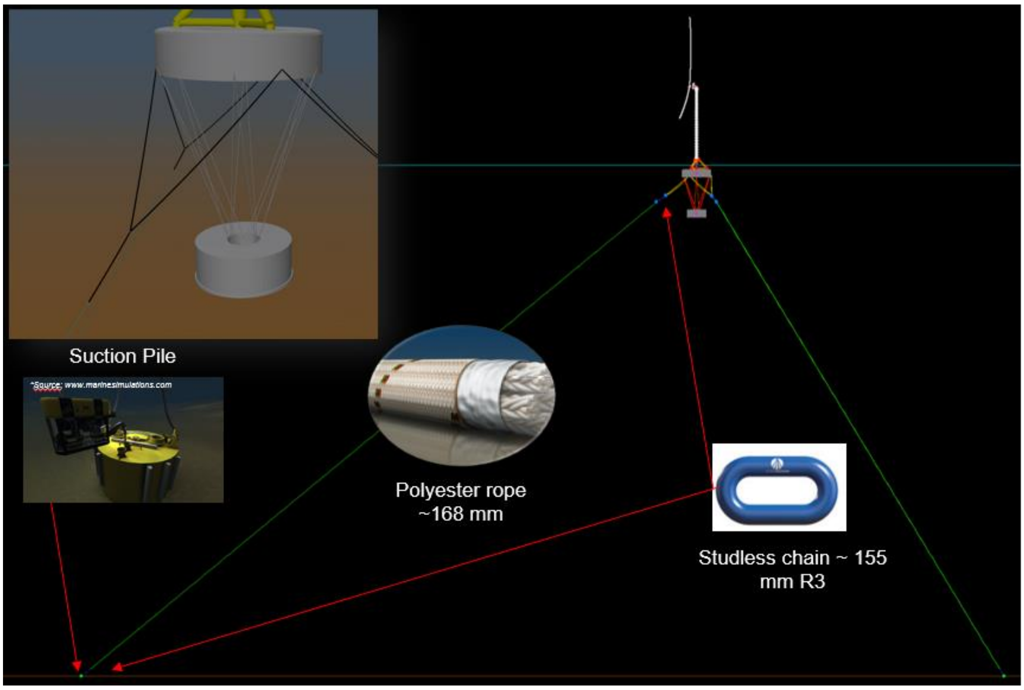


FIGURE 41. GENERAL ARRANGEMENT OF THE WHEEL OFFSHORE PLATFORM MOORING FOR THE MORRO BAY PROJECT

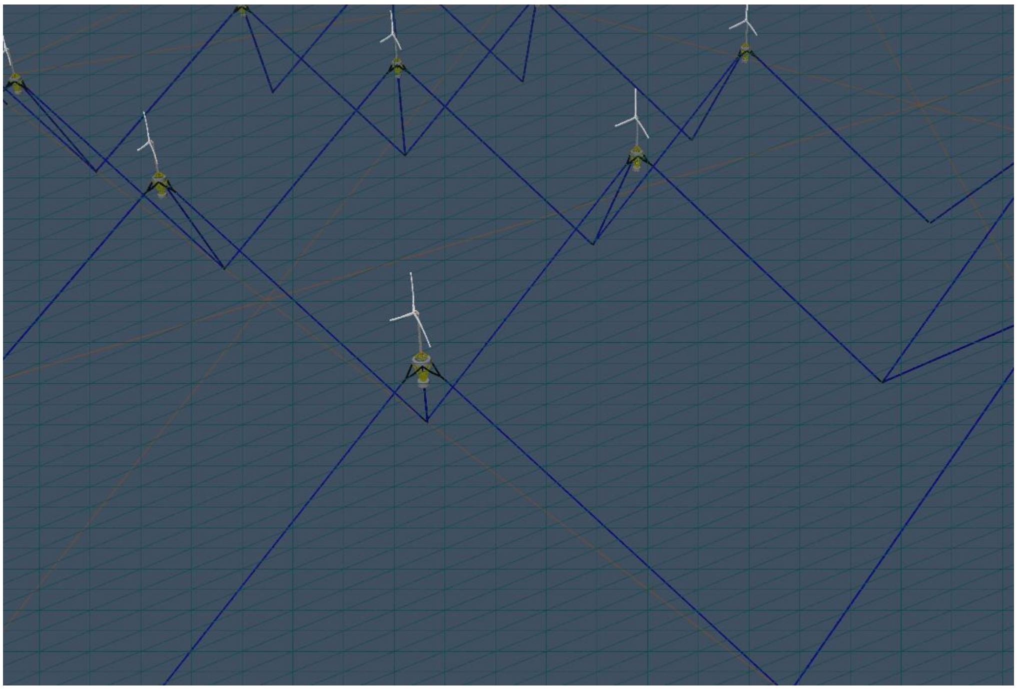


FIGURE 42. MOORING CONFIGURATION CAN BE ADAPTED FOR SHARING ANCHOR POINTS WITH SUCTION PILES

- Bridle lines pre-installed in floater. Hook-up based on connection of the pre-laid main lines with the bridle pre-installed on the floater (on the deck of the anchor handling vessel AHTS). No need to acess the flaoter.
- Tensioning of mooring lines with chain tensioner (in one of the lines)

The mooring system parameters and nomenclature are shown in the next figure:

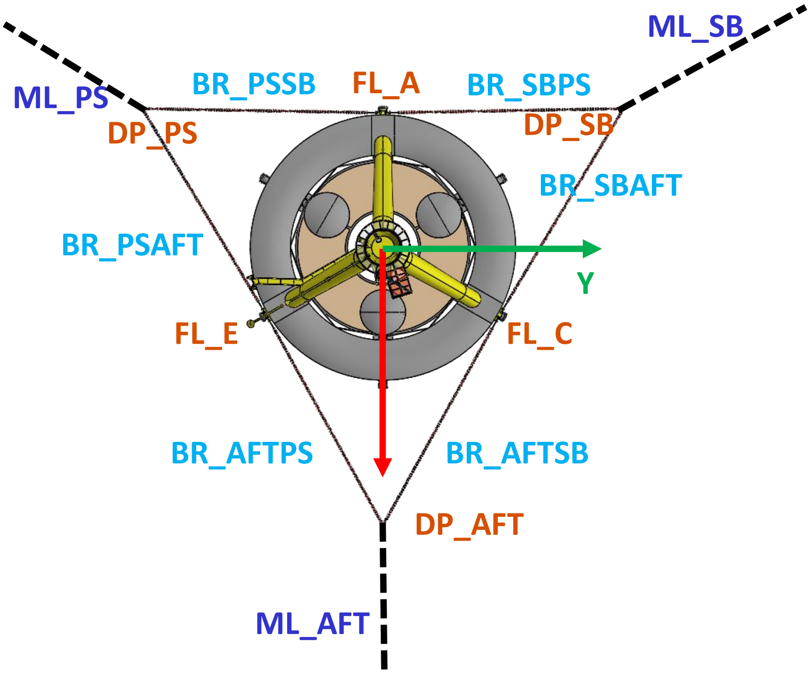


FIGURE 43. MOORING GENERAL ARRANGEMENT

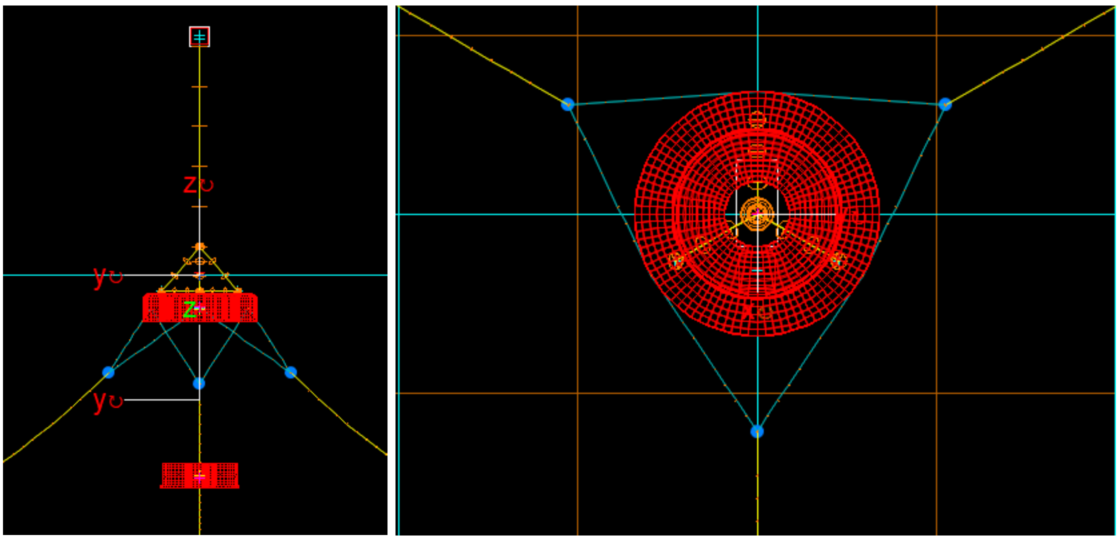


FIGURE 44. WHEEL'S ORCAFLEX MOORING MODEL: SIDE VIEW (LEFT), PLAN VIEW (RIGHT).

The following tables show the position of mooring connections:

- Fairleads: connection between the bridle lines in their connection with the upper tank. Note that Z coordinate is given in local coordinates (referred to UT keel, whose draught in operating conditions is 21 m).

Name	x [m]	y [m]	z [m]
FL_A	--26	0.00	5.1
FL_E	13	-17.75	5.1
FL C	13	17.75	5.1

TABLE 18. MOORING FAIRLEAD POSITIONS

- Delta plates: connection between the bridles and the main lines. Some coordinates are given as a reference of the equilibrium position for the delta plates. Global coordinates (referred to MSL).

Name	x [m]	y [m]	z [m]
DP_AFT	39.00	0.00	-40.00
DP_SB	-21.00	34.64	-40.00
DP_PS	-21.00	-34.64	-40.00

TABLE 19. MOORING DELTA PLATES POSITIONS

The following tables shows description of the mooring lines included in the model:

- Bridles: These lines connect the fairleads to the delta plates. The line type characteristics are shown in the table below.

Parameters for Bridle lines	Value	Unit	Description
Line type name	R3 Studless chain D155	-	
Material	Steel R3	-	
Reference document	Vicinay web page	-	
NumLines	3x2	-	Number of lines disposed
LUnsLen	51.3	m	Line unstretched length
LMassDen_air	477	kg/m	Line mass density in Air
LEAStff	2050e3	kN	Line Extensional Stiffness
CDN	2.4	-	Normal Drag Coefficient
CDT	2.4	-	Tangential Drag Coefficient
CAN	1	-	Normal Added Mass Coefficient
CAT	1	-	Tangential Added Mass Coefficient

TABLE 20. BRIDLE LINE TYPE PROPERTIES

The table below depicts the connection points of the bridles and its pretension in the equilibrium, i.e. when no external force is acting on the structure (differences between the pretension values are given due to the turbine eccentricity, oriented to the PS and SB bridle lines).

Name	From	To
BR_AFTPS	DP_AFT	FL_D
BR_AFTSB	DP_AFT	FL_C
BR_PSAFT	DP_PS	FL_D
BR_PSSB	DP_PS	FL_A
BR_SBPS	DP_SB	FL_A
BR_SBAFT	DP_SB	FL_C

TABLE 21. BRIDLE LINE CONNECTIONS

- Main lines: Main lines are made by a single type of section. Tables below shows the chain properties.

Parameters for Bridle lines	Value	Unit	Description
Line type name	Bridon-Bekaert Rope MoorLine Polyester D168	-	
Material	Polyester	-	
Reference document	Bridon-Bekaert Polyester Catalogue	-	
NumLines	3	-	Number of lines disposed
LEAStff	Non-Linear, see Figure 12	-	Line Extensional Stiffness
CDN	1.2	-	Normal Drag Coefficient
CDT	1.2	-	Tangential Drag Coefficient
CAN	1	-	Normal Added Mass Coefficient
CAT	1	-	Tangential Added Mass Coefficient

TABLE 22. MAIN LINE CHAIN TYPE PROPERTIES

The table below shows the connection points of the Main lines:

Name	From	To
ML_AFT	DP_AFT	AP_AFT
ML_PS	DP_PS	AP_SB
ML_SB	DP_SB	AP_PS

TABLE 23. MAIN LINES CONNECTIONS AND PRETENSION

For the fatigue analysis, a simplified approach based on in-house SN curves for the chains has been carried out just as a starting point. It is important to remark that fatigue is normally driving the chain dimensions, but the current study has not covered a full fatigue assessment but rather a first approach to evaluate the potential response against fatigue.

5.1.4 Assumptions

The following assumptions were made during the development of the analysis process:

- Both bodies of the Lower and Upper tank are modelled as diffraction bodies.
- The drag coefficients to account for the current on the diffraction bodies and on the tower used were set to 0.8.
- The fatigue analysis (FLS from now on), performed is based on a rainflow type analysis.
- The corrosion is regarded in the following ways (shifts of 5 mm for the chain diameter selection):
    - The FLS analyses are performed considering the mid-life of the line (6 years), reducing the chain diameter from 105mm to 100mm.
    - The ULS and ALS analyses are performed under the assumption of the end-life of the chain (12 years), in which the chain diameter is reduced from 105mm to 95mm.

5.2 Task 4 conclusions

A design of the mooring arrangement for the 15MW WHEEL floater designed for operation in the Morro Bay Area (California) has been developed. The resulting design is anticipated to be highly competitive, taking profit of the transparency of the Wheel floaters, which has very little exposed area on the sea surface. This may prove particularly relevant in locations with so large water depths as California, in which costs linked to the Station Keeping System (SKS) will cover a significant fraction of the total wind farm CAPEX Costs.

In addition, Esteyco has developed an innovative solution of self-installing gravity anchors, which may prove a cost-effective and competitive solution, particularly when hard or rocky soil conditions make it more complicated to used conventional anchoring methods such as drag anchors or suction piles.

CONCLUSIONS

Key conclusions regarding WHEEL floater sizing and scalability (Task 1):

A complete design of the WHEEL floater for the next generation of large offshore wind turbines (IEA 15MW reference turbine) has been developed and validated by Esteyco and NREL, confirming the suitability of the solution to deliver units of reduced width (52m), draft (5.3m) and weight (8300 tn of concrete), which roughly halve those of an equivalent semisub floater solution.

Key conclusions regarding operative performance of the WHEEL floater (Task 2)

A detailed fully coupled analysis of the WHEEL floater platform supporting the IEA-15MW turbine has been completed with positive results. Complete simulations with specific tuning of the control system have been developed and run by NREL with OpenFast software. Results of contrast models developed by Esteyco in Orcaflex and OpenFast have been well aligned.

A good seakeeping performance has been verified, with values for the key control parameters used to monitor motions and forces in the wind turbine comfortably below the pre-established reference design thresholds. The large safety margin with respect to such design thresholds suggests that there may be room for optimization in the sizing of the platform. Key design considerations and lessons learned have been obtained and outlined to be duly considered in further detailed design stages of the WHEEL platform.

Key conclusions regarding west coast implementation strategy for large-scale deployment (Task 3)

The exercise performed in task 3 contributed to a good understanding of the WHEEL suitability for floating wind projects in the US West Coast. The following key aspects can be highlighted:

- WHEEL floaters are suited to be built locally in California, based only on existing harbors (including WTG and floater integration)
- Compact beam and low draft allow for constructive strategies that largely reduce the requirements on harbor infrastructure. These emulate the extensive experience in cost-effective serial production of concrete caissons built on floating barges.
- Fast production rates of circa 1 unit per week can be met (using two floating barges for construction)
- Being based on conventional concrete construction processes and means, WHEEL may be sourced using a strong and available local supply chain (no need for a large shipyard)
- Fabricating close to the site not only increases local content qualitatively but also contributes to overcoming logistical challenges, allowing for a lean Marine Spread with no need for heavy transport vessels

- Mooring hook-up at the Morro Bay wind farm has been identified as a key driver for the floater installation schedule. The marine spread can however be sized to allow for the complete installation of a 40/50-unit wind farm in a single 9-month installation season.
- The use of concrete, the reduced transport needs thanks to local manufacturing and the low material usage (between one third and one half of the weight of a concrete semisub) results in a very low carbon-footprint as compared to other solutions and particularly steel semisubs
- WHEEL has excellent scalability and the implementation strategy and global conclusions described in the present exercise may as a rule be extrapolated for the use of even larger wind turbines

Key conclusions regarding Station Keeping System (Task 4)

A conceptual design of the mooring arrangement for the 15MW WHEEL floater designed for operation in the Morro Bay Area (California) has been developed. The resulting design is anticipated to be highly competitive, taking profit of the transparency of the Wheel floaters, which has very little exposed area on the sea surface. This may prove particularly relevant in locations with so large water depths as California, in which costs linked to the Station Keeping System (SKS) will cover a significant fraction of the total wind farm CAPEX Costs.

In addition, Esteyco has developed an innovative solution of self-installing gravity anchors, which may prove a cost-effective and competitive solution, particularly when hard or rocky soil conditions make it more complicated to used conventional anchoring methods such as drag anchors or suction piles.

Challenges and next steps

Among the main next steps envisioned to build on the work and lessons learned from the present project, the following may be highlighted:

- *Detailed Carbon Footprint analysis:* the potential of WHEEL technology to reduce carbon emissions thanks to its focus on concrete and its reduced material usage has been identified. To specifically assess and quantify such reduction in a specific US-based scenario is identify as a valuable next step to pursue.
- *Deeper engagement with US Local Supply Chain:* an in-depth validation of the implementation strategies in California as preliminarily developed by Esteyco and NREL with participation of representatives of the US local supply chain that would potentially be involved in the industrial manufacturing and installation of the WHEEL floaters. Such next step shall be pursued, building on the outputs of the present project, by a consortium led by Esteyco incorporating relevant representatives of the US industry such as TotalEnergies, IEA Infrastructure, SSA Marine or Sarens USA. The WHEEL technology and this consortium has been selected by the Department of Energy (DOE)

as winner of phase-1 of the FLOWIN prize to progress the potential that WHEEL brings to large scale US based production of next generation floating wind units.

The aforementioned consortium has been invited to participate in Phase Two of the Floating Offshore Wind Readiness (FLOWIN) Prize, where a plan for the mass manufacturing and deployment of gigawatt-scale floating offshore wind energy farms using the WHEEL technology will be developed.

- *Large scale experimental demonstration:* Showcasing the advantages and suitability of the WHEEL floating solution that have been studied in the present project in a real scale pilot unit is a key step for the demonstration and commercial deployment of the technology. The EU funded and currently ongoing project WHEEL (GA nº 101084409) led by Esteyco that is planned to deliver an operative 6MW pilot unit in the Canary Islands (Spain) at the end of 2025 shall allow such decisive next step. It is envisioned that this pilot project shall also provide the opportunity for Esteyco and NREL to maintain the successful and fruitful collaboration initiated in the present project.