Self-Installing Concrete Gravity-Base Substructure (Elisa Technology). Sizing for 15 MW Turbine and Holistic Approach for its Implementation in the U.S.

D12.1

FINAL REPORT

Lead authors: ESTEYCO S.A.

Contributors: NREL

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Notice

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Acronyms and Abbreviations

AHTV	Anchor Handling Transport Vessel
ALS	Accidental Limit State
a.m.	Above Mentioned
ASD	Allowable Stress Design
BCM	Ballasting Central Module.
BEM	Boundary Element Method
BoQ	Bill of Quantities
CapEx	Capital Expenditure
CCL	Characteristic Combination of Loads
CIP	Cast in Place
CoG	Center of Gravity
COP	Construction and Operations Plan
D	Deliverable
DLC	Design Load Case
DoE	Department of Energy
DNV	Det Norske Veritas
DoF	Degree of Freedom
EPCM	Engineering Procurement and Construction Management
ESS	Extreme Sea States
EWP	External working platform
FEM	Finite Element Model
FFIV	Floating Foundation Installation Vessels
ft	feet
FTE	Full-time equivalent
GBF	Gravity Based Foundation
GBS	Gravity Based Structure
GM	Metacentric Height
IEA	International Energy Agency
Hs	Significant Wave Height
JEDI	Job and Economic Development Impact model
kWh	Kilowatt hours
LC	Load Case
LCOE	Levelized Cost of Energy
LRFD	Load and Resistance Factor Design
MHW	Mean High Water level
MLLW	Mean Lower-Low Water level
MSL	Mean Sea Level
MW	Megawatt
m/s	Meters per second

NM	Nautical Mile
NOWRDC	National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NSS	Normal Sea States
NYSERDA	New York State Energy Research and Development Authority
OEM	Original Equipment Manufacturer
ORBIT	Offshore Renewables Balance-of-System and Installation Tool
PLC	Programmable Logic Controller.
PPR	Polypropylene
PSD	Power Spectral Density
RAO	Response Amplitude Operator
RLS	Robustness Limit State
RNA	Rotor Nacelle Assembly
SLS	Serviceability Limit State
TIM	Transport and Installation Modular platform
T0	Concrete shaft
T1	Steel tower
T&I	Transport and Installation
ULS	Ultimate Limit State
WEA	Wind Energy Area
WTG	Wind Turbine Generator
WTIV	Wind Turbine Installation Vessels

Executive Summary

The trend of increasing size and weight of offshore wind turbines has greatly reduced the number of capable installation vessels. This limitation becomes more pronounced in the US where vessel availability is lower, and "Jones Act" restrictions are added. Furthermore, depending on these large installation vessels not only generates high availability risk but also high installation costs. The analysis of the ELISA technology in the US market has shown that this support substructure technology is a viable solution to address those issues (cost and availability risk reduction) for next generation 15MW+ offshore.

Fully certified and demonstrated offshore in Europe since 2018 (ELICAN 5MW demo project), ELISA has become the first system ever to allow for the installation of bottom-fixed offshore wind turbines with full independence of marine cranes or heavy lift vessels. ELISA uses a self-buoyant Gravity-Based Foundation (GBF) that makes it possible to assembly the wind turbine on harbor. Both can be then towed and installed together at the offshore wind farm, using only readily available US-flagged tugboats.

Figure 1. ELISA Technology

(Left) ELISA allows installation of bottom-fixed offshore turbines using only locally available tugboats; (right) ELISA 5MW unit operative since 2019, first bottom-fixed offshore wind turbine ever installed with full independence of heavy-lift installation vessels.

In addition to overcoming such critical dependence on heavy-lift installation vessels, which is particularly crucial in the US market, ELISA also targets relevant reductions in the construction, installation, and maintenance costs of offshore wind farms which the present study quantifies for three representative US East Coast Locations. The study is intended to substantiate how the ELISA technology has been conceived for effective scalability and adaptation to the present and future generations of very large offshore wind turbines.

The project has shown a pathway for near-term deployment of ELISA in the US, providing a cost-effective solution that enhances local supply chain and is suitable for next generation turbines.

To do so, the project has been divided into the following tasks whose key results are reported in the present final report:

- Task 1: High-level screening of the potentially available facilities on the US east coast.
- Task 2: T&I analysis for the conceptual design.
- Task 3: Development of a conceptual design for the 15MW reference turbine and representative metocean conditions of the US east coast.
- Task 4: Evaluation of the cost and logistics of fabricating and installing projects using the ELISA technology.
- Task 5: Ballasting system industrial design and tank testing site selection.
- Task 6: Tank test campaign to fine tune 15-MW design for US installation.
- Task 7: Telescopic joint detailed design for substructures supporting large turbines.
- Task 8: Adapt the conceptual design to existing supply chain and facilities.
- Task 9: Manufacturing costs and LCOE benefits for the completed design at specific locations
- Task 10: Analysis of the opportunity space for ELISA technology in the United States

The project targeted a series of key questions, the answers to which have been substantiated along the different tasks and deliverables and are summarized next:

1. *How ELISA technology scales with turbine size, using the IEA 15-MW turbine as a reference.*

   Along Tasks 2 and 3 mainly, it has been analyzed and substantiated how the ELISA technology can be adequately adapted to the future generation of large offshore turbines. As compared to the 5-year field-proven 5MW design, the required resizing for the 15MW foundation is moderate and does not require any shift in the design philosophy or in the required implementation means and infrastructure, either for on-harbor construction or for offshore installation. This is backed not only by the analytical design work and advanced simulations of the installation process performed by NREL, but also by the ambitious tank testing campaign developed as part of Task 6 to contrast and validate experimentally the expected performance and conclusions of the study.

2. *How can ELISA be fully manufactured in the US, with a lower upfront investment cost for its facilities than for other bottom fixed foundations*

   How port requirement for ELISA technology can be found relatively easily compared to steel type foundations.

   Throughout the reporting of Tasks 4 and 8, the reader will understand how ELISA's suitability for serial manufacturing strategies aboard floating barges can allow mass production of foundations based on existing harbor infrastructure, qualitatively reducing the required acreage and bearing capacity of the port yard to be used. This can be crucial to overcome the challenge that the US offshore wind industry is facing with regards to harbor availability.

   The preferred construction technique for ELISA emulates the very extensive and successful serial production of concrete caissons, of which many hundreds (often weighting twice as much as the ELISA foundations) have been produced typically achieving 1 unit/week production ratios.

   The project has developed and costed in detail the implementation of such foundation construction strategy in three different real scenarios along the east coast. For comparison of required upfront investments with monopiles and jackets, refer to section 9.3 (Task 8), where, based on NREL's previous study, it is shown how upfront investments for port upgrade for the ELISA technology can be expected to be one order of magnitude lower than for monopiles or jackets.

3. *How can ELISA be installed with US vessels, without imported jack-ups and why the major vessel availability constraint does not affect to the ELISA technology.*

   As explained in Task 10, currently the global fleet of WTIV or jack-up vessels capable to install 15 MW and larger turbines in waters of 50+m depth is estimated to be limited to only seven vessels, which are as a rule fully booked years ahead and only one of which is Jones Act compliant.

   Tasks 2 and 3 have demonstrated that the self-installing process afforded by the ELISA technology is fully applicable to 15MW turbines and beyond and can be based only on local readily available US-flagged tugboats. Such conclusions have been experimentally endorsed through an ambitious tank testing campaign (task 6) that fully validated the expected performance of the system based on NREL's advanced simulations of the installation process.

   As such, the ELISA technology is unaffected by the critical bottleneck linked to the scarcity of Wind Turbine Installation Vessels (WTIV) and floating foundation installation vessels (FFIV), which will only grow more pivotal as wind turbines grow larger.

   Furthermore, it has also been assessed how the increased transparency of ELISA slender configuration (as compared to cone-shaped GBF configurations) and reduce scour protection requirements and allow in most cases single-layer seabed preparations suitable to act both as bedding layer and scour protection. This can make it possible to perform all required seabed interventions in one single trip and, as such, allow -if convenient- Jones Act compliant use of foreign seabed intervention vessels.

4. *What are the estimated costs for ELISA in the US and how do they vary along the East Coast?*

   In close collaboration between Esteyco and NREL, throughout Tasks 4, 8 and 9 the project has performed and substantiated a complete and detailed cost assessment for the implementation of the ELISA technology in three different scenarios along the East Coast:

   - Scenario 1: North Carolina: Morehead harbor to Wilmington WEA
   - Scenario 2: New York: Arthur Kill Terminal to NY Bight Wind WEA
   - Scenario 3: Bridgeport Marina to Martha's Vineyard WEA

   Depending on the scenario, the ELISA-GBF substructure CapEx varied between \$360/kW to \$460/kW

5. *How does ELISA compare to monopiles in terms of cost reduction and local supply chain use.*

   As part of Task 9 NREL performed a comprehensive comparative study on the costs of the ELISA technology as compared to current costs of monopile foundations, showing a CAPEX saving potential of circa 30%.

   In addition, NREL's study shows that the local content and job creating potential of the ELISA-GBF would more than double those of a scenario based on monopile foundations.

Purpose and scope

This document aims to gather non-proprietary/non-confidential information, covering key aspects of the Work performed under this Agreement #105-165314.

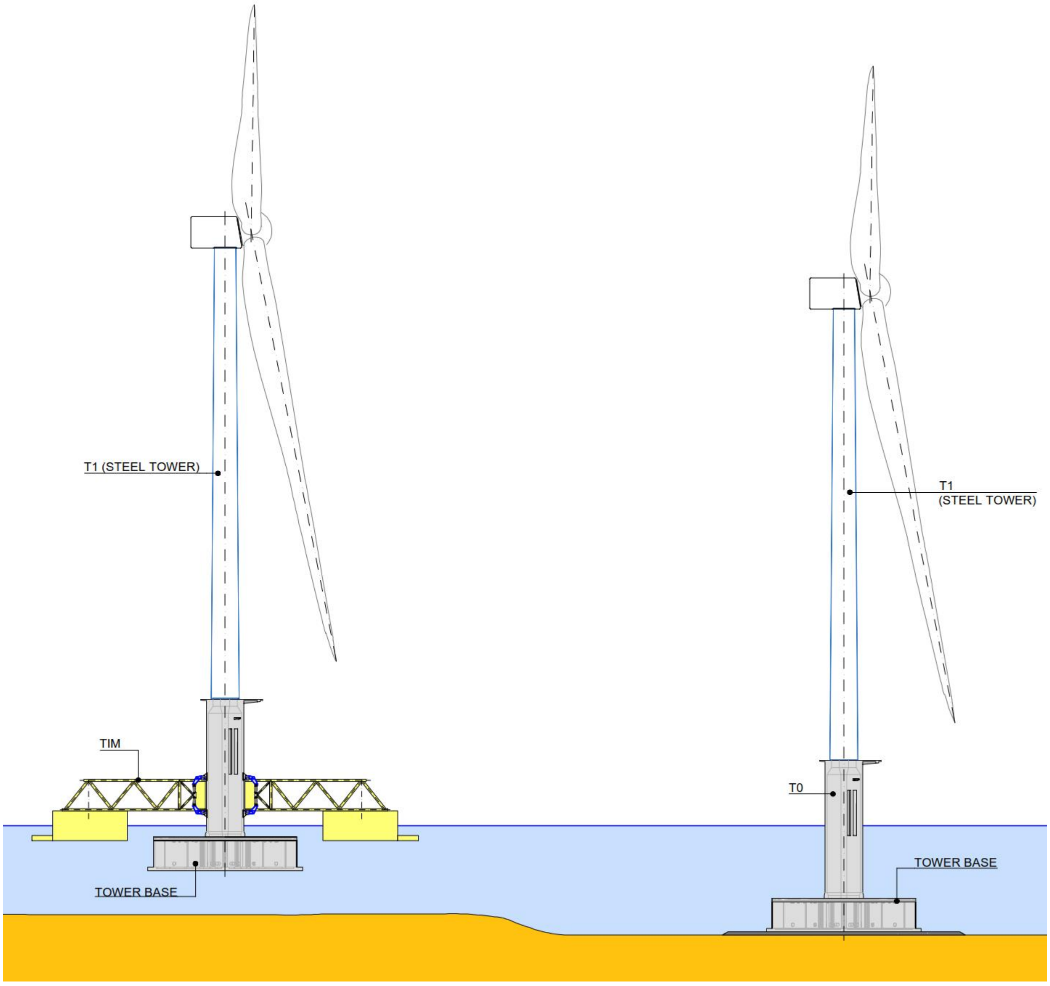
Conceptual Description of the ELISA Technology

The ELISA technology is disruptive being the only proven solution which allows the installation of bottom-fixed offshore wind turbines with no need for heavy-lift installation vessels; this can make it possible to overcome a critical bottleneck in the US market considering the limitations imposed by the Jones Act for use of the current float of turbine installation vessels, none of which have, as of today, American flag. It is also a solution which can be manufactured locally based on existing infrastructure a local supply chain, with the corresponding benefits in terms of local content and linked economic benefits for the US regions making use of offshore wind energy.

The ELISA foundation is a Gravity Based Structure (GBS) which comprises a disc shaped foundation platform and a concrete shaft (T0); it is self-buoyant during temporary installation stages. ELISA allows for the substructure and WTG to be assembled and pre-commissioned onshore and transported and installed offshore using only conventional tugboats. A temporary and reusable floating structure, called TIM, is coupled to the foundation to increase stability during temporary floating stages and make installation possible in a wide range of weather conditions (see Figure 2).

Figure 2. ELISA substructure

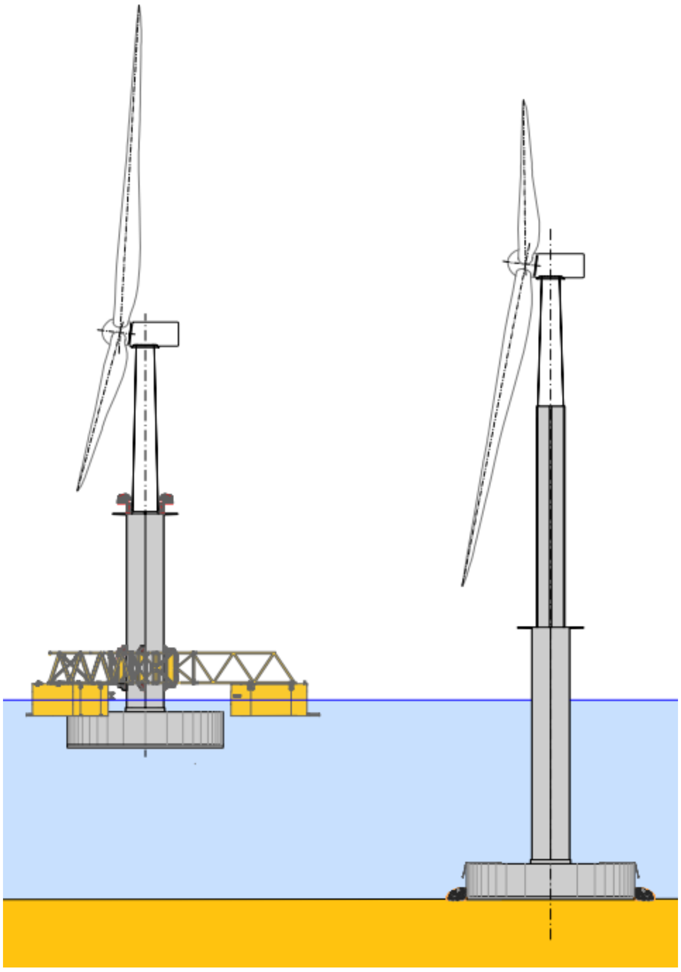
General arrangement of the ELISA substructure during transport (left) and operation (right).



The ELISA technology may use a conventional tower or a telescopic tower which is lifted with reusable heavy-lift strand jacks once the GBS is installed offshore (see Figure 3). If needed, the telescopic tower allows to reduce the RNA installation height at port and lowers the CoG during towed transport. Current base case for WTG sizes up to 22MW and water depths up to 45m (approx.) is a configuration without telescopic tower, since there are commercial onshore cranes capable of performing the onshore assembly of the WTG. For future scenarios with even larger turbine rated power or water depth, the configuration with telescopic tower may be selected to ensure that commercial onshore cranes can adequately perform the onshore installation of the wind turbine. Please refer to Task 7 for detailed information regarding the telescopic tower.

Figure 3. ELISA substructure

General arrangement of the ELISA substructure during transport (left) and operation (right). Alternative with telescopic tower which can lower requirement for the onshore assembly

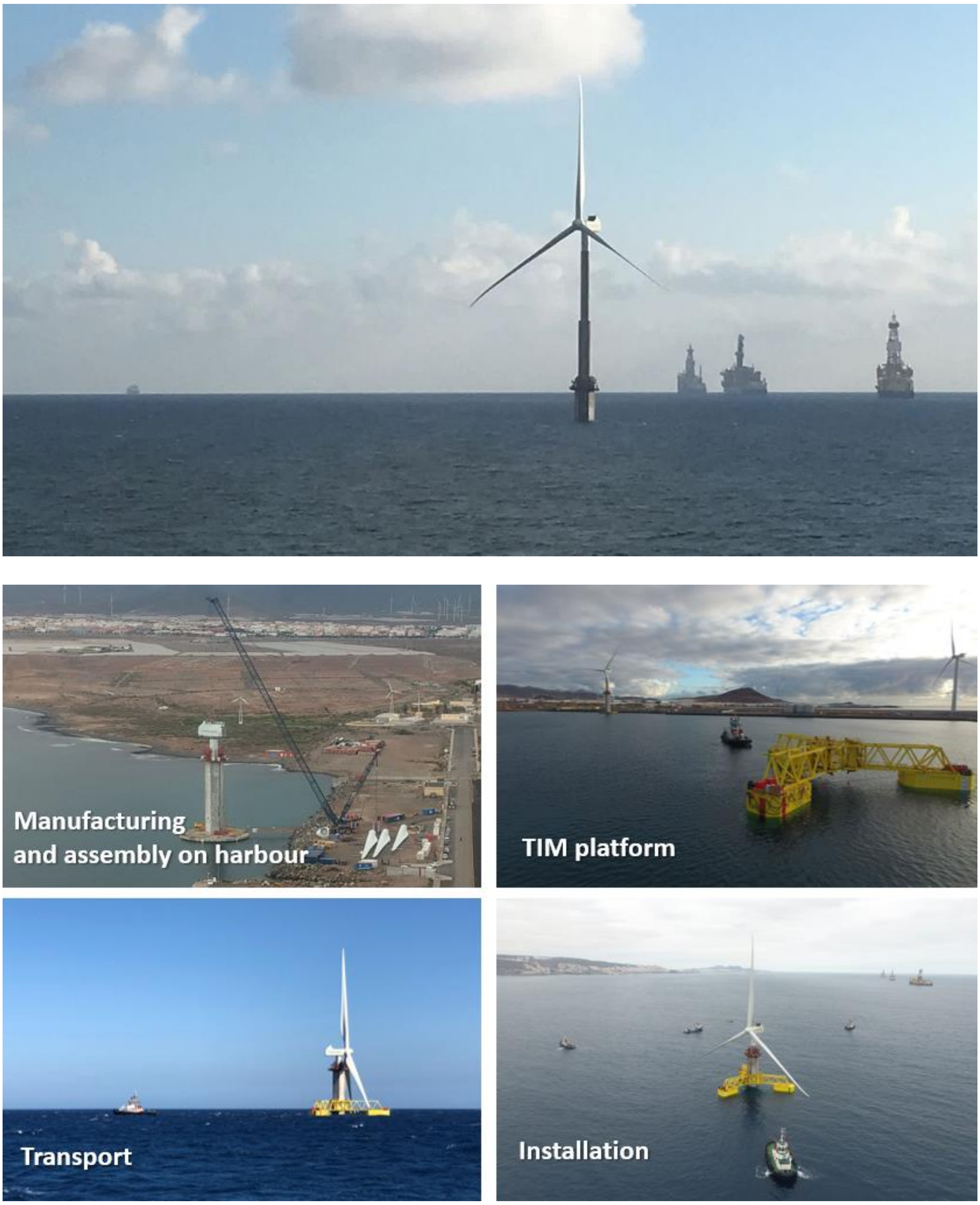


Depending on the client needs and project circumstances, the foundation may also leave the port without the RNA installed, in which case the WTG would be installed offshore with heavy lift vessels as conventionally done with other foundation concepts. This alternative is called ELI instead of ELISA. ELI uses a smaller TIM platform. The use of ELI is not within the scope of the present project, which is focused on the ELISA technology, but it is here described for information purposes.

Next figure shows images of the ELISA 5MW pilot unit which has been operative since 2019 in Europe and is the first and only bottom-fixed offshore turbine ever installed with full independence of heavy lift vessels. A short video of the ELISA pilot construction and installation is available at https://www.youtube.com/watch?v=y1HaokUSulw

Figure 4. ELISA pilot unit

ELISA pilot unit operative since 2019; first and only bottom-fixed offshore turbine ever installed with full independence of heavy lift vessels



Performed work

This project started on October 21st, 2021, Administrative Kick of Meeting date. The work performed has had a duration of approximately 27 months and has been organized in 10 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 & GO/NO GO evaluation

As a multi-phase project, it included a Go/No-Go decision point at the conclusion of Phase IIA. The Project Manager notified that the decision from DOE and NYSERDA was a “Go” and that ESTEYCO could move forward on October 3rd, 2022.

Figure 5. Project Tasks and linked Deliverables

TITLE: SELF-INSTALLING CONCRETE GRAVITY-BASE SUBSTRUCTURE (ELISA TECHNOLOGY). SIZING FOR 15 MW TURBINE AND HOLISTIC APPROACH FOR ITS IMPLEMENTATION IN THE U.S.	
TASK O	**PROJECT MANAGEMENT AND PROGRESS REPORTING**
	D0.1: Written periodic Progress Reports
	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 Reports
	D0.6: Team Member Contact List
	D0.7: Project Gantt Chart
TASK 1	**HIGH-LEVEL SCREENING OF THE POTENTIALLY AVAILABLE FACILITIES ON THE US EAST COAST**
	D1.1 Sites assessment report
TASK 2	**T&I ANALYSIS FOR THE CONCEPTUAL DESIGN**
	D2.1 Technical report that assesses whether the tow-out of a 15-MW turbine stays within expected OEM warranty limits.
TASK 3	**DEVELOPMENT OF A CONCEPTUAL DESIGN FOR THE 15MW REFERENCE TUR**
	D3.1 ELISA technology platform design report to be scaled up to support the increasing size of wind turbines, through the use of the IEA-15MW WTG
TASK 4	**EVALUATION OF THE COST AND LOGISTICS OF FABRICATING AND INSTALLING PROJECTS USING THE ELISA TECHNOLOGY**
	D4.1 A report summarizing the material, manufacturing, and workforce requirements of the gravity-based units
TASK 5	**BALLASTING SYSTEM INDUSTRIAL DESIGN**
	D5.1 Ballasting system industrial design report.
TASK 6	**TANK TESTING CAMPAIGN TO FINE TUNE 15 MW DESIGN FOR US INSTALLATION**
	D6.1 Detailed specifications of the transport and installation processes Tank Testing
	D6.2 Transport and Installation tank experimental tests results
TASK 7	**TELESCOPIC JOINT DETAILED DESIGN FOR SUPPPORTING LARGE TURBINES**
	D7.1 Telescopic joint for very large turbines design report.
TASK 8	**ADAPT THE CONCEPTUAL DESIGN TO EXISTING SUPPLY CHAIN AND FACILITI**
	D8.1 Industrial design report
TASK 9	**MANUFACTURING COSTS AND LCOE BENEFITS FOR THE COMPLETED DESIGN AT SPECIFIC LOCATIONS**
	D9.1 An updated version of the Task 4.1 report
TASK 10	**ANALYSIS OF THE OPPORTUNITY SPACE FOR ELISA TECHNOLOGY IN THE UNITED STATES**
	D10.1 A report describing the limitations and constraints associated with the near term deployment of offshore wind in the US
TASK 11	**DRAFT REPORT AND CLOSEOURE**
	D11.1 Draft Final Report
	D11.3 DOE required closeout reporting per Exhibit F
	D11.4 Market Engagement Report
TASK 11	**FINAL REPORT**
	D11.2 Final Report

1.2. Progress reporting

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

Table 1. Quarterly reports

Quarterly reports length and submission.

Deliverables D0.1.1 to D0.1.8 Quarterly Progress Reports.

Quartely Report	Months included	Date of submission	Total cost
Q1	M1 -M2	01/07/2022	$5,000
Q2	M3-M4-M5	04/20/2022	$5,000
Q3	M6-M7-M8	07/22/2022	$5,000
Q4	M9-M10-M11	10/13/2022	$5,000
Q5	M12-M13-M14	01/25/2023	$5,000
Q6	M15-M16-M17	04/20/2023	$5,000
Q7	M18-M19-M20	07/19/2023	$0
Q8	M21-M22-M23	10/23/2023	$0

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.

Table 2. Advisory Board meetings

Advisory board meetings dates.

Advisory Board	Date	Minutes
AB1	12/20/2021	D0.3 Advisory Board D0.1.1 Q1 Progress Report
AB2	03/08//2022	D0.1.2 Q2 Progress Report
AB3	06/02/2022	D0.1.3 Q3 Progress Report
AB4	09/01/2022	D0.1.4 Q4 Progress Report
AB5	03/15/2023	D0.1.6 Q6 Progress Report
AB6	06/26/2023	D0.1.7 Q7 Progress Report
AB7	12/14/2023	N/A

2. Task 1 - High-level screening of the potentially available facilities on the US east coast

This task aimed to examine how the ELISA GBS could be manufactured in series fully using the US supply chain, taking advantage of precast concrete and modularity to increase efficiency and enhance local content. The manufacturing strategy of the ELISA technology aims for high levels of industrialization and promotes local content intensive products, both in raw material and workforce, contributing to the USA growth, jobs and strengthened industrial technology base.

In addition, the use of concrete reduces the dependence of steel, a commodity with high price volatility often related to bottlenecks in the tower and substructure supply chain. By focusing on a less strained and locally driven supply chain (concrete suppliers and contractors), the technology shall open new industrial opportunities and nurture the capacity of the USA Industry to produce the required components.

The strategy for manufacturing has been focused on the on-shore assembly of the wind turbine, and the use of the structure's self-buoyancy to avoid heavy-load handling equipment, avoiding large heavy-lifting vessel and equipment, and focusing on lower costs and readily available local auxiliary means.

2.1. Facilities high-level screening

To identify potential manufacturing and assembly sites for the ELISA foundation at the likely rates required in commercial wind farms, a high-level screening on the US east coast was carried out, including the following states (from north to south): Massachusetts (MA), Rhode Island (RI), Connecticut (CT), New York (NY), New Jersey (NJ), Maryland (MD), Virginia (VA), North Carolina (NC) and South Carolina (SC).

At the following sections, some matrixes are presented compiling the information on 38 existing ports or properties that could support the ELISA manufacturing and assembly. The matrixes are organized by state, and include information on the location, available area, berth dimensions (if exist), channel depths, air restrictions, interferences, load capacities and other information.

In addition, each port has been classified regarding its characteristics in:

- *Manufacturing port*: locations with the appropriate space and quay characteristics to manufacture the ELISA foundation at the required rates, but with some interferences (bridges, power cables or airport proximity) that make WTG assembly unfeasible. It is noted that, thanks to the suitability of ELISA for caisson-type manufacturing on floating barges, the requirements in terms of port yard area and bearing capacity are qualitatively reduced (See further details in Tasks 4&9)
- *Manufacturing & Assembly port*: locations with the appropriate space to manufacture the ELISA foundation at the required rates and have no air draft restrictions, therefore also allowing for WTG assembly in harbor.

- *Auxiliar port*: locations close to manufacturing and assembly ports, with limited availability of space and berth length. These locations could be used for waiting positions, minor components manufacturing (i.e., prefabricated elements) and assembly (i.e., davit cranes), TIM assembly and others.

All the depth references are made using the Mean Lower-Low Water (MLLW) level and all the air draft references are made using the Mean High Water (MHW) level.

Deliverable 1.1 provided full details of the characteristics and potential suitability of each harbor analyzed. The following sections include a brief summary of the facilities screened in each state assessed along the East Coast.

2.1.1. Massachusetts locations

In this section, the potential sites for the ELISA projects in the State of Massachusetts are presented, the following figure shows the 6 locations identified. Table 3 shows the main characteristics of each one.

Figure 6. Potential locations in the state of Massachusetts

Deliverable 1.1 Sites assessment report

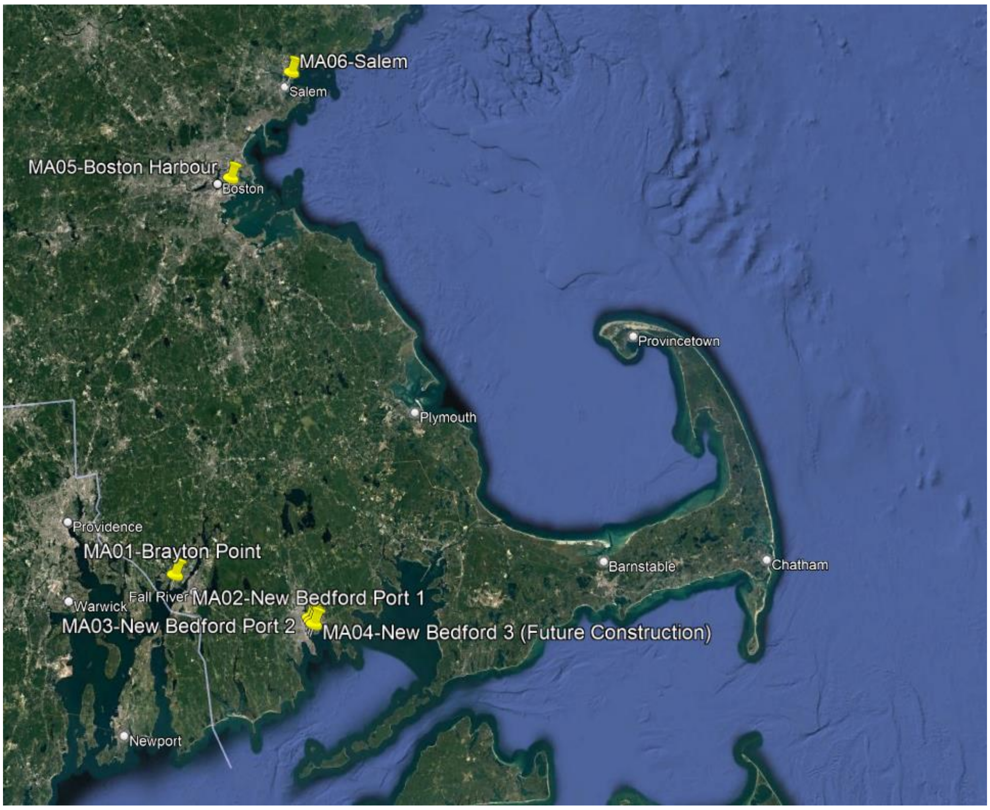


Table 3. Massachusetts' potential locations.

Main characteristics of the potential locations in the state of Massachusetts.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
MA01	Brayton Point	MA	Manufacturing & Assembly	24	230	10,5	11	41,2	MT Hope Bridge	10
MA02	New Bedford 1. Marine Commerce Terminal	MA	Auxiliar	8,6	360	9,1	9,1	No	Hurricane barrier (45m horizontal clearance)	20
MA03	New Bedford 2	MA	Auxiliar	5,5	_	_	9,1	No	Hurricane barrier (45m horizontal clearance)	_
MA04	New Bedford 3 (Future construction)	MA	Assembly	8,9	650	_	9	No	Expansion Outside hurricane barrier	_
MA05	Boston Harbour	MA	Manufacturing & Assembly	11,8	300	11	12,8	No	Airport proximity	_
MA06	Salem	MA	Manufacturing & Assembly	8,3 (17)	260	9,7	10,3	No	No	_

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
MA01	Brayton Point	MA	Manufacturing & Assembly	24	230	10,5	11	41,2	MT Hope Bridge	10
MA02	New Bedford 1. Marine Commerce Terminal	MA	Auxiliar	8,6	360	9,1	9,1	No	Hurricane barrier (45m horizontal clearance)	20
MA03	New Bedford 2	MA	Auxiliar	5,5	_	_	9,1	No	Hurricane barrier (45m horizontal clearance)	_
MA04	New Bedford 3 (Future construction)	MA	Manufacturing & Assembly	8,9	650	_	9	No	Expansion Outside hurricane barrier	_
MA05	Boston Harbour	MA	Manufacturing & Assembly	11,8	300	11	12,8	No	Airport proximity	_
MA06	Salem	MA	Manufacturing & Assembly	8,3 (17)	260	9,7	10,3	No	No	_

2.1.2. Rhode Island locations

The following figure shows the 2 locations identified in the State of Rhode Island. Table 4 shows the main characteristics of each one.

Figure 7. Potential locations in the state of Rhode Island

Deliverable 1.1 Sites assessment report

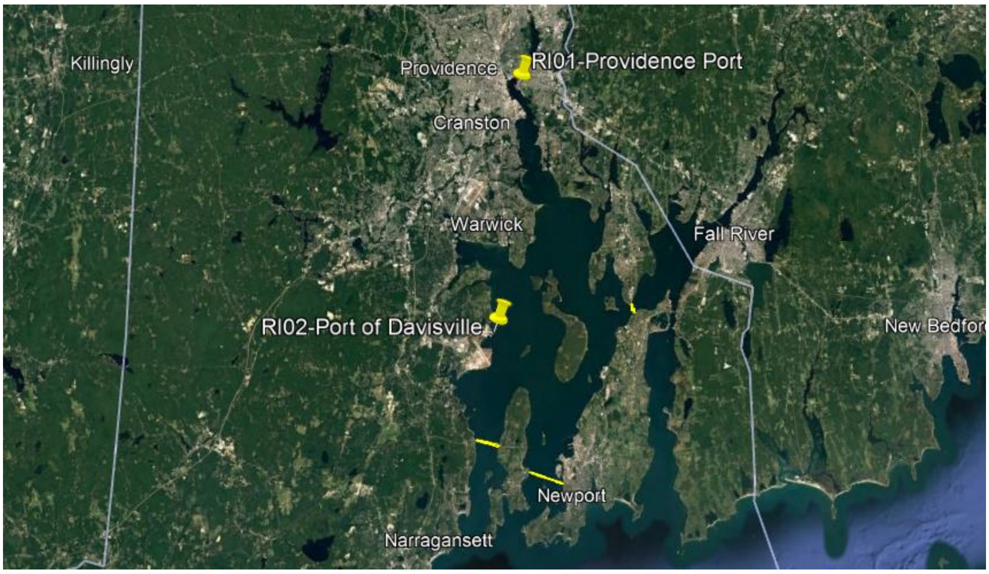


Table 4. Rhode Island's potential locations.

Main characteristics of the potential locations in the state of Rhode Island.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
RI01	Providence Port 1	RI	Manufacturing & Assembly	13,5	–	–	12,2	59	Newport Bridge	–
RI02	Port of Davisville	RI	Auxiliar	1,2	270	8	10	59	Newport Bridge & Airport proximity	–

2.1.3. Connecticut locations

The following figure shows the 3 potential locations identified projects in the State of Connecticut. Table 5 shows the main characteristics of each one.

Figure 8. Potential locations in the state of Connecticut

Deliverable 1.1 Sites assessment report

Table 5. Connecticut's potential locations.

Main characteristics of the potential locations in the state of Connecticut.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
CT01	BridgePort Harbor 1	CT	Assembly	15,4	280	8,2	9,1	No	No	_
CT02	BridgePort Harbor 2	CT	Manufacturing & Assembly	11,5	No	No	9,1	No	No	_
CT03	New London State Pier	CT	Assembly	14,8	1550	10	12	No	_	_

2.1.4. New York locations

The following figure shows eight of the 10 locations identified. There are two more locations identified in the Hudson River, close to the city of Albany.

Figure 9. Potential locations in the state of New York

Deliverable 1.1 Sites assessment report

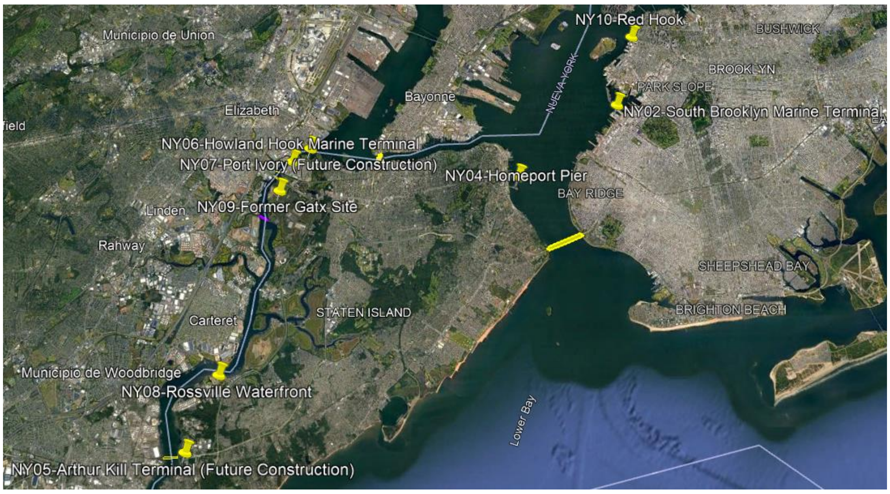


Table 6. New York's potential locations.

Main characteristics of the potential locations in the state of New York.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
NY01	Port of Coeymans	NY	Manufacturing & Assembly	19,1	90	9,1	9,8	40,8	Mid Hudson Bridge	15
NY02	South Brooklyn Marine Terminal	NY	Auxiliar	8,8	950	9,8	12,2	65,5	Verrazano-Narrows Bridge	_
NY03	Port of Albany (Future construction)	NY	Manufacturing & Assembly	30,7	400	10,3	9,8	40,8	Mid Hudson Bridge	15-30
NY04	Home port Pier	NY	Auxiliar	1,2	430	12	15,5	65,5	Verrazano-Narrows Bridge	_
NY05	Athur Kill Terminal (Future construction)	NY	Manufacturing & Assembly	13	400	10	10,7	No	No	_
NY06	Howland Hook Marine Terminal	NY	Manufacturing & Assembly	19,4	122	8,2	15,2	64,5	Bayonne Bridge	_
NY07	Port Ivory (Future construction)	NY	Manufacturing & Assembly	29,8	400	8,9	15,2	64,5	Bayonne Bridge	15-30
NY08	Rossville Waterfront	NY	Manufacturing & Assembly	30,9	No	No	10,7	43,5	Outerbridge Bridge	_
NY09	Former Gatx Site	NY	Manufacturing & Assembly	124	No	No	10,7	43,5	Outerbridge Bridge	_
NY10	Red Hook	NY	Auxiliar	7,1	500	10	12	65,5	Verrazano-Narrows Bridge	_

2.1.5. New Jersey locations

The following figures shows the 6 of the 8 locations identified. There are two more locations identified in the north, close to Staten Island. Table 7 shows the main characteristics of each one.

Figure 10. Potential locations in the state of New Jersey

Deliverable 1.1 Sites assessment report

Table 7. New Jersey's potential locations.

Main characteristics of the potential locations in the state of New Jersey.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
NJ01	Port of Paulsboro	NJ	Manufacturing	81	920	12,2	13,7	56,4	Delaware Memorial Bridge & Airport proximity	_
NJ02	New Jersey Wind Port - Parcel A (Future construction)	NJ	Assembly	13,1	475	14,5	10,8	No	No	15-30
NJ03	New Jersey Wind Port - Parcel B (Future construction)	NJ	Manufacturing & Assembly	40,2	970	_	10,8	No	No	_
NJ04	Repauno Port	NJ	Manufacturing & Assembly	31,7	210	13,1	12,8	56,4	Delaware Memorial Bridge	6-8
NJ05	Chemours Chambers	NJ	Manufacturing & Assembly	142	No	No	12,8	56,4	Delaware Memorial Bridge	_
NJ06	Carney´s Point	NJ	Manufacturing & Assembly	36,5	No	No	12,8	56,4	Delaware Memorial	_
NJ07	North & Mclester	NJ	Manufacturing & Assembly	29,5	_	_	15,2	64,5	Bayonne Bridge & Airport proximity	_
NJ08	South Amboy	NJ	Manufacturing & Assembly	22,6	200	7	7	No	No	_

2.1.6. Maryland locations

In this section, the potential site for the ELISA projects in the State of Maryland is presented, the following figure show the only one location identified. Table 8 shows its main characteristics.

Figure 11. Potential locations in the state of Maryland

Deliverable 1.1 Sites assessment report

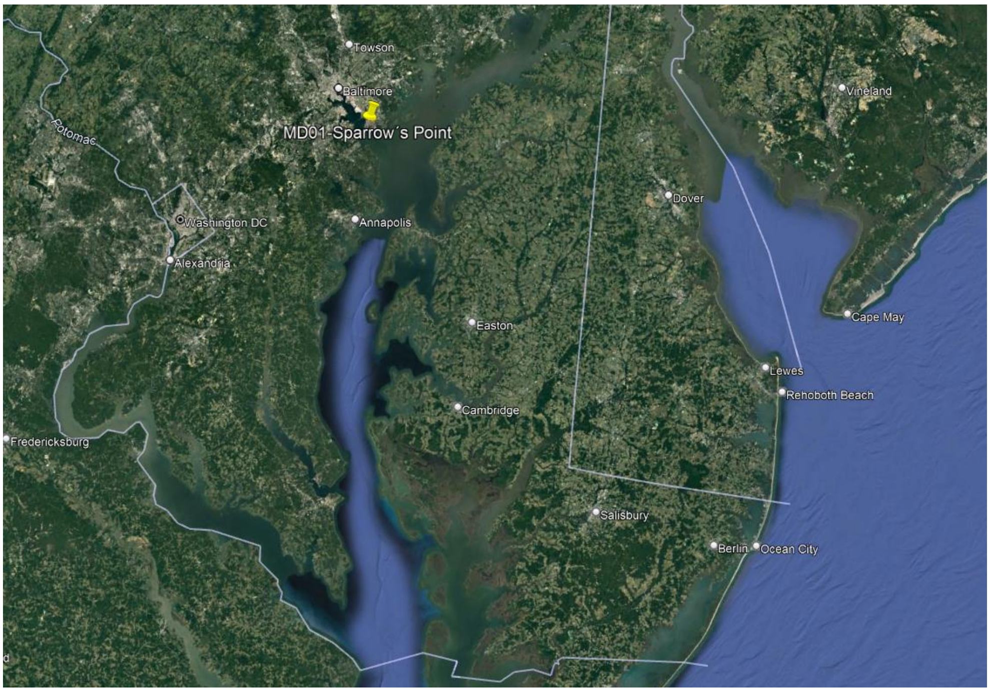


Table 8. Maryland's potential locations.

Main characteristics of the potential locations in the state of Maryland.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
MD01	Sparrow´s Point	MD	Manufacturing & Assembly	135	No	No	15,5	55,5	William PL Memorial Bridge	_

2.1.7. Virginia locations

The following figure shows the 3 locations identified in the State of Virginia. Table 9 shows the main characteristics of each one.

Figure 12. Potential locations in the state of Virginia

Deliverable 1.1 Sites assessment report

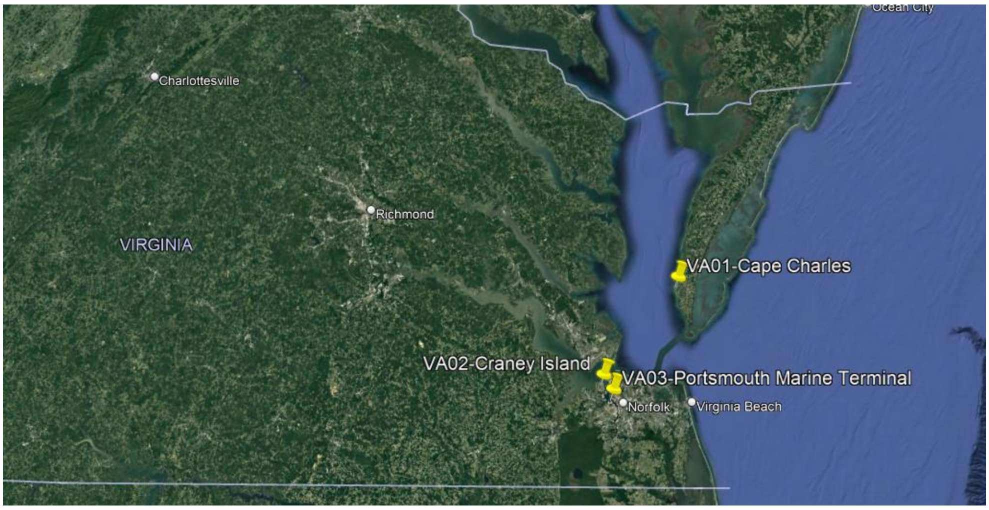


Table 9. Virginia's potential locations.

Main characteristics of the potential locations in the state of Virginia.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
VA01	Cape Charles	VA	Auxiliar	8,8	No	No	5,8	No	No	_
VA02	Craney Island	VA	Manufacturing & Assembly	910	No	No	15,5	No	Airport proximity	_
VA03	Portsmouth Marine Terminal	VA	Assembly	41,6	1400	12	14,3	No	No	_

2.1.8. North Carolina locations

The following figure show the only one location identified in the State of North Carolina. Table 10 shows its main characteristics.

Figure 13. Potential locations in the state of North Carolina

Deliverable 1.1 Sites assessment report

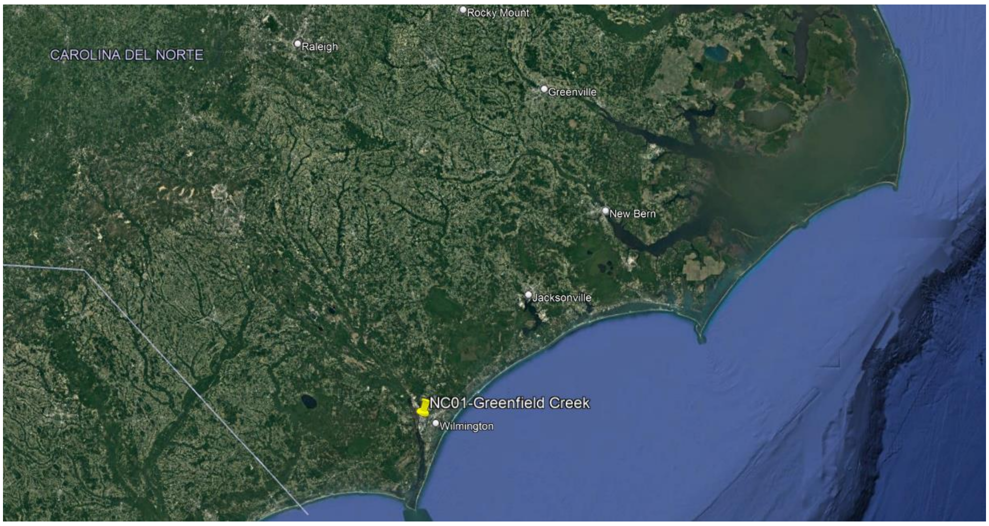


Table 10. North Carolina's potential locations.

Main characteristics of the potential locations in the state of North Carolina.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
NC01	Greenfield Creek	NC	Manufacturing & Assembly	33,4	No	No	11,6	No	No	_

2.1.9. South Carolina locations

The following figure shows the 4 locations identified in the State of South Carolina. Table 11 shows the main characteristics of each one.

Figure 14. Potential locations in the state of South Carolina

Deliverable 1.1 Sites assessment report

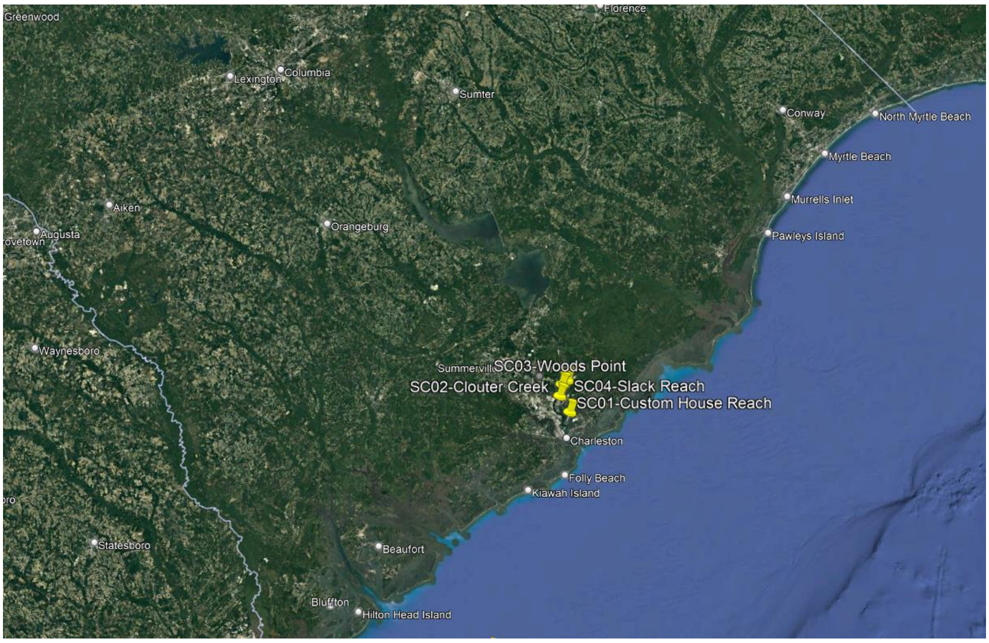


Table 11. Main characteristics of the potential locations in the state of South Carolina.

Deliverable 1.1 Sites assessment report

Code	Site	State	Classification	Available Area (Ha)	Berth length (m)	Berth depth (m, MLLW)	Channel depth (m, MLLW)	Air draft (m, MHW)	Interferences	Bearing capacity (t/m2)
SC01	Custom House Reach	SC	Manufacturing & Assembly	368	No	No	14,6	56,7	Arthur Ravenel Jr Bridge	_
SC02	Clouter Creek	SC	Manufacturing & Assembly	600	No	No	13,7	56,7	Arthur Ravenel Jr Bridge	_
SC03	Woods Point	SC	Manufacturing & Assembly	113	No	No	11,6	56,7	Arthur Ravenel Jr Bridge	_
SC04	Slack Reach	SC	Manufacturing & Assembly	232	No	No	11,6	56,7	Arthur Ravenel Jr Bridge	_

2.2. Task 1 Conclusions

A high-level screening of the potential locations for the manufacture and assembly of ELISA technology has been carried out on the East Coast of the US, from Massachusetts to South Carolina. 38 potential manufacturing, assembly or auxiliar sites for the ELISA foundation at the likely rates required in commercial wind farms have been identified.

The suitability of ELISA for caisson-type manufacturing strategies on floating barges (see further details in Task 9) largely reduces the requirement in terms or area and bearing capacity of the port yard required for serial manufacturing of foundations and thanks to this there are multiple harbors that, if available, would be suitable for manufacturing of ELISA foundations with none or limited need port upgrades.

Regarding water depth requirements, the ELISA GBS foundation has a draft of ca.5m for float-off of the construction base, and ca.8m upon completion of the concrete shaft and installation of the steel tower and WTG, therefore ensuring compatibility with virtually any major harbor infrastructure or navigation channel.

However, not all harbors are suitable for the WTG on-harbor assembly works, mainly due to air draft limitations that prevent towing the foundation&WTG from the port to the offshore site. WTG assembly ports will typically also require increase area for WTG marshalling activities as well as potential local bearing capacity upgrades for supporting the large crane required for WTG assembly.

It is highlighted that ELISA is also suited for implementation strategies based on the use of different ports. Foundations can be manufactured in one port, and then towed to a different port with no air draft restrictions where the WTG is integrated and pre-commissioned prior to the final tow to the offshore site.

3. Task 2 - T&I analysis for the conceptual design

One of the pioneer characteristics of the ELISA technology is the fact that it allows for full wind turbine installation and integration with the substructure in harbor, so the WTG can be towed to the wind farm together with the foundation and be installed offshore with no need for any heavy lift vessels.

A relevant aspect of ELISA's design is therefore assessing the performance of the foundation&WTG assembly in all temporary conditions afloat during the installation process, verifying an adequate seakeeping performance and in particular that the wind turbine will not experience any condition or force it is not prepared for.

In that sense a project using the ELISA bottom-fixed technology is more similar to a floating wind project (in which WTGs will typically be installed onshore) than to a bottom-fixed project. Truly, the development of floating wind solutions has contributed to increase confidence in the industry about the fact that turbines are well prepared to comfortably go through a properly designed towing process.

The ELISA foundation and TIM platform are designed to deliver very high stability levels (with metacentric heights in the vicinity of GM=10m) and also very high natural periods, in particular in roll and pitch (typically above 30s), which results in very slow motions that are not relevantly dynamically amplified by waves whose possible periods are of course much lower, particularly considering that ELISA towing is a weather restricted operation with limited wave heights.

This adequate performance during installation must of course be duly verified through adequate analysis and advanced simulations which in this project have been performed by NREL as renowned expert in the IEA 15MW turbine and advanced hydrodynamic simulations based on OpenFast, both the turbine design and OpenFast software package having in fact been originated in NREL.

The purpose of the following sections is to described the ELISA design and its hydrodynamic properties during all key T&I temporary floating conditions, and to report on the results of the advanced hydrodynamic simulations independently performed by NREL for assessing the seakeeping performance of the system and in particular the conditions that the WTG will undergo during the T&I process, aiming to confirm that the forces that the wind turbine may experience during a weather restricted towing are less demanding than those that it may experience during its operating life and it is therefore designed for.

All simulations and results reported for the T&I process correspond to the reference ELISA designed described in detail in Task 3.

3.1. Weather limits for transport and installation

The T&I process is a weather restricted operation. The following table shows operational limits for transport and installation operations as typically used for the ELISA foundation and considered in the present project and analysis. ELISA may also be designed for other weather limits depending on specific project circumstances, but the proposed values have been found to deliver a good balance to deliver a sufficiently high number of installation windows in most projects while avoiding overdesigning the operation for conditions that are infrequent and can be conveniently avoided through adequate controls and weather forecasts. It is noted that in order to assess workability and compute the expectable availability of weather windows, the following weather limits must be adequately adjusted with the corresponding Alpha-factors (as per DNVGL-ST-N001 section 2.6.11 or equivalent) in order to safely cover risks linked to imprecisions in weather forecasting.

Table 12. Operational limiting criteria.

Operational limiting environmental criteria (OP_{LIM}).

Deliverable 2.1

Operation	Significant height	Peak period	Wind Speed at 10 m (10-min av.)
	[Hs] (m)	[Tp] (s)	[Wv] (m/s)
ELISA T&I	2.00	14	14.00
TIM transport	2.50	14	20.00

Two towing speeds are defined for offshore and inshore towing operations. ELISA towing is performed at 3.5 knots and TIM return at 6 knots. Towing speed values have relatively little influence on the seakeeping performance and motions or forces experience by the WTG and are more directly linked with the required power and bollard pull of the tugboats used for the operation. The a.m. reference values have been found to be aligned with the capacity of offshore tugs that may be sufficiently available in the US east coast, but they may also be adjusted as convenient depending on project circumstances (for projects with a longer distance from harbor to wind farm site in may be worth investing in more powerful tugboats that can deliver larger speeds, while for projects with very shorts distances lower towing speeds may suffice and allow for use of cheaper tug boats).

3.2. Motion limits on the WTG during transport and installation

The design of the ELISA and the TIM platform, together with the weather limitations established, must ensure that motions and thus inked forces in the WTG remain within admissible values, which are here set as the expected Original Equipment Manufacturer's (OEM) Warranty Limits.

Multiple control parameters in different parts or components of the wind turbine shall be monitored in the detailed simulations which incorporate the complete wind turbine model. However, it is expected that the limits that may be set by the OEM and monitored during the actual towing operation will be linked essentially to accelerations in the nacelle as the primary parameter for warranty limits.

It is hereby confirmed that nacelle accelerations where the key threshold established by SIEMENS-GAMESA (SGRE) during the installation process of ELISA's pilot unit which supported an SGRE turbine.

A secondary parameter that may also be used for warranty limits is the maximum tilt of the structure, although it is noted that effect of tilt on the WTG components is in every way equivalent to the effect of a horizontal acceleration "a_h" with value a_h = g·sen a, where g is the gravity acceleration (9.81 m/s^2) and a is the tilt angle. When the accelerometer in the nacelle measures horizontal acceleration, it is in fact including in such measurement the combined effect of change in horizontal speed and tilt. In other words, an observer sitting on the nacelle and sensing horizontal acceleration would not be able to tell if such acceleration is generated by variations in horizontal speed or by a tilt on the nacelle, just in the same way in which a flight simulator reproduces the changes in horizontal speed of a plane by tilting the simulator.

Based on ESTEYCO's experience and specific workshops for discussion and coordination of reference limits held with reference OEMs including GE, SGRE and VESTAS, the expected OEM's Warranty Limits for the present exercise are set as:

- Maximum horizontal acceleration: $a_h < 4.5$ m/s^2
- Maximum vertical acceleration: $a_v < 3.0$ m/s^2

It is noted that these proposed thresholds for design are in fact more restrictive than the reference limit values proposed by DNV-RP-0286 section 5.5 (maximum acceleration: 0.6g=5.9 m/s2) and that some of the above-mentioned OEM's did propose higher (less restrictive) limit values. They are in any case far from driving the design of ELISA T&I operations, in which maximum accelerations do remain comfortably below the a.m. thresholds, as shall be described, and quantified in the following sections.

While the key parameter governing the forces that the WTG will experience during the T&I process is ass the acceleration in the nacelle, a good practice limit on the maximum pitch/roll angles of the platform is also established in the present exercise as a potential secondary OEM warranty limit, although as above explained the limits in horizontal acceleration do cover the effects of tilt: Maximum pitch/roll angle: a < 5 deg

Again, this value is indeed more restrictive than design thresholds recommended in DNV-RP-0286 section 5.5 (10deg in operational Design Loads Cases and 15deg in non-operational load cases as would be the T&I operation). In any case, this limit is also met with comfortable margin by the ELISA foundation as described and quantified in the following sections.

3.3. Installation sequence

The following figures provide a visual description of the ELISA offshore ballasting process for installation of the GBS on the seabed.

Figure 15. Towed Transport

Towed transport of the ELISA 5MW Pilot unit, performed with a single Tugboat

Figure 16. Positioning and ballasting.

Deliverable 2.1

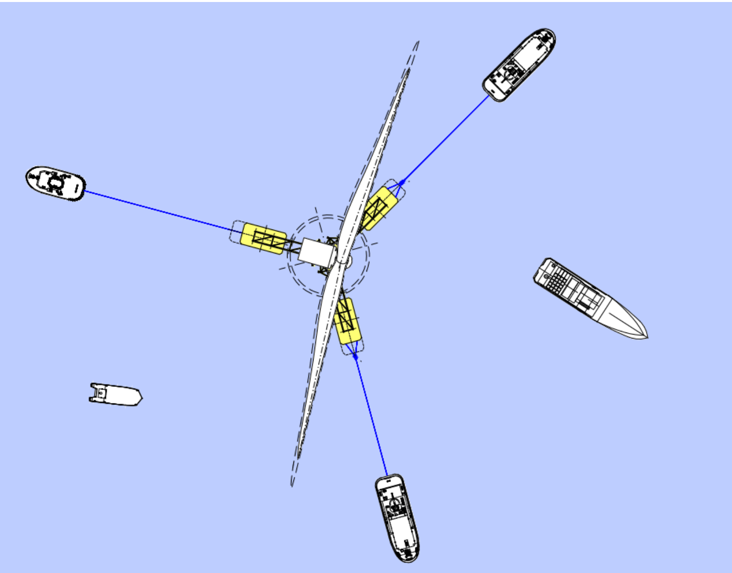
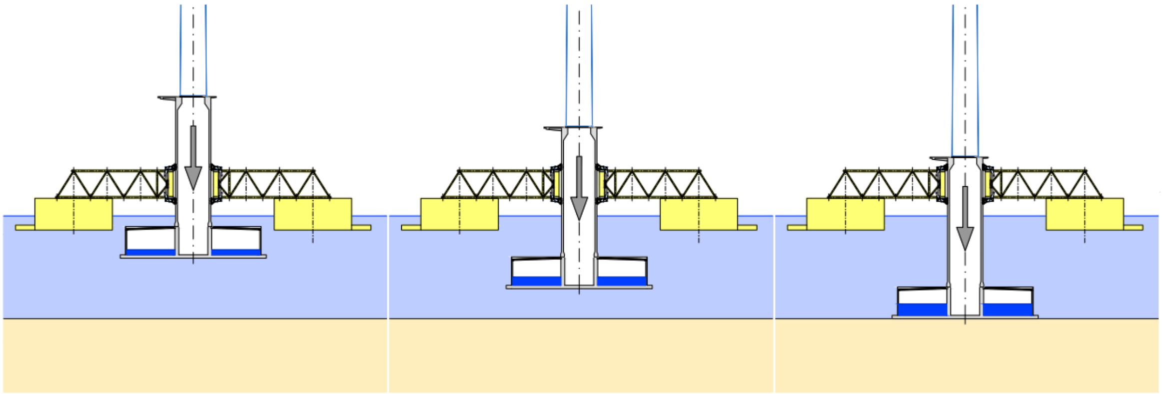


Figure 17. Ballasting sequence

Deliverable 2.1



3.4. Parameters for numerical models

The analysis of the T&I process has covered multiple conditions or load cases representative of different stages that the structure must undergo after it is towed out of the harbor and until it rests safely on the seabed. These include of course the conditions during towed transport, as well as the conditions during the ballasting process, along which the draft of the GBS is gradually increased by controlled water ballasting, with the corresponding variation of the overall hydrodynamic properties of the system (as a rule, movements tend to be slightly lower as the structure is ballasted, since when the GBS is lowered the overall stability increases and the foundation platform is moved away from the action of the waves)

The different conditions assessed are:

- Load case 00: GBS inshore transport (without WTG and without TIM)
- Load case 01: offshore towed transport of the GBS and WTG
- Load cases 02-03-04: ballasting for installation

The hydrodynamic damping parameters have been calibrated in multiple tank testing campaigns performed by Esteyco during the development of the ELISA technology.

3.5. Task 2 Conclusions.

This section provided a description of simulations run for the assessment of the T&I process of the ELISA structure designed for conditions representative of East Coast of the US, with the IEA 15 MW turbine on top, performed by NREL. Refer to Task 3 for details on the foundation design.

Multiple parameters and results of the simulations in different control sections and components of the wind turbined have been monitored and assessed with positive results. The most relevant parameter in terms of representativeness of force levels experience by the WTG during the installation process is deemed to be the maximum horizontal and vertical accelerations experienced by the nacelle. Maximum values obtained are 0.6 m/s2 (0.02g) in the vertical direction and 1.9 m/s2 (0.15g) in any horizontal direction, well below the reference design thresholds described in previous sections (3 m/s2 for vertical acceleration and 4.5 m/s2 for horizontal acceleration).

While less relevant, maximum tilt is also a reference control parameter whose maximum value during ELISA T&I has been predicted to be 3.9 deg., again comfortably below the admissible threshold pre-established for design (5deg).

Also, the bending moments observed at the bottom of the concrete shaft (T0) and at the bottom of the steel tower during T&I remain comfortably below the design forces for the operational condition of the turbine, so T&I stages are not requiring any strengthening of the structure.

The report from NREL also provides comparison of these and several other control parameters obtained from the advanced simulations of ELISA T&I with reference values that the same wind turbine would experience when operating on top of a bottom-fixed monopile foundation or on top of a reference floating substructure, with positive results that further strengthen the conclusion that the conditions of the wind turbine during ELISA transport and installation are more benign than those that commercial wind turbines are designed to adequately bear by default.

4. Task 3 – Development of a conceptual design for the 15MW reference turbine and representative metocean conditions of the US East Coast.

The purpose of this task was to provide a basic design of the ELISA technology adjusted for the requirements of the IEA 15 MW turbine and for conditions representative of the US East Coast.

4.1. Reference location

For the design of the WTG and the foundation, a reference location has been stablished. This location is the New York Bight, the bight forms by the shore of New Jersey and Long Island (NY). This reference location has been selected in agreement between ESTEYCO and NREL as representative of future offshore developments, although naturally significant changes are to be expected along the east coast, with metocean conditions typically become more benign as in the more southern regions.

Figure 18. Reference location.

Reference location for the ELISA study

Deliverable 3.1

In terms of water depth, the ELISA technology can cover a wide range ranging from 20m to 65m. However, for the present exercise a mid-water depth of 35m has been considered as representative of averaged conditions in the East Coast, where the range of water depths for a majority of projects ranging between 25 and 55m, although some wind farms may lay outside this range.

4.2. Summary of metocean conditions

Following table provides an overview of the metocean conditions for this study.

Table 13. Overview of the metocean conditions.

Deliverable 3.1

Parameter	Return period (years)	
	50 (ULS)	500 (RLS)
Wind speed at 140 m, 10-minute average (m/s)	45.4	54.5
Mean wind speed (m/s)	9.8	
Significant wave height (m)	9.5	12.6
Individual wave height (m)	17.6	23.4
Associated wave period (s)	10.5 to 14.0	15.0 to 16.5
Current speed (cm/s)	130	170
Maximum water level over MSL (m)	3.9	5.0

It is important to remark that the East Coast of the US is a hurricane-prone zone, so a Robustness analysis is required, following the recommendations form IEC 61400-3-1 Ed. 2019 Annex I. for RLS (Robustness Limit State) the extreme hurricane conditions corresponding to a return period of 500 years are considered.

4.3. Turbine characteristics

The turbine chosen for this project is the on developed by NREL for the IEA. It has 15 MW of nominal power output and a rotor diameter of 240 m.

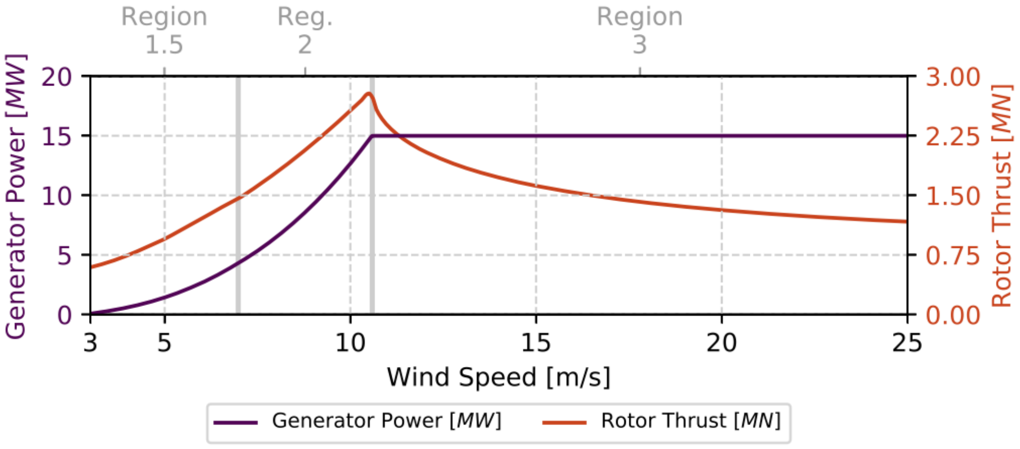
Table 14. Turbine main parameters.

Deliverable 2.1

Parameter	Value
Output power	15 MW
Rotor diameter	240 m
Hub diameter	7.94 m
Hub height above MSL	144.0 m
Nacelle mass including rotor *	950.1 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

Figure 19. Thrust and power curve

Deliverable 3.1



4.4. Possible GBS configurations

The ELISA GBS foundation can be designed with different configurations regarding:

- Use of water ballast only or use of additional solid (sand or proprietary slurry) ballast to provide the required foundation weight in installed condition.
- Use of flat foundation bottom or use of short skirts at the soil interface

These design alternatives may have a significant influence in the sizing of the foundation and the resulting bill of quantities.

The reference configuration has been selected as the one leading to the largest and heaviest foundation design, which is a foundation ballasted only with water and with no skirts. This configuration has been considered as base case on the safe side being the one more restrictive and demanding regarding the construction and installation process, thus acting as an envelope to alternative configurations leading to smaller and lighter configurations of the concrete structure.

In many cases the use of solid ballast within the foundation and/or the use of short skirts may be preferred and lead to significant reductions in foundation size and concrete weight. While the present project cannot cover in detail every configuration, the project also takes into account a second alternative with a reduced foundation diameter and the use of sand ballast (see Task 8).

4.5. Substructure geometry and characteristics

For the present Task, and as the reference configuration, the GBF has been sized for the scenario in which the base is exclusively ballasted with water and uses no skirts.

The substructure is built with structural concrete and steel. Concrete is used in the parts in contact with seawater since it is a more robust material for the aggressive offshore environment, making it possible to reduce the maintenance requirements.

Figure 20. General Dimensions of ELISA

Deliverable 6.1

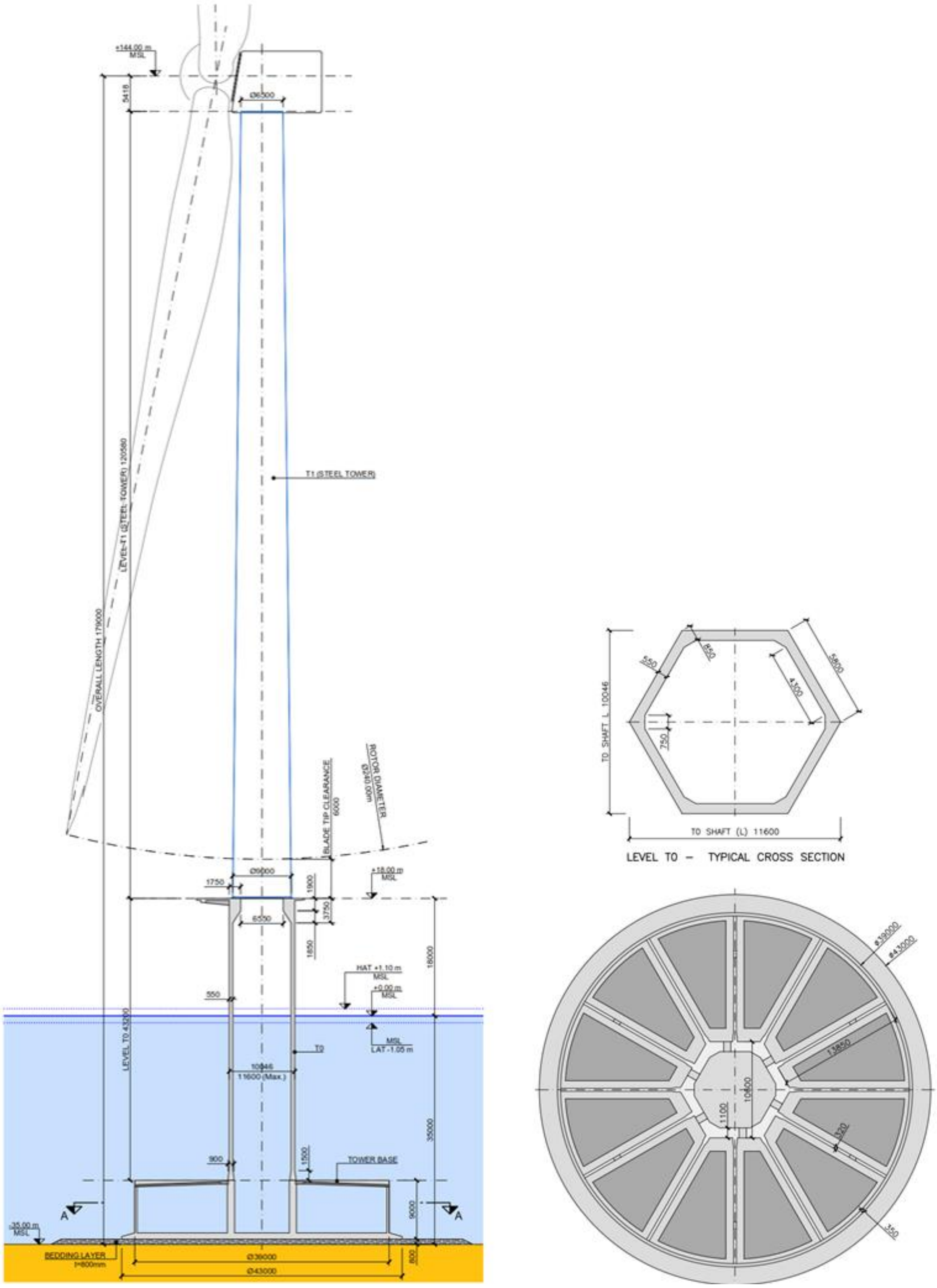
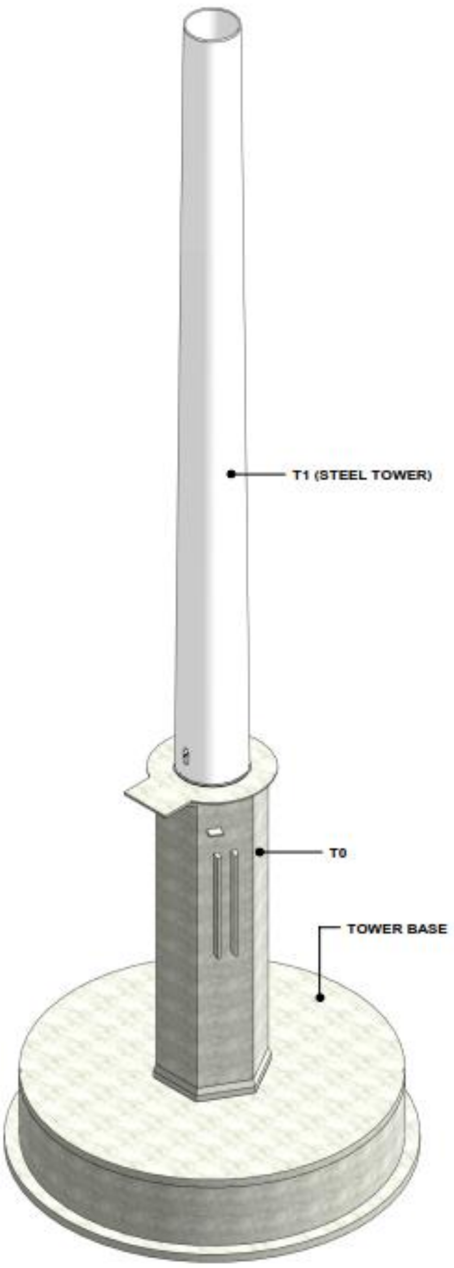


Figure 21. Substructure.

3D view of the substructure

Deliverable 2.1



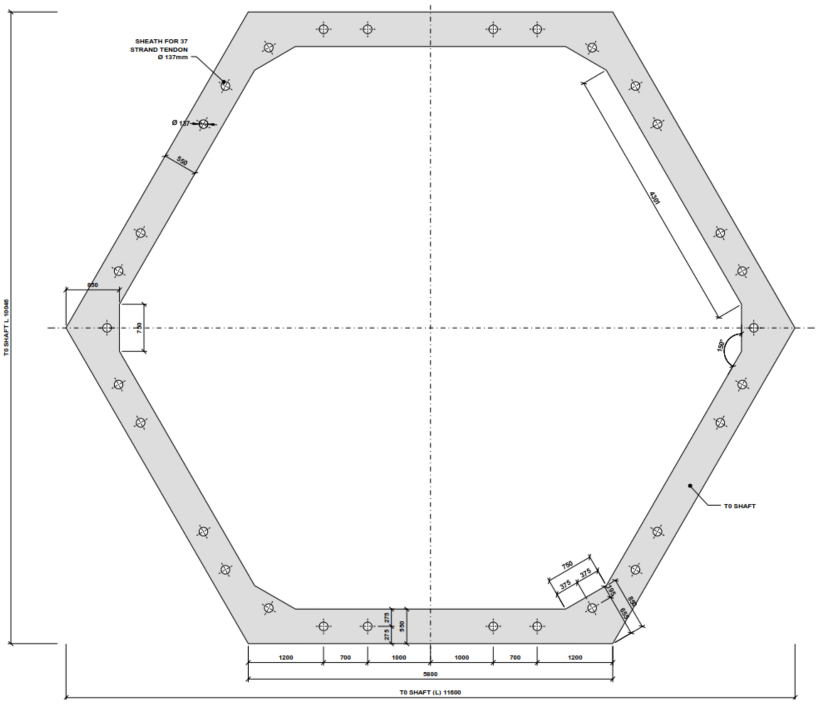
The concrete tower (called T0) consists of a concrete tubular shaft connecting the base and the steel tower, at the level of the external working platform. The height of the external access platform at the top of the concrete tower has been located at 18 m above MSL, which has been considered enough to remain above the maximum wave crest.

It has a hexagonal cross section, slightly chamfered on the inside (Figure 22). Such hexagonal cross section provides high capacity and robustness for the self-installation process of the ELISA GBS foundation, for which the tower is effectively coupled to the TIM platform (see Figure 2).

Figure 22. Concrete tower shaft (T0)

Typical cross section of the concrete tower shaft (T0)

Deliverable 3.1



The T0 cross section consists in a hollow hexagonal section with a side of 5.80 m and a wall thickness of 55 cm, which is increased to 90 cm at the connection with the base. This leads to a minimum tower dimension of 10.05m (between opposite hexagon sides) and a maximum tower dimension of 11.60m (between opposite hexagon corners).

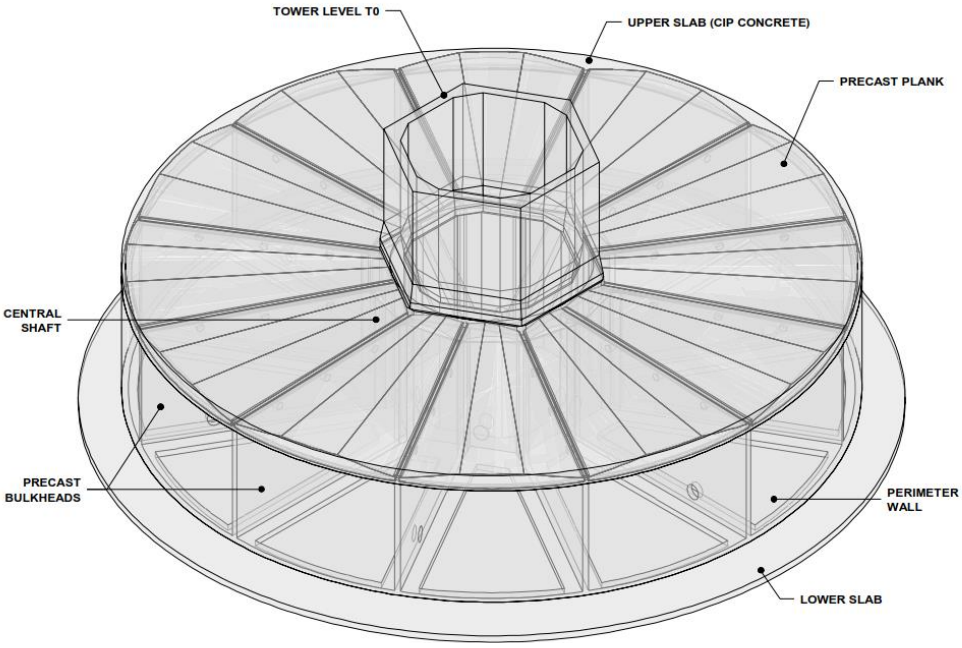
Prestressing is provided to maintain the tower shaft and its connection to the foundation base compressed under relevant loading conditions. The post-tensioning cables run all the way from the top of the T0 tower section to the lower end. The cables from the T0 segment are continued to the base central shaft, up to approximately 2 m from the base lower slab, thus crossing the connection between tower and base. A total of 24 37-strands (Ø15.7, 150mm2) tendons are defined. The prestressing force per strand is 195 kN (70% of the ultimate stress), which correspond to a total initial force of 173156 kN. Losses are calculated to be 18%, so the long-term prestressing force is 141988 kN.

The base of the WTG is the lower disc-shaped structure of the platform with simple geometry. The base plays a double function: in installed condition it provides a wide base with sufficient weight and diameter to adequately spread the acting loads on the soil. Moreover, in temporary conditions along the construction and installation process, the base will act as buoyant platform, allowing for the self-installation crane-free installation process of the GBS and WTG assembly.

Figure 23. Base.

3D view of the base (designed to use water ballast only, without need for solid ballast)

Deliverable 2.1



The base comprises the following main elements:

- Lower slab: 43 m diameter disc with maximum thickness of 0.95m below the central shaft, bulkheads, and perimeter wall, and with a minimum thickness of 0.60m.
- Bulkheads: a total of 12 units which divide the foundation into 12 different cells. Cells are used as tanks for controlled ballasting during the installation process and are later completely flooded during the in-service phases. The bulkheads behave as shear walls, with a constant thickness of 0.32m
- Central shaft: it generates a central cell which is the continuation of the concrete tower (T0) hexagonal section until the lower slab. The inner space of the central shaft will be used as a dry room for the ballasting system during the installation process. Once the installation is complete, this central compartment will also be flooded (including the submerged part of the T0). It has a constant thickness of 1.1m allowing for high robustness in the critical connection area with the concrete tower shaft.
- Perimeter wall: it has a circumferential shape with the diameter of the upper slab (39m) and a constant thickness of 0.35 m.
- Upper slab: it consists of precast planks, which have the shape of each cell in plan view, and a cast-in-place (CIP) concrete part, poured on top of them. Precast planks make it possible to build the upper slab with no need for formworks or scaffolding and do contribute to the final structural capacity of the upper slab. The upper slab is vault-shaped on the interior side, with a constant minimum thickness of 0.35m at the center of the cells, and a varying maximum thickness between 0.60m and 1.00m from the central shaft towards the perimeter wall.

Please note that the base case is the simplest configuration and bigger base footprint of 43m of diameter. However, in many cases the use of solid ballast within the foundation and/or the use of short skirts may be preferred and lead to significant reductions in foundation size and concrete weight. The option with reduced diameter by means of the use of sand ballast is developed in Task 8.

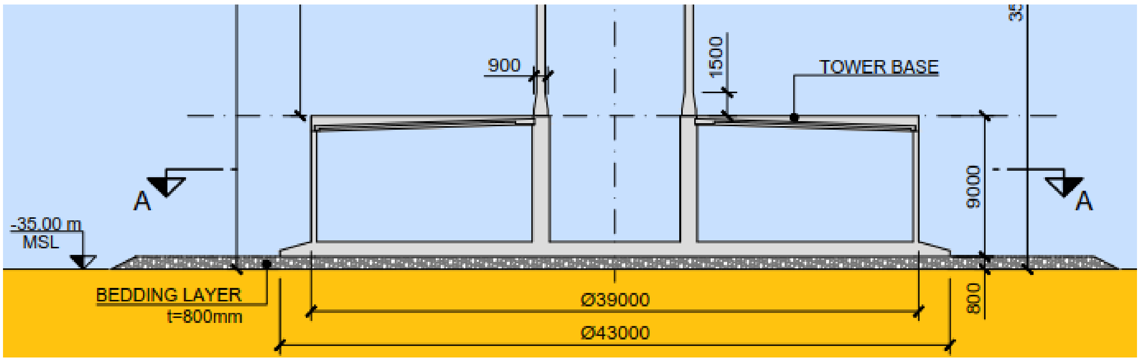
The seabed that will receive the gravity foundation has to be prepared accordingly. Typical preparation is a to install a rock bedding layer with a diameter of 60m and a thickness of 0.8m. This layer ensures proper seabed-GBS contact and also serves as anti-scour protection (see further details in section 4.9.4)

Note that in many cases in which the natural seabed has sufficient horizontality and flatness, the seabed preparation may not be strictly required. As reference, ELISA's pilot unit (see Figure 1) was installed directly on the natural seabed and has been performing adequately for more than 5 years. Nevertheless, without detailed geotechnical and bathymetrical information the assumption made along the present project was to use a prior seabed preparation to receive the ELISA foudnations.

Figure 24. Seabed

Typical seabed detail

Deliverable 4.1



4.6. Material characteristics

The following table shows the characteristics of the main materials used in the structure.

Table 15. Material characteristics.

Deliverable 3.1

Parameter	Concrete	Reinforcement Steel	Post-tensioning Steel
Weight (kN/m^3)	25	78.5	78.5
Characteristic strength (MPa)	70 (T0) 48 (base)	355	1860
Elastic Modulus (MPa)	40743	210000	200000
Shear Modulus (MPa)	15715	81000	-

4.7. Design loads

The reference documents for the load calculation are DNV-ST-0126 and DNV-ST-0437.

Table 16. Load safety factors.

DNV-ST-0437

Functional and environmental loads					Permanent loads*		
ULS		FLS	ALS	SLS	ULS		FLS, ALS, SLS
Normal	Abnormal				Favourable	Unfavourable	
N 1,35***	A 1,1	F 1,0	F 1,0	F 1,0	0,9**	1,1**	1,0

* Permanent loads include dead loads and pretension loads for the support structure design.

For submerged sub-structures, for example a GBS placed on the seabed, the Permanent load is the total weight minus the buoyancy determined at the still water level

** Factors for permanent loads in ULS may be taken as 1,0 if appropriate measures are taken.

*** For DLC 1.1 the partial load factor shall be $\gamma_F = 1{,}25$; for DLC 2.5 the partial load factor shall be $\gamma_F = 1{,}2$

The following formulation according to IEC 61400-1, Table 3 may be applied:

If for normal design situations the characteristic value of the load response $F_{gravity}$ due to gravity may be calculated for the design situation in question, and gravity is an unfavourable load, the partial load factor for combined loading from gravity and other sources may have the value

$$\gamma_f = 1{,}1 + \varphi\varsigma^2 \text{ and } \varphi = \begin{cases} 0{,}15 \text{ for DLC } 1.1 \\ 0{,}25 \text{ otherwise} \end{cases}$$

$$\zeta = \begin{cases} 1 - \left|\frac{F_{gravity}}{F_k}\right| ; & |F_{gravity}| \leq |F_k| \\ 0; & |F_{gravity}| > |F_k| \end{cases}$$

where F_k = characteristic value for loads

4.7.1. WTG Wind loads

Refer to NREL/TP-5000-75698 (chapter 6) for details on the publicly available WTG model considered. The loads considered in the design are based on a reference wind speed of 50 m/s (Vref). Due consideration has been made of the specific dynamic system response and out-of-vertical allowances.

4.7.2. Wave loads

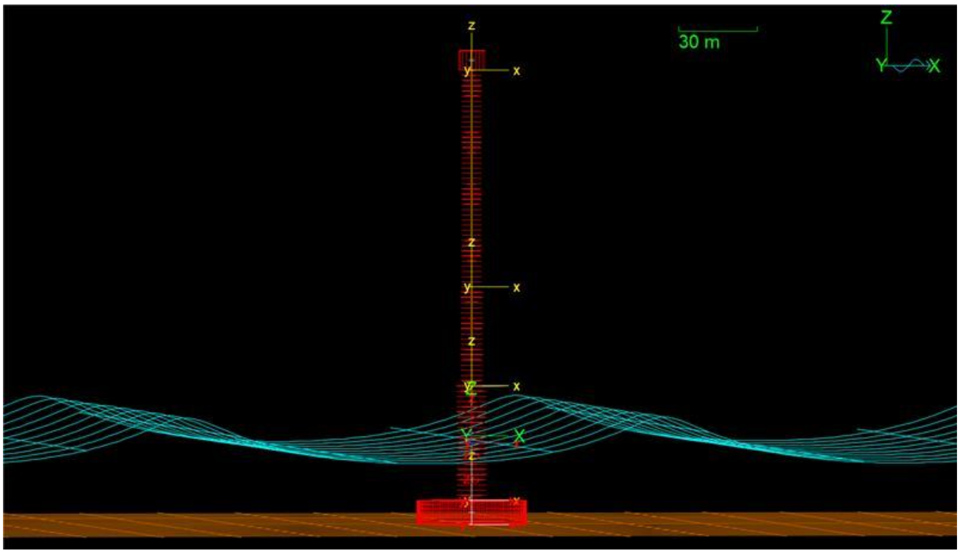
For the conditions at the selected location, Stream Function theory has been considered the most suitable for analyzing the maximum waves loads, capturing their non-linear behavior, in accordance with DNV-RP-C205. For calculating the load effects of maximum waves, a dynamic model has been built with software package ORCAFLEX which accurately reproduces the expected dynamic properties of the system.

The ORCAFLEX model consist of two parts: the base modelled with boundary elements (BEM), and the concrete tower simulated as a slender tube element to which the Morison equation is applied. The range of application of Morison equations is normally accepted for wave lengths greater than 5 times the diameter of the structure, which the tower fulfils for all the sea states in the DLC's.

Figure 25. Orcaflex model.

View of the Orcaflex model for hydrodynamic loading calculation

Deliverable 3.1



In such a massive element as the base, maximum wave forces are driven by inertia forces (see DNVGL-RP-C205, Fig. 7-1), with drag forces being very low in comparison to inertia forces and happening mostly in instants of maximum particle velocity which are different than the instants of maximum particle acceleration which drive the maximum design forces at the base. That is why the BEM method which computes inertia forces has been considered as suitable for the analysis of wave loading at the base.

The loads have been obtained with the metocean conditions described in previous sections.

Regarding to obtain maximum wave loads, the following aspects or assumptions are noteworthy:

- The model adequately captures structure dynamics.
- A 3% damping ratio relative to critical damping has been considered for the GBS structure in accordance with DNV-ST-C502].
- Maximum wave loads have been obtained for two different wave periods per case: Tmax,low and Tmax,high, as indicated in section 4.2. It is observed that as a rule, and as expected, maximum design forces are generated by the Lowest Period Waves.
- An increase of 150 mm in the tower diameter due to marine growth has been assumed for computing maximum wave forces. A surface roughness of 0.01 meters has been considered, which is a mean value within the range recommended by DNV for members covered in marine growth.
- The obtention of wave loads have considered the concurrent action of maximum current.
- A separation between the GBS lower slab and the seabed has been modelled so that complete under pressure effects are computed on the safe side.

The ELISA GBS is configured as a slender tower element, which aims to maximize transparency to wave loading near the sea surface, where wave energy is concentrated, and a horizontal foundation base. An aspect that is characteristic of such configuration, which differs from more typical cone-shaped GBS geometries, is the effect of wave forces on the upper slab of the foundation base, which will obviously influence the maximum Design Loads at the Mudline. These pressures on the Base horizontal slabs will tend to generate favorable variations in both bending moments and vertical loads. Specifically:

- When the maximum bending moment on the tower-base connection happens, wave pressures acting on the GBS horizontal slab generate a bending moment in opposite direction that partly counteracts the larger bending moment being transmitted by the tower, which contributes to reducing the maximum bending moment at the mudline.
- When the maximum bending moment and horizontal force at the mudline happen, wave pressures acting on the GBS horizontal slab generate an increase of vertical forces acting on the seabed which is positive for the GBS. Conservatively this effect has not been taken into account, i.e. no favorable variation of the vertical force due to wave action has been considered, although it is to be expected.
- In the instant in which wave pressures on the base horizontal slabs lead to a limited reduction of the vertical load acting on the seabed, the concurrent horizontal and bending moment forces are minimum, so this situation does not govern the design and performance of the GBS.

4.7.3. Governing loads used for Design

Design Load Calculation has been based on IEC 61400-3-1. The more governing load conditions can be summarized in the following reference ULS cases for basic GBS design:

- Maximum forces for DLCs in NSS (normal sea states): these are governed by maximum wind forces generated by the operating turbine (DLC 1.4). The contribution of wave loading is minor and will shift direction being favorable half of the time (approx..) and unfavorable the other half, which average contribution in the proximity of zero.
- Maximum forces for DLCs in ESS (extreme sea states): In this DLCs (DLC 6.1 and I.1 in this case) maximum wave load may be driving the maximum loading instant for the lower parts of the foundation (tower-platform interface and mudline) while maximum design loads in the upper part of the concrete shaft will be largely governed by wind loads. The maximum design loads considered are consistent with the constrained wave method and do take into account the non-linear effects of the maximum waves.

For SLS cases, the following cases are computed:

- Characteristic Combination of Loads (CCL) corresponds to those DLCs which are considered “Normal” by DNV-ST-0437, with unfactored loads.
- LDD 10-4 combination corresponds to load levels which will not be exceeded 99.99% of the time. These are essentially driven and turbine wind loads.
- LDD 10-2 combination corresponds to load levels which will not be exceeded 99% of the time. These are also essentially driven and turbine wind loads.

4.8. Design philosophy

The following sections define the main acceptance criteria for the design of the GBS.

4.8.1. SLS acceptance criteria and verification

4.8.1.1. Decompression limit for T0 sections

Prestressing of the tower T0 will be such that all sections will remain compressed under relevant operation service loads LDD10^{-4}. This criterion will be checked with the minimum long-term prestressing force.

4.8.1.2. Crack width control for base sections

According to DNVGL-ST-0126 [5.8.5] and DNVGL-ST-C502 [Table 6-10], a maximum crack width of 0.4 mm under LDD10^{-4} loads (99.99% probability of non-exceedance) is allowed for base sections (exposure class XS2) to prevent durability issues during the structure lifetime.

The crack width calculation will be based on DNVGL-ST-C502 [6.15.8].

4.8.1.3. Stress limitation for concrete/grout

The concrete compressive stresses for the characteristic extreme load (maximum CCL) shall be limited to 0.6 f_{cck} as per DNVGL-ST-0126 5.8.4.1.

The concrete compressive stresses under permanent loads (self-weight and prestressing) shall be limited to 0.45 f_{cck} as per DNVGL-ST-0126 5.8.4.2. This criterion will be checked with the maximum short-term prestressing force.

4.8.1.4. Stress limitation in passive reinforcement

The tensile stresses in passive reinforcement for the characteristic extreme load (maximum CCL) shall be limited to 0.9 f_{yk} as per DNVGL-ST-0126 5.8.4.3. This criterion will be checked with the minimum long-term prestressing force.

4.8.2. ULS/ALS/RLS acceptance criteria

4.8.2.1. Bearing strength under combined global forces (bending, shear, torsion) and local forces

DNVGL-ST-C502 establishes that under relevant ULS/ALS/RLS design load cases, strains in any point of the structure generated by the combined effect of global forces acting on the tower section (bending, shear, torsion) and local forces acting on the tower shall remain below applicable thresholds.

Specifically, maximum strains to be considered are:

- Maximum strain in the concrete shall remain below □cu as per DNVGL-ST-C502 6.3.2.1, where:
  - $e_{cu} = -3.5 \cdot 10^{-3}$ (for $f_{cck} < 50$ MPa)
  - $e_{cu} = -(2.6+35 \cdot (90-f_{cck}/100)^4)\ 10^{-3}$ (for $f_{cck} > 50$ MPa); (For f_{cck}=70 MPa, $e_{cu} = -2.66 \cdot 10^{-3}$)

- Maximum strain in passive reinforcement shall remain below $e_{su}=10\cdot10^{-3}$ as per DNVGL-ST-C502 6.3.4.3. For prestressing steel, the initial prestressing strain can be added to such limit.

4.8.2.2. Adequate local shear reinforcement (perpendicular to the wall/slab plane)

Local shear reinforcement (perpendicular to the wall/slab plane) will be provided where needed as per DNVGL-ST-C502 [6.6].

- The effect of concomitant axial forces and local bending in the transverse shear strength shall be considered as per DNVGL-ST-C502 [6.6.2.3] (for axial compression) and DNVGL-ST-C502 [6.6.2.4] (for axial tension).
- The required local shear reinforcement, if any, shall be determined as per DNVGL-ST-C502 [6.6.2.6 or 6.6.3.6]. It must be determined in the governing direction which may differ from horizontal or vertical (see DNVGL-ST-C502 [6.6.1.7]).
- The local shear reinforcement provided will be hooked to the in-plane reinforcement layers. They should be hooked to the outer rebars which resist local bending in the direction in which local transverse shear is larger.
- The effect of transverse shear to in-plane vertical/horizontal reinforcement, as per DNVGL-ST-C502 [6.6.4], should be accounted for.

4.8.2.3. Concrete compressive strength under local transverse shear

The capacity of concrete compressive struts to transfer local transverse shear shall be verified in accordance with DNVGL-ST-C502 [6.6].

- The capacity at compression failure due to out-of-plane shear forces shall be verified as per DNVGL-ST-C502 [6.6.2.7 or 6.6.3.8].
- Additionally, as per DNVGL-ST-C502 [6.6.1.9], the compression failure capacity shall never be larger than the shear force, which combined with other load effects, results in a principal compression equal to f_{cd}.

4.9. Geotechnical verification

4.9.1. Soil bearing capacity

In the present study, in the absent of a refine non-linear finite element analysis, which would be carried out in an actual detail design, the foundation bearing capacity checks have been carried out by the conventional bearing capacity expressions (Brinch-Hansen), thereby verifying equilibrium between design loads and capacity. This analytical verification method is on the safe side and optimized results are to be expected in detailed engineering stages when advanced FEM methods are used.

The safety factors with respect to bearing capacity for factored loads combinations for the designed GBS are checked, using the classic formulations based on the resistant ground parameters and the theory of the plasticity against failure, according to Brinch-Hansen equation. In particular, the verifications are carried out as per LRFD method, using the equations adopted by DNVGL-RP-C212 and Eurocode 7 (approach 2).

To verify the bearing capacity according to LRFD method, the following condition shall be complied: $E_d \leq R_d$.

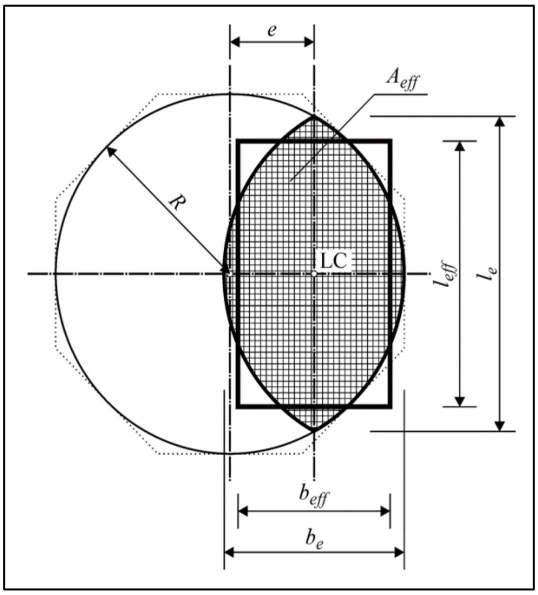
Where design resistance must be higher than factorized loads acting on the foundation.

In addition, and just for comparison, the traditional verification using ASD method, as per API formulation is also carried out.

Soil bearing pressures are calculated analytically with unfactored (ASD method) and factored design loads (LRFD method) over the effective foundation area, A_{eff}, centred at the point of the resultant placed at the eccentricity $e = M_d/F_{z,d}$ from the centre.

Figure 26. Effective foundation area.

Deliverable 3.1



4.9.2. Sliding

The safety against sliding is verified taking into account the factored horizontal shear force and the torsional moment at the foundation base.

According to the DNVGL, Hd depends on the shear force at the base of the foundation ($F_{xy,d}$) and is corrected based on the torsional moment $M_{z,d}$ transmitted by the tower. Then, the force Hd, is calculated according to the following expression:

$$Hd = \frac{2 \cdot M_{z,d}}{l_{eff}} + \sqrt{{F_{xy,d}}^2 + \left(\frac{2 \cdot M_{z,d}}{l_{eff}}\right)^2}$$

In this study, for the sake of simpliciy, the corresponding $M_{z,d}$ with the maximum $F_{xy,d}$ has been assumed as neglectable.

For drained granular soil, the stabilizing force is the factored vertical load multiplied by the friction coefficient at the soil-foundation interface and the cohesion by the effective area. Thus, in drained conditions, the following condition must be considered:

$$H_d < r \cdot (A_{eff} \cdot c_d + V_d \cdot \tan\phi_d)$$

Where:

- H_d is the equivalent design horizontal force at the foundation base (factored)
- V_d is the design vertical force at the foundation base (factored)
- $\tan\Phi_d$ is the design friction dependent on the angle of internal soil friction
- c_d is the design soil cohesion
- A_{eff} is the effective foundation area
- r is the roughness between soil and foundation

For cohesive soils the verification needs to fulfill the next equation:

$$H_d < A_{eff} \cdot r \cdot s_{ud}$$

Where:

- H_d is the equivalent design horizontal force at the foundation base (factored)
- s_{ud} is the design undrained shear strength
- A_{eff} is the effective foundation area
- r is the roughness between soil and foundation

Interface roughness between soil and foundation has been assumed with r=1.0 since it is expected that the base-slab will be cast directly on a sufficient coarse aggregate bed or on a special formwork.

Sliding can be a governing verification for the design of the base diameter and effective weight. The use of additional ballast weight or skirts can be effective for improvement in this regard, but these potential improvements have not been considered in the verifications performed for the present design and application.

4.9.3. Assumed geotechnical conditions

Soil capacity verifications as described in the previous sections have been performed for two different reference soil profiles which have been defined as representative of expectable conditions, although naturally more favorable or unfavorable soil conditions may be found.

Table 17. Soil profiles

Deliverable 3.1

Soil profile 1	Soil profile 2
A typical uniform medium-dense granular soil has been assumed with the following properties: ○ Effective angle of friction φ′=35º ○ Cohesion is neglected on the safe side (c=0.0 MPa) ○ Unit submerged weight of soil γ' =9.0 kN/m^3 The material factor for effective stress analysis has been assumed as γ_m= 1.15.	A reference cohesive soil profile with a stiff clay in the upper layers has been assumed with the next properties: ○ Effective angle of friction φ′= 0º ○ Undrained shear strength su= 135 kPa ○ Unit submerged weight of soil γ' =10.0 kN/m3 The material factor for total stress analysis has been assumed as γ_m= 1.25. It is noted that the required strength for cohesive soil layers can be significantly lower when they are located at a certain depth and/or have limited thickness.

It is noted that in the geotechnical verifications performed and described in previous sections, no improvement or positive influence of the bedding layer has been considered on the safe side.

4.9.4. Seabed preparation and scour protection

ELISA can be suitable and designed for a wide range of soil conditions, from relatively soft to rocky seabeds. In particular ELISA provides a robust solution for projects where presence of rock or boulders makes piling too risky or unfeasible.

Seabed preparation shall be needed or not depending on site conditions. By way of example ELISA's operative pilot built in the Canary Islands (Spain) did not require any seabed preparation. Many projects have similar favorable soil conditions and will not require seabed preparation.

There may be basically three reasons for seabed preparation prior to GBS installation:

- Soil horizontality / flatness: ELISA allows for verticality correction to compensate natural inclinations on the seabed, but natural soil inclinations larger than 0.75deg will typically demand seabed preparation.
- Soil capacity / deformation: ELISA's increased foundation diameter is as a rule more effective in reducing demand on the natural soil than most seabed preparations.
- Surfacing rock on seabed: This will require seabed preparation to provide a regular bedding layer to support the GBS without hard points.

In the present project, and on the safe side, a seabed preparation shall be considered for constructability and costing analysis, maintaining the possibility that such preparation may not be required as a potential value improvement dependent on specific project conditions.

Cases in which soil capacity is very poor, soil dredging, substitution or improvement techniques can be applied, covering also risk of liquefaction.

As a rule, scour protection systems shall be required in all cases, to be selected and sized depending on site conditions and project casuistry. Flat geometry of the ELISA base platform reduces scour protection requirements as compared to vertical structures, since a major part of water flow is deviated above the base rather than accelerated around it. Different scour protection systems can be applied, from conventional pre-installed or post-installed rock armor solutions to systems which can be installed together with the foundation and deliver significant cost reduction. Esteyco has performed multiple tank testing campaigns to evaluate the performance and contrast the design criteria for multiple systems.

4.9.5. Rotational stiffness verification

The wind tower foundation and the soil must provide enough rotational stiffness to avoid an excessive reduction of the natural frequency of the tower, which would have detrimental effects on the dynamic behavior of the structure and in the end, could generate dynamic resonance amplification if the first natural frequency descends and coincide with the vibration frequency of the rotor (1P). In addition, the 3P blade phasing needs to be above the first natural tower frequency.

According to the turbine characteristics listed in previous sections, the rotor and blade phasing frequencies are (with a safety margin of 10%):

for 1Pmax	(7.56*1.1)/60	f_{min} = 0.139 Hz
for 3Pmin	3x(5*0.9)/60	f_{max} = 0.225 Hz

According to structural design the natural frequencies of the tower are the following:

Table 18. Natural frequencies of the GBS

Deliverable 3.1

	$k_{soil + base}$ (kNm/rad)	1st	2nd
STIFF SOIL	∞	**0.220**	**1.519**
FLEXIBLE SOIL	6.00E+08	**0.215**	**1.416**

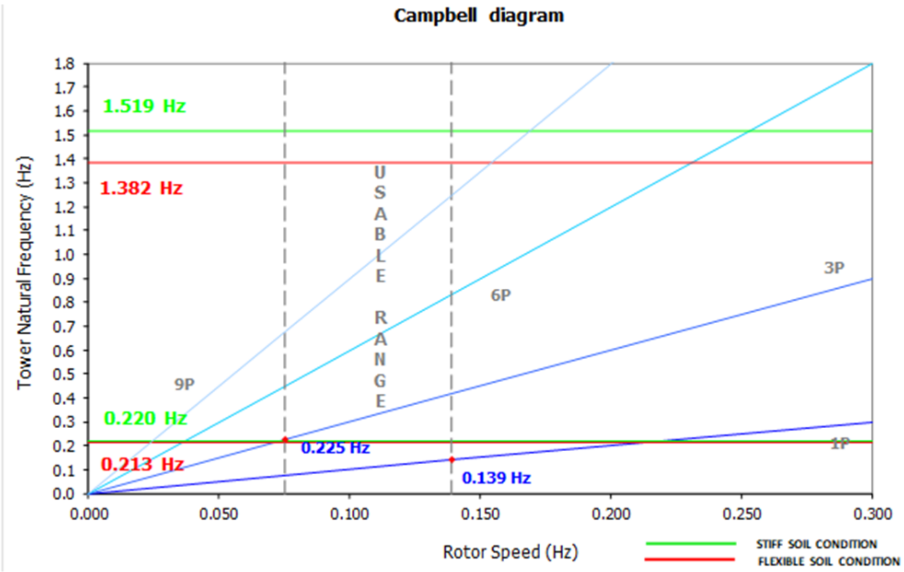
Note that in the table above, the value of $k_{soil+base}$ is shown only for reference. The lower figures correspond to an assumed soil of K_{soil}= 1000 GNm/rad combined in series with a k_{base}=1500 GNm/rad in order to compute also the flexibility of the base.

Note that the tower natural period remains below 5s, thus sufficiently apart from the peak periods of larger waves which are as a rule considerably higher.

With the above data, the typical Campbell diagram can be constructed:

Figure 27. Campbell diagram.

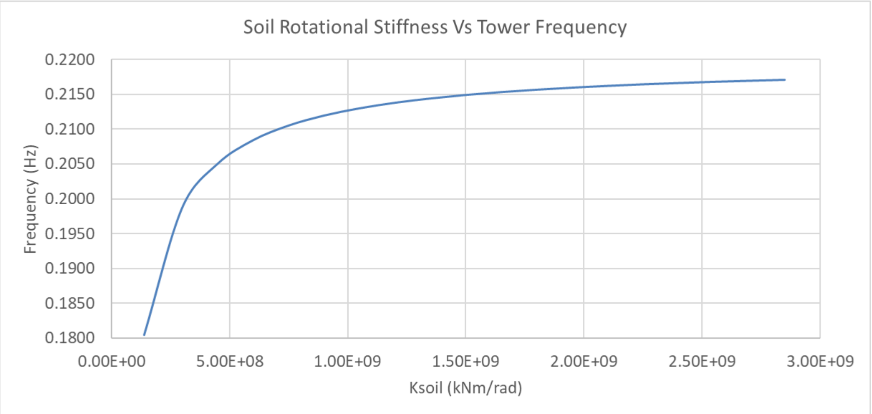
Deliverable 3.1



In the next figure, the soil rotation stiffness Vs tower first frequency diagram is plot. It can be seen that the 3P frequency (0,225 Hz) is always above the maximum first frequency of the tower (0,220 Hz), and that for a flexible soil the 1P frequency (0,139 Hz) is always below.

Figure 28. Soil rotation stiffness vs tower 1st frequency.

Deliverable 3.1



However, in this case a minimum rocking stiffness of soil of 1500 GNm/rad has been set out in order to limit the first natural frequency reduction of the tower in the case of an unexpected event (area of the curve with approximately zero slope).

From this value, using an assumed Poisson ratio of 0.35 and a value G/G_0= 0,5, it follows that, for the proposed spread foundation of 43.0 m of diameter.

The equivalent initial shear modulus G_0 of the ground below foundation should be greater than 76.0 MPa. In terms of shear wave velocity (Vs) this value should be greater than 200 m/s for soil. These low values of G_0 or V_s leads to the conclusion that the rotational stiffness verification will as rule not be an issue or governing factor in the design of the ELISA foundation.

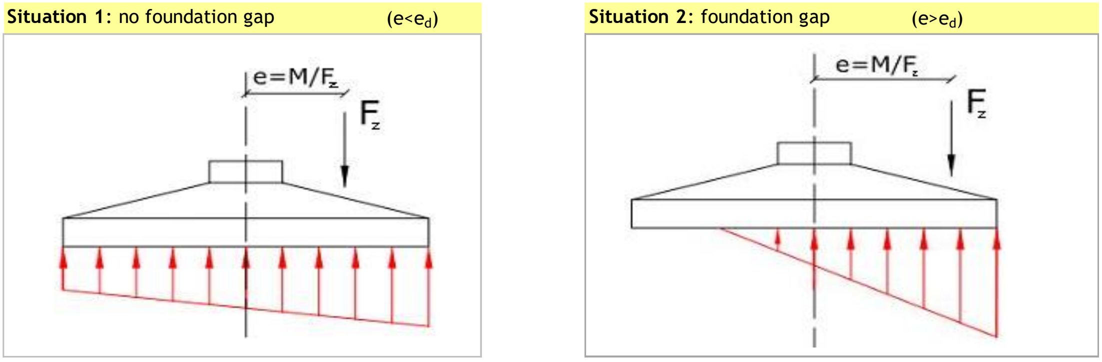
4.9.6. Gapping at foundation-soil interface

It must be ensured that no gapping occurs between the foundation and the soil for LDD 10^{-2} (loads which are not exceeded 99% of the time). This is verified if the eccentricity $e=M/F_z$ is less than the limit eccentricity $e=W/A$, being for a circular shape $e= D/8$.

Figure 29. Foundation bottom

Eccentricity of the resultant force on the foundation bottom and the consequent pressure distribution on the ground

Deliverable 3.1



Furthermore, it needs also to be checked that, under the characteristic load combination, at least half the foundation base area remains in contact with the ground. This is ensured with a maximum eccentricity $e= 3\pi D/32$.

In the present design, these verifications are met comfortably.

4.10. Structural verification

4.10.1. Verification of the concrete shaft

The verification is done following considerations:

- The forces along the tower behave as in a simple cantilever:
  - Forces from the turbine are applied at the top of the concrete tower to obtain the same loads as the ones included in NREL/TP-5000-75698 at the control section.
  - Wave loads at the submerged part of the tower are obtained from the hydrodynamic models described in section 4.7.2.
  - Loads are added following the criteria defined in section 4.7.3.
  - Prestressing forces are computed as described in section 4.8 and added to the remaining loads.
  - Self-weight is computed based on structural dimensions and considering the WTG weights defined in NREL/TP-5000-75698.
- Stress verifications at the concrete, passive and active reinforcement are carried out with conventional formulations using the homogenized section.
- ULS verifications at each section are carried out with conventional formulations, following the prescriptions of the DNVGL-ST C502.

4.10.1.1. SLS verifications

Decompression limit: As previously described, prestressing of the concrete tower is defined so that all sections remain compressed under operation loads LDD10^{-4}, (loads with a 99.99% probability of non-exceedance as defined by DNVGL-ST-0437). This criterion has been checked with the minimum long-term prestressing force.

Stress limitation: As previously described, it is checked that the concrete compressive stresses for the characteristic extreme load shall be limited to 0.6 f_{cck} as per DNVGL-ST-0126 5.8.4.1. This criterion is be checked with the maximum short-term prestressing force.

The concrete compressive stresses under permanent loads (self-weight and prestressing) are limited to 0.45 f_{cck} as per DNVGL-ST-0126 5.8.4.2. This criterion is checked with the maximum short-term prestressing force.

As previously described tensile stresses in the vertical passive reinforcement for the characteristic extreme load are limited to 0.9 f_{yk} as per DNVGL-ST-0126 [5.8.4.3]. This criterion is checked with the minimum long-term prestressing force.

4.10.1.2. ULS/RLS verification

Next figure shows vertical steel reinforcement required vs provided at ULS and RLS for the different load cases analyzed to comply with the acceptance criteria in section 4.8.

4.11. Bill of quantities

Estimated bill of quantities for the reference design described in previous sections have been estimated as given in the following table. These values are approximate:

Table 19. Bill of quantities

Bill of quantities for the reference envelope GBS configuration (water ballast only and flat soil interface)

Deliverable 3.1

Bill of Quantities for the Envelope GBS configuration		
Concrete Volume T0 (fck=10ksi)	908	m3
Concrete Volume Base (fck=7ksi)	2670	m3
Passive Steel reinforcement T0 (Gr. 75 ksi)	163	Tn
Passive Steel reinforcement Base (Gr. 75 ksi)	411	Tn
Prestressing steel (Gr 270 ksi - 0.62" Low relaxation)	55	Tn
Prestressing bars for Connection to steel tower (Gr. 150 ksi)	10	Tn

It is noted that the above Bill of Quantities corresponds to a scenario in which only water ballast is used in the GBS and a flat soil interface is used, which leads to the larger foundation size and material usage. This has been the envelope case considered as reference on the safe side for analysis of install-ability and constructability of the foundation in the USA market and based on

US infrastructure and supply chain.

However, the project includes in Task 8 a comparison of dimensions and BoQ in the case of GBF with sand ballast. Please also note that an update of BoQ for the reference GBF (without sand ballast) is also available in Task 8.

4.12. Task 3 Conclusions

This task provides a thorough description of the ELISA structure for reference conditions selected as representative of the East Coast of the US, with the IEA 15 MW turbine on top, including geometry, design philosophy and main structural and geotechnical verifications. It has been described how the reference design complies with the requirements from DNV standards as the most common and renowned reference in the offshore wind market.

The resulting design has a draft of ca.5m for float-off of the construction base, and ca.8m upon completion of the concrete shaft and installation of the steel tower and WTG, therefore ensuring compatibility with virtually any major harbor infrastructure or navigation channel.

The ELISA GBS technology can be designed with different configurations regarding ballast material (water or solid/sand) or geometry of the soil interface (flat or skirted). The reference configuration for this project has been selected as the one using only water ballast with flat geometry at the soil interface, being the one leading to the larger and heaviest concrete structure, thus serving as an envelope to other configurations in terms of constructability and installability. A sensitivity analysis on how the foundation size and weight would be reduced in case of using solid ballast has been performed in Task 9.

5. Task 4 – Evaluation of the cost and logistics of fabricating and installing projects using the ELISA technology.

The purpose of this task was to provide a summary of the material, manufacturing, and workforce requirements of the gravity-based units and a comparison of representative project LCOE and fabrication/installation logistics against the representative project using conventional monopile solutions.

The analysis has been primarily performed using NREL's Offshore Renewables Balance-of-system and Installation Tool (ORBIT) cost model.

The analysis is based on ELISA technology and adjusted for the requirements of the IEA 15 MW turbine and for conditions representative of the East Coast of the United States.

The costs and installation logistics has been modeled for a representative project requiring serial production of 50 units.

Please note that the cost estimates developed during this task were completed and updated in Task 9. Thus, please refer to Task 9 for cost estimates.

5.1. Fabrication and installation procedures

Task 4 included an analysis and description of the construction and installation process of the ELISA foundation. Applicability of these to different scenarios, with detailed analysis of implementation solutions in different harbors and production rates were analyzed in Task 8. Please refer to section 9.2 for further details

The ELISA technology allows the installation of the wind turbine on the GBS at harbor.

Once the turbine has been assembled onto the GBS, an auxiliary floater (TIM) is attached to ensure stability during transport offshore and during installation, when the water ballasting is carried out.

Transport and positioning are performed by simple towing with conventional tugboats.

Water ballasting takes place by flooding the GBS internal chambers in a controlled manner. The full operation is unmanned, performed from a Control Vessel that accompanies the whole process.

Once the foundation lies on the seabed, water ingress is completed, the auxiliary floater is decoupled (an unmanned operation, too) and returned to port by towing with one of the tugboats used.

In the case of using solid ballast, the final stage is to fill the central shaft at its final position.

A more detailed description of the fabrication and installation procedure is included in the next sections.

5.1.1. Fabrication procedure

The GBS fabrication can be done either on shore, on the port yard and then floated of with a semi-submersible barge or in the water, alongside the quay. The latter scenario has been assumed for the present analysis.

The process consists of fabrication on the semi-submergible (semi-sub) deck of a CIP lower slab, as explained 43m diameter and less than 1m thick. Then formwork is used to construct the walls of the base.

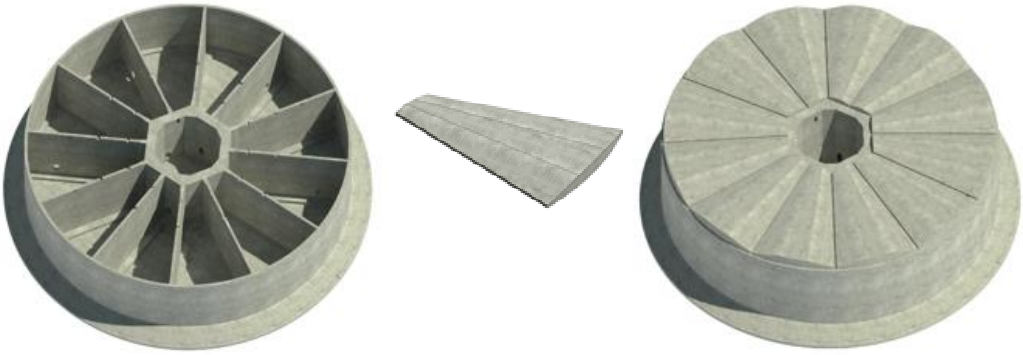
Once the walls are finished, the base can float on its own, so the semi-sub barge is no longer needed. To be able to start another GBS on the barge as soon as possible, the unfinished base is floated off and moved to a position moored to the quay where the upper slab of the base and the tower are fabricated.

The upper slab fabrication starts by placing 12 precast concrete planks on top of the walls, each of them covering one of the chambers of the base delimited by the internal walls (or bulkheads). Once these pre-slabs are positioned, a compression CIP slab of concrete is poured on top, and the base is finished.

Figure 30. Construction

Construction stages of the base.

Deliverable 4.1



The tower is constructed in situ, with either a slip-formwork or with climbing formworks, the same way that big concrete chimneys, concrete building cores or bridge piers are constructed.

Finally, some spare time must be considered for finishings, repairs and installation of the water ballasting system, internals and secondary steel, and to perform a water tightness test.

Figure 31. Construction

Final construction stage of the ELISA GBS.

Deliverable 4.1

The finished GBS then goes either to a wet storage position or directly to the port zone where turbines are installed, the TIM auxiliary floater is clamped, and the full set goes out to the windfarm.

The process on the barge takes between 9 days and 13 days. The process of base upper slab, tower fabrication and finishing take 3 to 4 weeks. The turbine assembly takes 2-2.5 days. Further information regarding production rates on Task 8.

In the present scenario, a fabrication pace of one foundation per week delivery has been modelled. This implies usage of two semi-sub barges (or one barge with room for simultaneous construction of two bases) and having quay space for four GBS for upper slab, tower and finishings. This sums up to 6 positions for manufacturing. Each position will be close to 50m wide, totaling 300 quay meters needed. For material handling, precast planks fabrication, rebar preassembly and others, 70m space deep inland would be desirable, therefore totaling port quay and yard area of 70m x 300m = 21.000m2.

Regarding cranes, trucks and other construction means usage, a big tower crane per position plus a medium sized crawler (LR1400 or similar) are considered. Apart from the precast planks, most lifts are formwork.

Figure 32. Construction

Example of GBS construction with one semi-sub barge (top) and two semi-sub barges (bottom)

Deliverable 4.1

5.1.2. Wet storage

As installation takes place in 8 months but manufacturing finishes just one GBS per week (4.2 per month), a necessity to store a number of units arises. Wet storage can be done in selected, sheltered waters. 16-18 wet storage positions have been estimated to be needed. Wet storage can take place either floating (with moorings) or using the ballasting system to allow them to lay on the seabed, in areas with the adequate depth so that the auxiliary floater is not needed. This implies a depth of around 7 to 9 meters. In the considered scenario, such an area exists at the Southwest side of the navigation channel from the ocean to the construction port (Morehead City Port).

Tugboats needed for this operation are small, harbor tugs, as there is no turbine installed on the GBS, the auxiliary floater is not installed, and it is sheltered waters.

Figure 33. Wet storage

Example of floating wet storage at sheltered water (top), wet bottom-supported storage (bottom)

Deliverable 4.1

5.1.3. Turbine assembly

For the turbine installation, a big ringer crane such as SARENS SGC 120 is needed, because of the weight of the nacelle and the installation height resulting.

The need for quay length is 120m, because two positions are desired, and they have to be a bit wider so that the auxiliary floater can be clamped prior to going to sea for installation. To install the turbine, it is desirable that the GBS is not floating but resting on the seabed. To ensure horizontality and a correct water depth, a bedding layer in harbor is also considered.

Figure 34. Turbine assembly

Example of turbine assembly (5 MW prototype at Canary Islands)

Deliverable 4.1

5.1.4. Offshore installation

When offshore installation campaign commences, GBSs are sent to turbine assembly quay. As stated above, turbine installation takes 2 – 2.5 days and the full sets are then towed to site and installed.

The total time for the towing and ballasting operation takes 56 hours for the selected scenario (75 miles from port to windfarm site).

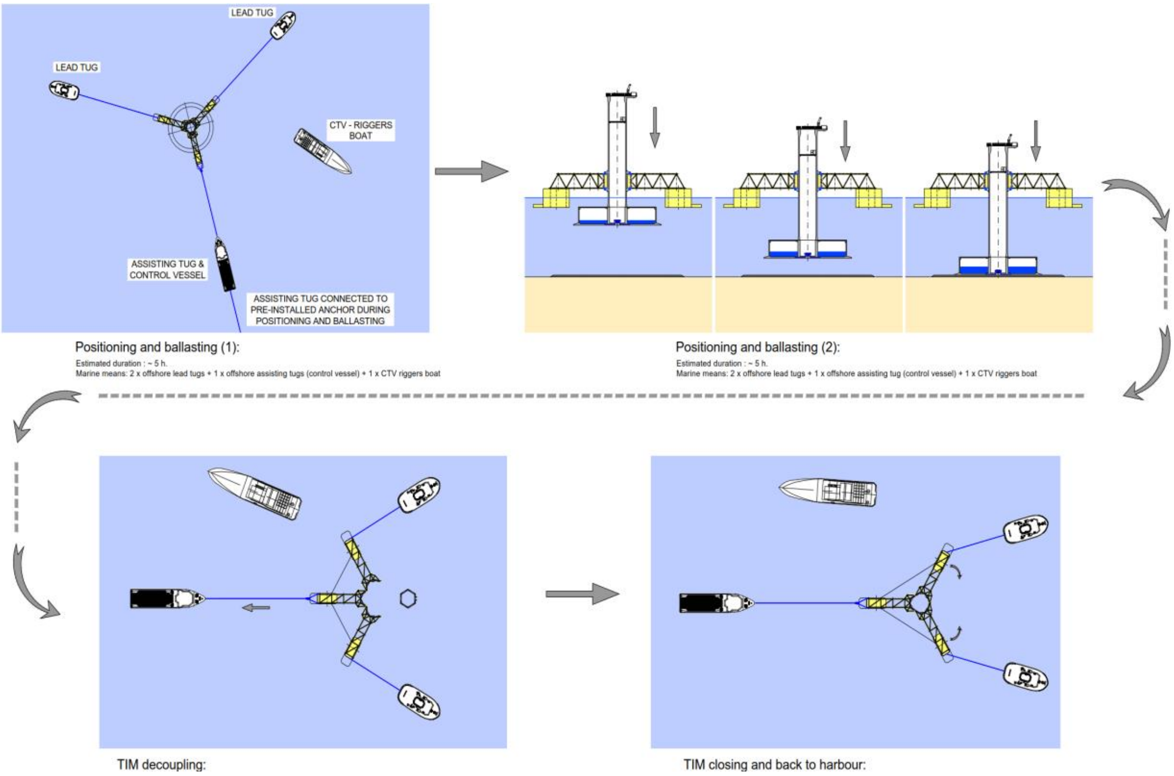
There are limitations in wave height and wind speed to be able to perform the towing and ballasting. Because of that, installation takes place usually avoiding winter season. In this scenario, East Coast conditions have been assumed to determine the available weather windows for the installation. From April to October, installation of the 50 GBS takes place.

There is a need of three tugs: two 80 bollard pull tons tugs transporting the units and a bigger tug/anchor vessel to temporarily lay an anchor at each position to ensure exact positioning. Apart from them, a control vessel where the controlling crew work and a crew transfer vessel are needed.

Figure 35. Installation

ELISA GBS positioning and ballasting (top). TIM decoupling/coupling (bottom)

Deliverable 4.1



5.2. ELISA cost estimate

For reporting on cost estimates, please refer to Task 9

5.3. Task 4 Conclusions

This task describes the fabrication and installation procedure of the ELISA GBS technology, adjusted for the requirements of the IEA 15 MW turbine and for conditions representative of the

East Coast of the United States. It also covered the material, manufacturing, and workforce requirements of the gravity-based units and a provides a comparison of representative project LCOE and fabrication/installation logistics against the representative project using conventional monopile solutions.

The preliminary comparative LCOE study, carried out by NREL, has been primarily based on NREL's Offshore Renewables Balance-of-system and Installation Tool (ORBIT) cost model. Please refer to Task 9 for the final CapEx and LCOE comparative study.

6. Task 5 – Ballasting system industrial design and tank testing site selection.

This task aimed to deliver a design of the ELISA GBS ballasting system that will be used for the controlled ballasting and lowering of the GBS units and how it has been conceived for industrialized manufacturing and use and to check that it is well suited to be conveniently supplied by a local US supply chain.

The ballasting system comprises a water intake and distribution system, an air distribution system and a control and communications system.

6.1. General description

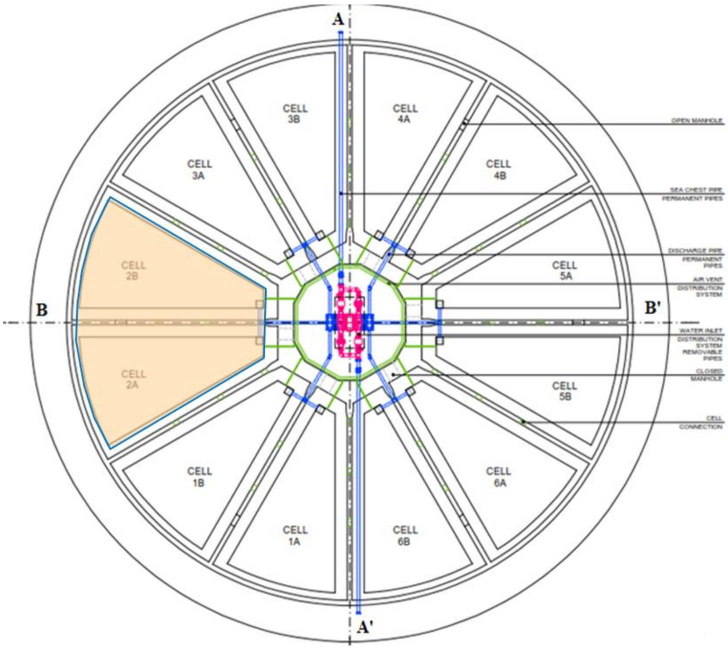
The main components of the ballast system are housed in the central dry-room of the ELISA GBS base. The base is divided in 12 radial cells around a central dry room, arranged in 6 pairs of adjacent interconnected cells. Two interconnected cells are separated by a lightened bulkhead which allows free water passage between both cells. Therefore, there are six pairs of cells which are watertight and can be thus filled (or de-ballasted) independently (see Figure 36).

With the only exception of fixed permanent pipes connecting the dry room with the cells and the exterior, all components of the ballasting system (valves, pumps, sensors, filters, etc.) are housed in the tower shaft or in base central dry room to ease accessibility and installation/removal.

Figure 36. Configuration and identification cells

Independent watertight cell pair shadowed (orange); water intake and distribution pipes (blue); BCM for controlled distribution of water into the 6 independent cell pairs (pink); air venting system (green).

Deliverable 5.1



Once towed to the site the GBS will be ballasted with sea water, gradually lowering it until it rests on the seabed. Ballasting is performed by letting sea water flow into the external cells of the base (by gravity). The central dry-room and tower remain dry during the ballasting process and until the GBS rests safely on the seabed. Once the GBS is on the seabed, the water filling of the external cells is completed. Finally, the central dry-room and tower shaft will also be filled with sea water for the final operating condition of the GBS.

Sensors measuring water level in cells, air pressure in cells and inclination of the GBS allow adequate control of the ballasting process.

The ballast system also comprises an air distribution and venting system for adequate control of the air pressure and air venting of the cells during the ballasting process.

Finally, the ballast system comprises diesel generators for power supply, PLC cabinets for the control and communications systems and reserve air compressors, all of which will be in the access platform at the top of the tower shaft; all heavy equipment in the access platform is located within reach of the Davit crane to ease its retrieval after installation.

Redundancy is set as a requirement for all these systems.

Next figures show a general reference configuration of the water intake and distribution system and its position at the central dry room in the base. Figure 37 shows the 6 discharge pipes connecting the dry-room with the cells (green), the 2 sea chest pipes connecting the dry-room with the exterior (blue), and the piping for distribution of water flow into the cells (yellow).

Figure 37. Ballast system

Ballast system general view

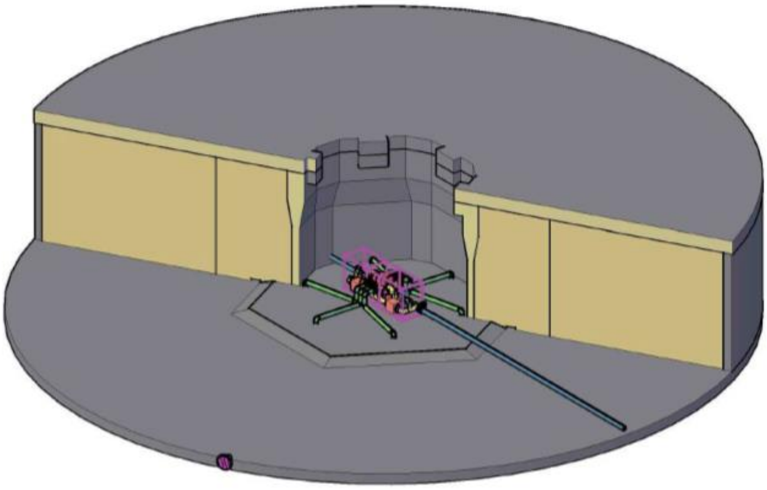
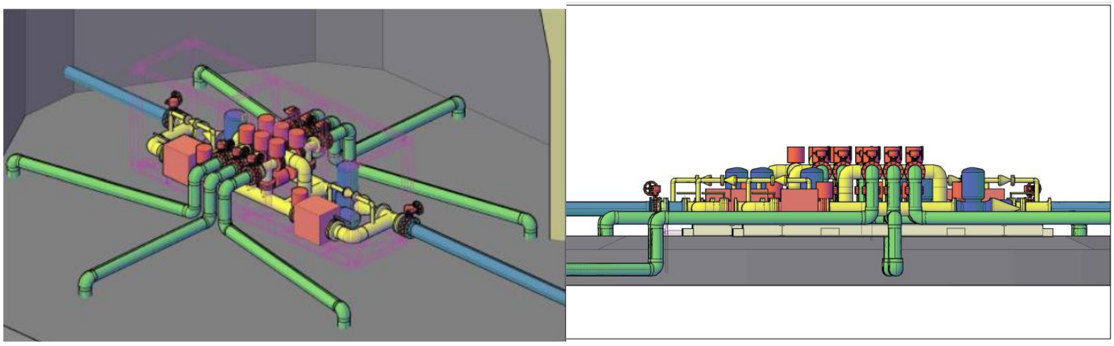


Figure 38. Ballast system

Possible configuration of the ballast system. Isometric and 3D view



6.1.1. Ballasting process

The water ballasting of the GBS may be divided in three main stages described below.

It is worth mentioned that while the whole operation is defined and planned to be unmanned, access of personnel to the tower and the dry-room is possible in case of contingency (provided that such contingency does not affect personnel safety). Accessibility means and tower internals have been designed and verified to that purpose.

6.1.1.1. Preliminary inshore ballasting

An initial partial ballasting will take place inshore once the TIM platform has been coupled to the tower and before towing in open waters. This initial ballasting is intended to bring the GBS to the tow draft and will happen in the vicinity of the construction port.

This preliminary inshore ballasting serves two main purposes: i) it improves the seakeeping performance of the system during the offshore tow; ii) it makes it possible to perform a significant fraction of the ballasting in controlled harbor or inshore conditions, including the submerging of the base upper deck, reducing the needed duration of the subsequent offshore ballasting operation.

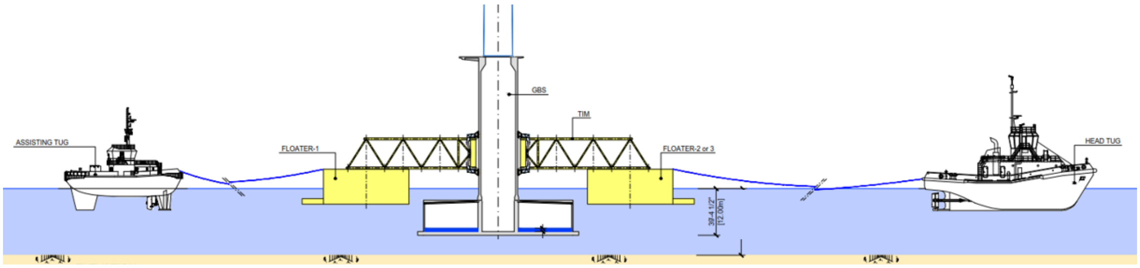
Between 45 and 60% of the total water ballast needed to lower the GBS to the seabed will be introduced in the base cells at this inshore stage (between 1.0 and 2.0m approximately), depending on the final water depth in which each GBS unit will be installed. The free surface effect that this may generate is duly considered in the design and analysis of the T&I process.

In this condition the GBS will be towed to the offshore site.

Figure 39. Ballasting process

1st stage: Preliminary inshore ballasting to bring the GBS unit to tow draft.

Deliverable 5.1



6.1.1.2. *Offshore ballasting for lowering the GBS onto the seabed*

Once the GBS has been towed to the offshore site, the ballasting will continue to gradually lower the GBS until it rests on the seabed. Water level in the cells at the moment of GBS landing will be between 3 and 4m depending on the water depth of each unit. This operation is performed with full independent control of the water flow into/from each cell.

As aforementioned, two sea-intake pipes have been considered to introduce the water into the cells. All cells will be filled with approximately the same amount of water, maintaining an adequate balance of the structure. Several pressure sensors will be installed to control the water level in the cells. The water flow into each cell can be increased or decreased by regulating the opening degree of the control valves in the discharge pipes, thus controlling the speed and balance of the lowering process. The opening of each valve to generate the pursued lowering speed and balance is pre-calibrated so that need for acting on the system during the lowering process is minimized, but the control team will monitor the process from the control vessels and can make any adjustment that may be convenient.

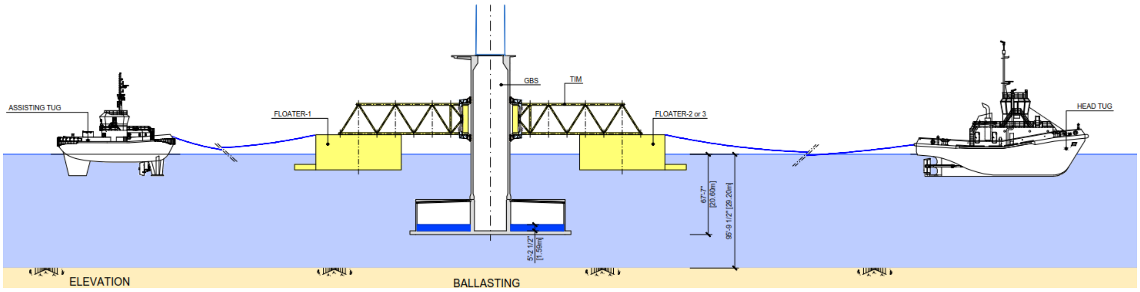
The two sea chest pipes can be operated independently in any situation, but normal operation condition has been defined to be carried out with both intakes opened. This means that if the operation requires the use of a single intake (if for example a valve malfunctions and fails to open), the operation can be carried out safely, but the lowering speed will be reduced.

The ballast system is designed to perform the lowering operation in normal conditions with a reference lowering speed of no less than 7m/h, which will result in a duration of the offshore lowering operation of approximately 3 hours, depending on the exact water depth at each position. The value adopted is balanced so that lowering can take place in a sufficiently short time without oversizing the water and air flow systems.

Figure 40. Ballasting process

2nd stage: Ballasting of the GBS at the offshore site until it rests on the seabed.

Deliverable 5.1



6.1.1.3. *Completion of the water filling of the GBS once it rests on the seabed*

Once the GBS rests on the seabed the ballasting continues until the filling of the GBS is completed for its operational condition. This is performed in two sub-stages: firstly, the cells are fully ballasted and secondly the dry-room and tower shaft are ballasted (Figure 41). Both the filling of the cells and the filling of the tower is performed through the water intake and distribution system.

Before the tower shaft is ballasted, it can be accessed for retrieval of reusable components of the BCM. It is clarified, however, that once the base cells have been filled, a safe point for the structure is reached and the subsequent works for the filling of the tower can be performed if convenient in a separate independent operation which needs not happen right away and can be planned and performed in a different weather window as more convenient for the overall project planning.

Filling of the tower shall be performed through two (for redundancy) specific pipes and valves provided in each of the sea chest pipes and, as with the cells, will happen by gravity.

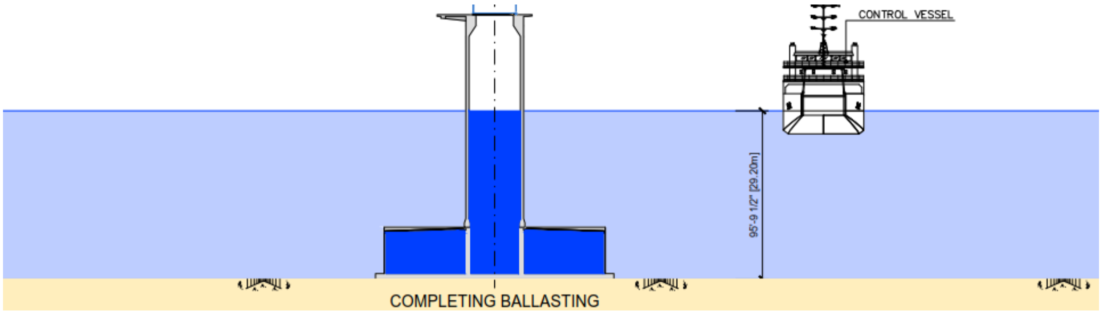
Once the tower is completely filled, the GBS installation operation is completed, and the submerged elements of the ballast system will already be in the planned condition for the project lifetime and for the future decommissioning process. The tower shall be connected to the sea through the sea chests (and eventually also through the J-tubes once the cable pull-in operation is complete). The cells will be connected with the tower through the BCM and the tower filling pipes, which ensures that pressure in tower and cells remains balanced and is also convenient for decommissioning (see section 6.1.5).

At this point, the equipment of the ballast system located in the upper part of the tower, above sea level, can be disconnected and retrieved (see section 6.1.4), which can of course happen in a separate operation and weather window as convenient. When the equipment is retrieved, the main venting pipe shall be closed with blind flanges to ensure the pursued airtightness of the upper part of the concrete tower (together with the steel tower and the WTG).

Figure 41. Ballasting process

3rd stage of the ballasting process: Once the GBS rests on the seabed, the cells will be completely filled, components of the ballasting system may be recovered from the tower and dry-room and finally the tower and dry room are also filled with water.

Deliverable 5.1



6.1.2. Capability for contingency de-ballasting

During the installation phase, an emergency situation may happen which could require to re-float the platform. This is of course highly unlikely, not only because all critical elements shall be designed with redundancy, but also because the protocol in most contingency situations will be to complete the ballasting operation to reach a safe point with the structure resting on the seabed, particularly if the lowering has already passed a certain depth. Nevertheless, a safe requirement of the system is that the ballasting process may be stopped, and the structure re-floated by pumping water out of the base.

The system has been designed with two emergency pumps which can be operated independently in any situation. Considering that use of the pumps will happen only in case of contingency, it could be argued that redundancy for the pumps is not strictly required, being a contingency for the contingency, but nevertheless two pumps shall be provided on the safe side so that even if one pump fails the GBS can still be de-ballasted with the other contingency pump.

The two redundant contingency pumps are part of the BCM (see section 6.2.1.2) and are therefore located in the central dry room of the base. Of course, the pumps are integrated in the control system and are thus powered and controlled by means of the same generators and PLC as all the other active components of the system.

In addition to the contingency pumps for de-ballasting of the cells, the ballast system also comprises redundant bilge pumps located in the dry-room as recommended by applicable design codes, so that in the event of any leakage happening in the dry-room or the tower, water can be duly evacuated.

As said, these contingency pumps for de-ballasting will only be used as a contingency during the offshore installation process. They can also be used for inshore marine operations in previous stages of the installation process. In particular, it is planned that the GBS units will be ballasted onto a gravel pad to ease the WTG installation works at New Jersey Wind Port. Once the WTG is fully installed and the TIM unit has been coupled to the tower, the GBS unit can be de-ballasted and refloated using these pumps.

6.1.3. Control of the ballasting operation

The ballast system is designed to allow for remote monitoring, control, and regulation of all the key aspects and elements involved in the ballasting operation. The functionalities of the control system include:

- Monitoring of water level in cells (6+6 sensors)
- Monitoring of air pressure in cells (3+3 sensors)
- Monitoring of GBS inclinations (2+1 sensors)
- Control and regulation of sea chest valves (1+1) which let water into the ballast system.
- Control and regulation of water discharge valves to the cells (6+6) which distribute water among the base cells.
- Control of air vent valves (1+1)
- Control of reserve air compressors (1+1)
- Control of contingency pumps for cell de-ballasting (1+1).
- Control of tower filling valves (1+1)
- Control of power generators (1+1)

All monitoring sensors have redundancy so that failure of one sensor will not prevent the control team from acquiring the information needed for a safe development of the operation. The wireless communication system transferring information between the control vessel and the GBS has also full redundancy.

Complementary to the multiple sensors comprised in the control system, a set of night vision cameras shall be provided in each GBS unit, providing the control team with visual control of the situation in each of the 12 cells and in the dry-room. Water level marks in each cell allow for visual control of water level in cells complementing and contrasting measurements provided by sensors. Cameras in the cells are not recoverable.

With the a.m. functionalities the ballasting process can be adequately monitored and controlled by the control team working from the control vessel.

6.1.4. Recoverable components of the ballast system

Most of the components of the ballast system are designed to be recoverable so they can be reused in different GBS units. To that aim, all recoverable components are designed so that their weights and dimensions can be handled by the Davit crane for recovery.

Elements of the ballast system which are removable, which can in turn be classified within two groups:

- Retrievable elements located in the upper part of the concrete tower (above sea level). These will always be removed after installation (to be reused in other GBS units)
- Retrievable elements located in the base, which are integrated into the BCM. Retrieval of these elements is an opportunity, not a need, and is of course dependent on safe

procedures and means as per applicable H&S regulations, which is indeed considered as an intrinsic part of a good design since it is initially conceived.

Task 5 deliverables provide full details on the recovery process and tools.

6.1.5. GBS decommissioning and linked role of the ballast system.

This section provides relevant information on the foreseen strategy for decommissioning of the offshore units once the lifetime of the project is completed and on the role of the ballast system for decommissioning of the GBS.

Decommissioning of the GBS can be performed reverting the installation process, removing the water ballast in order to refloat the structure. The fact that the GBS is ballasted only with water significantly eases the decommissioning process.

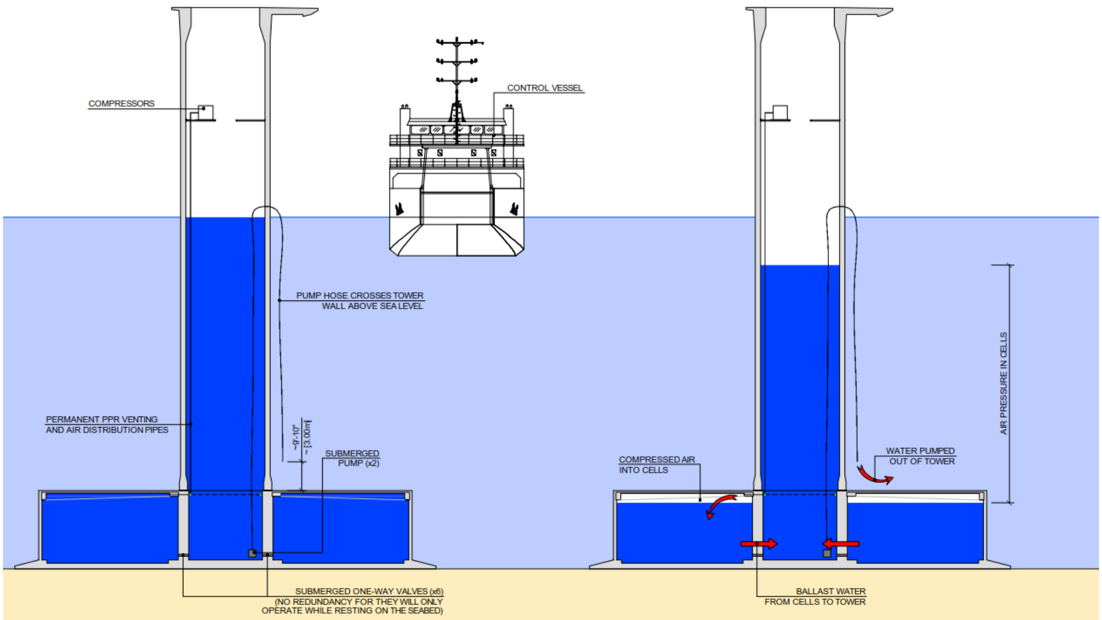
The decommissioning process must not consider any use whatsoever of valves or any other electro-mechanical equipment in the lost BCM, which of course will not be functional when the GBS is to be decommissioned. The permanent PPR pipes in the GBS, on the other hand, are highly durable and are designed for a lifetime in excess of 35 years under sea water, so they can be considered usable for the decommissioning process.

There may be different alternatives for the removal of ballast water from the GBS in order to refloat it at the end of the wind farm's lifetime. Task 5 developed in detailed a decommissioning process which is described in the corresponding deliverable and summarized next:

Figure 42. De-Ballasting Scheme for GBS decommissioning

A submersible pump will pump water out of the tower. Water from the cells will flow into the tower from where it will be pumped out. Air is introduced into the cells via the air distribution system.

Deliverable 5.1



The main steps for the water de-ballasting process for the GBS decommissioning would be:

- Sea chest and J-tubes will be plugged from the outside by means of blind stabs installed.
- Submersible pumps would be installed at the tower shaft to pump water out of the central shaft. Installation of these pumps can be performed from the working platforms in the upper part of the tower, above sea level.
- By pumping water out of the tower, tests will be performed to confirm that there is not relevant water entrance through the closed original water intake pipes.
- Air compressors would be reinstalled at the tower top working platform, reusing the permanent venting and air distribution pipes to pump air into the cells.
- Water will be pumped out of the central shaft with the submersible pump as air is introduced into the cells, gradually deballasting the GBS. By controlling pressure of the air introduced in the cells (which can be done from the tower upper working platforms) the water level in the tower can be controlled as convenient as the GBS is deballasted.

6.1.6. Testing and commissioning of the ballast system.

Once the ballast system is completely installed in the construction yard, it will be subject to a series of tests for its approval and commissioning before the GBS is loaded-out. This will be part of the testing plan for verifying and adequate tightness level in the structure. A specific workstation in the GBS production line is planned for this and other finishing tasks.

6.2. Task 5 Conclusions

A detailed description of the Ballast System for the installation of the ELISA GBS units has been provided, including a detailed explanation of the design philosophy followed to make the system suitable for an industrialized scenario to be applied in a large-scale commercial wind farm.

This includes a design of the ballast system which comprises modules than can be pre-assembled, cabled and tested at the workshop, so that their installation inside the GBS as part of the serial construction process can be fast and efficient. The options for retrieval and reusability of components of the ballast system has also been explored.

The key components selected the ballast system (pipes, valves, pumps, control system) have been verified to be commercially and readily available for a US-based supply chain.

7. Task 6 – Tank test campaign to fine tune 15-MW design for US installation.

This task aimed to provide the technical specification for ELISA technology tank testing, that evaluates the performance of the platform from the towing operation to the sinking process.

The T&I tank experimental testing campaign was carried out in CEHINAV and CITEEC facilities within this project during the first quarter of 2023.

Within this section the main results of the experimental tests campaign are highlighted and the main conclusions regarding the validity and representativity of the theoretical and numerical simulations performed by Esteyco and NREL in previous stages are summarized.

7.1. Scaled model

Test house was requested to manufacture a Froude law scaled model of the ELISA platform. The scale of the model was determined by the test house.

The model represents the exact exterior geometry of the prototype (see Task 3) with the proper internal slots to allocate masses/water to get the model into the proper scaled CoG, GM and inertias.

In order to reproduce the main physical phenomena involved in wave-structure interaction, the following scaling laws were applied which were based on a constant ratio between the gravitational and inertial forces at laboratory and prototype scale. Therefore, Froude number remained constant at both scales (Froude Scale). The specific density for sea water is 1.025 ton/m^3.

Table 20. Scale factors

Deliverable 6.1

Magnitude	Ratio
Geometry	λ
Time	$\sqrt{\lambda}$
Wave Height	λ
Linear Motion	λ
Angular Motion	1
Acceleration	1
Mass	$1.025 \cdot \lambda^3$
Force	$1.025 \cdot \lambda^3$

7.1.1. Weight distribution

The tank testing facility was provided with a spreadsheet with the detailed weight distribution of the model in the different configurations to be tested.

7.1.2. Draughts

The tank testing campaign tested and characterized the hydrodynamic behavior of the platform in 6 different drafts: a first group of 3 different drafts with the GBS platform near the water surface and a second group of 3 additional drafts with the GBS platform close to the seabed. One draft in each set was set equal to the one of the situations included in the numerical simulation to provide a direct experimental comparison. The other two drafts in each group provided an important sensitivity to assess the variability of the platform's hydrodynamic characterization.

All drafts were be specified to the testing facility before the start of the tests. In the following table a previous value for these drafts is shown. Due to the small scale, the difference between the different draughts was too small. It was known that the draughts of the platform close to seabed may change during the tests in order to carry out these in a physically reasonable manner.

Table 21. Draughts

Deliverable 6.1

Load condition	Draught	Description	Value
LC00	Transport draught	For the transport configuration	Var.
LC01	Mid ballasting draught	For installation phase	23.5 m
Close to sea surface			
LC03a	Draught 1 (equal to Transport draught)	First distance near the surface	12 m
LC03b	Draught 2	Second distance near the surface	11 m
LC03c	Draught 3	Third distance near the surface	10 m
Close to seabed			
LC04a	Draught 4	First distance near the seabed	32.5 m
LC04b	Draught 5	Second distance near the seabed	33.5 m
LC04c	Draught 6	Third distance near the seabed	34 m

7.2. Tests preparation

7.2.1. Environmental conditions

Table 22. Environmental conditions

Environmental conditions considered for the tests performed during the tank testing campaign.

Deliverable 6.1

Depth	About 35m.
Waves	White noise waves would be generated to assess non-linear effects, low frequency response and to obtain spectral RAOs with two different wave heights: selected regular wave height and double. Irregular waves would be generated using JONSWAP spectra or any other agreed upon depending on the specific applicable metocean data.
Wind	Wind effects are relevant when the turbine is installed on top of the tower. Hence, ELISA would have wind effects active. For wind simulation, wind drag over the turbine and the structure would be simulated by means of an orientable fan installed on top of the tower. The fan would reproduce a pre-stablished thrust time series calculated with a wind speed time series to provide the equivalent overturning moment on the structure

7.2.2. Instrumentation

Table 23. Instrumentation

Different variables of interest measured by means of precision sensors defined by test house based on their own “know-how”.

Deliverable 6.1

Tracking and accelerations	The motions are measured with respect to its center of gravity.
Loads	The loads are measured at the joint between truss-beam and floaters (TIM platform) for each DoF with 6-axis dynamometers fitted on floaters deck. At least two dynamometers are required, one on the floater that encounters the waves and the other on one of the other two available floaters.
Wave height	The waves or instantaneous water surface elevation are monitored.
Mooring lines	Load cells in soft-mooring lines.
Fan thrust	Dynamometer for Fan thrust.
Accelerations at the RNA	Accelerations can be derived from motions or directly measured with an accelerometer placed at nacelle height. Both horizontal and vertical accelerations are to be captured.
Videos	Both above and submarine videos are required to see what happens close to the seabed. Submarine videos are only strictly requested for all the tests close to seabed.

7.2.3. Calibration

Previous to the tests, calibration tests of all environmental conditions would be carried out.

Table 24. Calibration tests

Calibration test of environmental conditions carried out previous to the tests.

Deliverable 6.1

Wave calibration	Calibrations of the waves would be performed with the absence of the model. Free surface sensor array would be installed at the control position during calibration as well as during testing
Wind calibration	The device used for simulating the wind is calibrated in dry conditions. Calibration on the thrust applied by the fan would be carried out

7.3. Test definition

7.3.1. Dry characterization

Dry characterization are performed in order to check mass properties of the model such as total mass, position of the CoG and inertias of each involved structure, i.e. TIM and GBS, by means of pendulum tests. Data from these tests would fit with the tolerances for the construction of the models and calibration of the tests provided by the tank testing facility.

7.3.2. Wet characterization

Note that forced oscillations could be considered as an option in case the test house decides is more representative but, in any case, quoted separately from these tests.

7.3.2.1. Tilt tests

Tilts tests were carried out in still water at transport draught to evaluate the initial stability of each structure and to obtain the GMs. Tilt tests in roll and pitch movement were performed.

7.3.2.2. Decay tests

Decay tests conducted to obtain decay curves in at least 3 DoF (heave, roll and pitch). The purpose to these tests was to ensure that the scaled model properties were correct and to characterize damping and added mass variations when getting close to sea surface, mid ballast operation and close to seabed.

These free decay tests were carried out at three decreasing distances off the sea surface, at mid ballasting point and at three decreasing distances off the seabed.

The last distance was as close as reasonably and physically possible off sea surface and seabed. The number of realizations were enough to have sufficiently trusty results and to obtain the best approach filtering possible human errors during execution. The rest of DoFs were kept as much still as reasonably possible. They were monitored to discard any potential coupling during the execution.

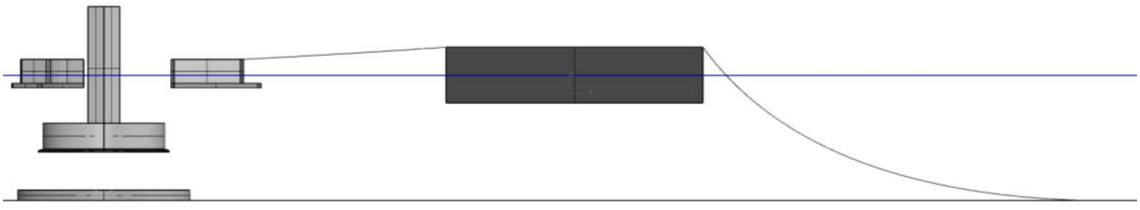
7.3.3. Wave response characterization

The aim of these tests was to characterize the behavior of the model under several sea states conditions and to obtain spectral RAOs that allowed to calibrate numerical models at different draughts. Non-linear effects and effects of the distance to the sea surface and seabed were captured.

These tests should be carried out with a soft-mooring configuration. The configuration represented the installation configuration where the three TIM floaters are connected to the tugboats in a star configuration (see Figure 16). However, when the platform is close to the seabed, these tests should be carried out with a different soft-mooring configuration. This tentative configuration is shown in figure below, where an element simulating an AHTV anchored to the seabed and connected to the TIM is represented. Anchor catenary was provided by Esteyco as well as general characteristics of the towline. The test house should propose the best configuration based on their own experience to represent this configuration and to characterize the towline behavior, which in general would be non-linear (catenary). A linear simplification was assumed valid as long as proper justification was provided. Non-linear options with two or more springs would be a first proposal. Back lines, connected to the other two “tugboats” would be represented as soft mooring lines whose stiffness do not affect to overall system response.

Figure 43. Tentative non-linear mooring configuration

Deliverable 6.1



Same draught configurations than those from decay tests are tested. Only one heading is enough. The duration of tests is 3 hours (real scale) after initial transients are damped.

Note that seabed distance sensitivity tests are carried out over the scaled bedding layer. In Figure 43 a representative scales bedding layer is shown.

7.3.3.1. White noise tests

The aim of white noise tests was to analyze the behavior of the model in a range of frequencies of the same energy. This would allow to capture low frequency responses and to compare the spectral RAOs with those obtained from irregular wave tests. Non-linear effects were captured by testing the two different wave heights. The range of frequencies was defined according to the results defined by the test campaign, as well as taking into account the operational capabilities of the wave generator.

The minimum results expected from white noise tests are summarized in the following bullet points. Nonetheless they are opened to additional information provided by the test house based on their experience.

- Displacement spectral RAO's.
- Acceleration spectral RAO's.
- Mooring tensions.
- Floaters loads.
- Power spectral density curves.
- Videos, both above water and submarine.

7.3.3.2. Irregular waves tests

The purpose of irregular waves tests was to characterize the behavior of the model under several sea states conditions and to obtain motion and load PSDs, percentiles and extreme values.

For each state, movements on each DoF were obtained. Accelerations of the model measured at CoG were registered as well as mooring tensions.

Irregular waves used are those corresponding to the maximum design wave for the transport and installation operation. Hence, the wave height for ELISA technologies is Hs = 2 m.

Three wave periods were tested according to the waves in the area, one low period, one mid and one large.

The results expected from the tests include time series, PSDs, percentiles and extremes of the following items:

- Motions.

- Accelerations.
- Mooring tensions.
- Floater loads.

7.3.4. Coupled tests

The purpose of these tests was to replicate the simulations carried out to confirm that results are trustable and to evaluate the potential installation tolerances achievable.

These tests were carried out with a soft-mooring configuration as same as wave response tests. The number of draughts performed was the same than for decay tests.

These tests consisted of several sea states with the wind effect emulating a 15MW WTG. For each state, movements on each DoF were obtained. Accelerations of the RNA were registered as well as mooring tensions.

Irregular waves used were those corresponding to the maximum design wave for the transport and installation operation and just for one heading. Hence, the wave height for ELISA technologies is Hs = 2 m.

Three wave periods were tested according to the waves in the area, one low period, one mid and one large. Only one wind heading was tested aligned with the wave heading.

Wind speed tested is the one corresponding to the design wind speed for transport and installation of the ELISA.

The duration of tests in which irregular waves are involved was 3 hours (real scale) after initial transients were damped. The results expected from the tests included time series, PSDs, percentiles and extremes of the following items:

- Motions.
- Accelerations at RNA.
- Floater loads
- Mooring tensions.

7.4. Test matrix

A complete test matrix covering multiple scenarios and loads for the towing and ballasting process was defined in coordination with the test house. Please refer to Task 6 deliverable for full details.

7.5. Test set-up

During this testing campaign, tests have been carried out in two different tanks due to the requirements of the tests. The three load conditions closer to the surface (LC00 and LC03) were tested at CEHINAV’s towing tank, while the three load conditions closer to the seabed were tested at CITEEC’s basin (LC04). Mid-ballasting load condition (LC01) was tested in both facilities in order to compare the results.

Figure 44. CEHINAV's facilities

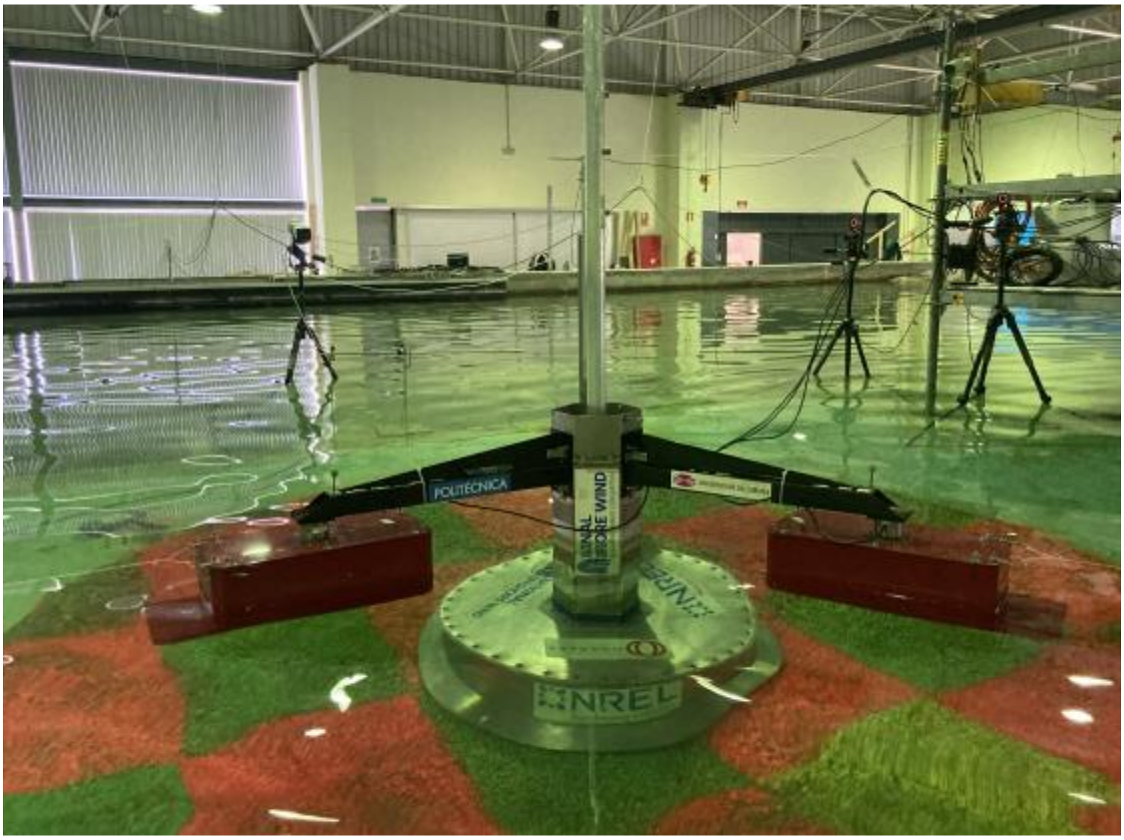
Set-up in CEHINAV's facilities

Deliverable 6.2

Figure 45. CITEEC's facilities

Model during tests in CITEEC's facilities

Deliverable 6.2



Wind reproduction was carried out with a time series of forces exerted on the tank turbine. For this purpose, the wind was aligned with the wave and a yaw misalignment of +8 degrees was taken into account. These conditions generated a resultant force on the turbine at 79.5 degrees with respect to the wind, so to reproduce these conditions the turbine used in the tests was placed at that heading so that the time series of thrust on the turbine in the channel reproduced the actual thrust on the IEA15MW.

7.6. Test results

This section summarizes some of the key results of the tank experimental test campaign.

7.6.1. Towed transport condition

First contrast performed between theoretical and experimental results was for natural periods which showed excellent agreement between the experimental data and the values predicted in previous numerical simulations by NREL:

Table 25. Natural periods of the ELISA GBS foundation in transport condition

Comparison between numerical predicted value in hydrodynamic simulations by NREL and test results

Deliverable 6.2

DoF	NREL	TANK
Heave [s]	18.9	19.2
Roll [s]	35.7	35.9
Pitch [s]	35.7	35.3

The tilt (pitch&roll) motions are of particular interest since they govern the horizontal motions and accelerations that the WTG undergoes. Experimental results (max 2.6 deg) were similar but lower than those obtained in the theoretical simulations (max 3.5deg) indicating that previously obtained results were sufficiently representative and that potential deviations were on the safe side. Part of the difference obtained was linked to minor difference in the average tilt due to weight eccentricity. The tilt variation range (+1.25deg in the tank tests, +-1.3deg in the numerical simulations) were also very well aligned.

Figure 46. Pitch motion for transport condition

Mean and characteristic maximum and minimum floater pitch motion for transport condition (12m) (*NREL results from previous numerical simulations: Max 3.3deg) - Deliverable 6.2*

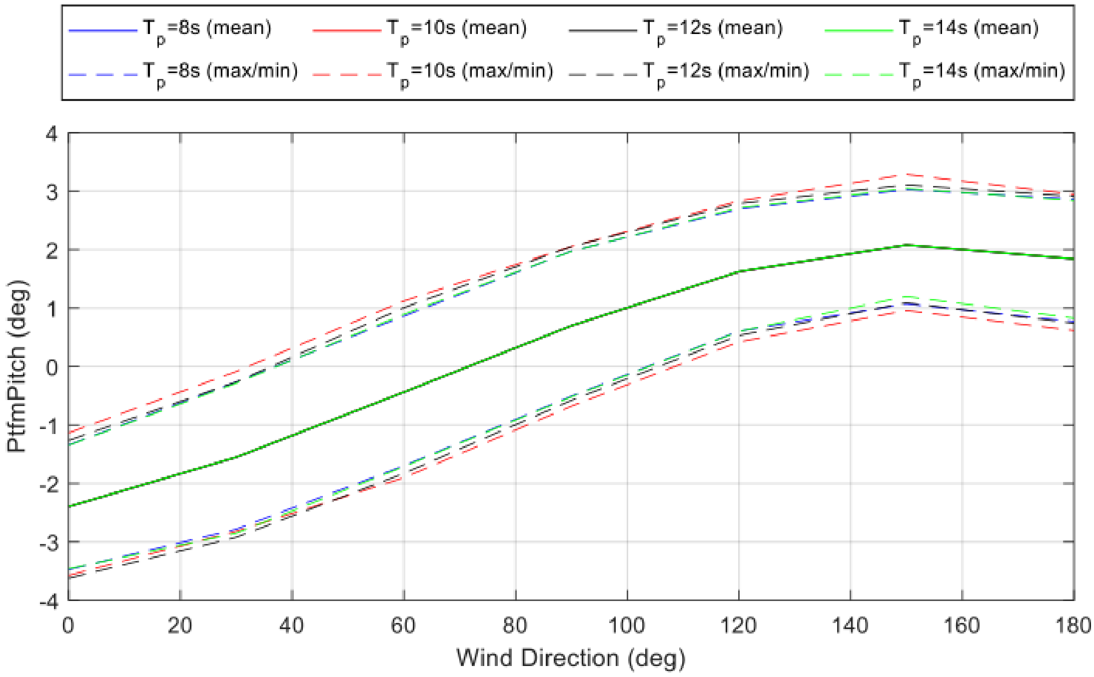


Table 26. Floater pitch motion for transport condition

Mean and characteristic maximum and minimum floater pitch motion for transport condition (12m)

Tank testing results (max.2,61deg) - Deliverable 6.2

Motion	Tp [s]	Std.	Max.	P99
Tilt (ROLL + PITCH)	14	0.5	2.47	2.04
	10	0.49	2.61	2.05
	7	0.49	2.58	2.05

The accelerations in the nacelle are a relevant control parameter since they govern the forces acting on the WTG during the T&I operations. These have compared to verify that experimental and theoretical values predicted are sufficiently aligned. Again, maximum values observed in the tests (1.01m/s2) were close but somewhat lower than the numerical predictions (1.25m/s2), and remained as expected very far from the design thresholds established for the allowable horizontal accelerations in the WTG (4,5m/s2), more than 4 times higher than the maximum observed values in the tests. These confirms that the motions experienced by the ELISA foundation during the tower transport are very slow and gentle, thus generating very moderate forces on the WTG components, indeed very far from their design capacity.

Figure 47. Nacelle fore-aft translational acceleration

Mean and characteristic maximum and minimum nacelle fore-aft translational acceleration along the shaft for transport condition (12m)

NREL results - Deliverable 6.2

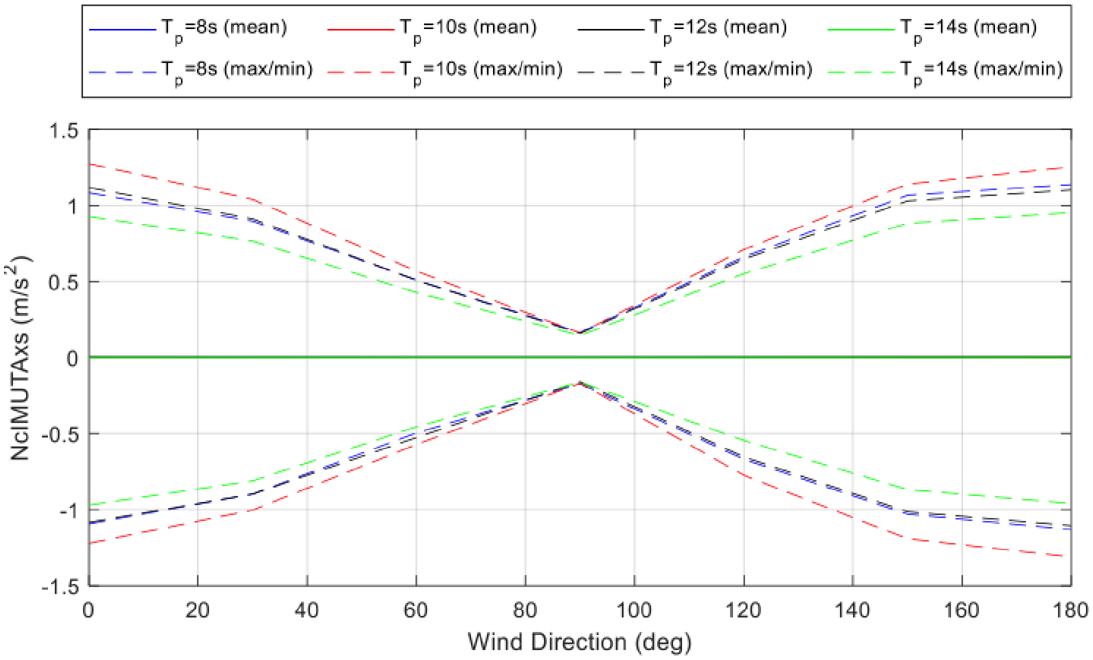


Table 27. Nacelle fore-aft translational acceleration

Mean and characteristic maximum and minimum nacelle fore-aft translational acceleration along the shaft for transport condition (12m)

Tank testing results - Deliverable 6.2

Motion	File Name	mean	rms	min	max	Perc. 1	Perc. 99
Accel X $[m\ s^2]$	seakeepingWind_LC01_irregLargeTp14s	0.00	0.16	-0.81	0.73	-0.38	0.39
	seakeepingWind_LC01_irregLargeTp10s	0.00	0.20	-0.99	0.89	-0.47	0.47
	seakeepingWind_LC01_irregLargeTp7s	0.00	0.22	-0.92	1.01	-0.50	0.50

Regarding vertical accelerations, which are deemed less relevant, results were also positive and sufficiently well aligned with numerical predictions, with values slightly lower than predicted for wave periods Tp=7s and Tp=14s, and slightly higher than predicted for wave period Tp=10s, and in any case very comfortably below the established threshold for the WTG vertical acceleration (3m/s2), around 4 times higher than the maximum vertical acceleration observed. Averaged results of max heave acceleration in tests (0.57m/s2) and in the numerical simulations (0.55m/s2) are very well aligned.

Figure 48. Nacelle vertical translational acceleration

Mean and characteristic maximum and minimum nacelle vertical translational acceleration perpendicular to the shaft for transport condition (12m)

NREL results - Deliverable 6.2

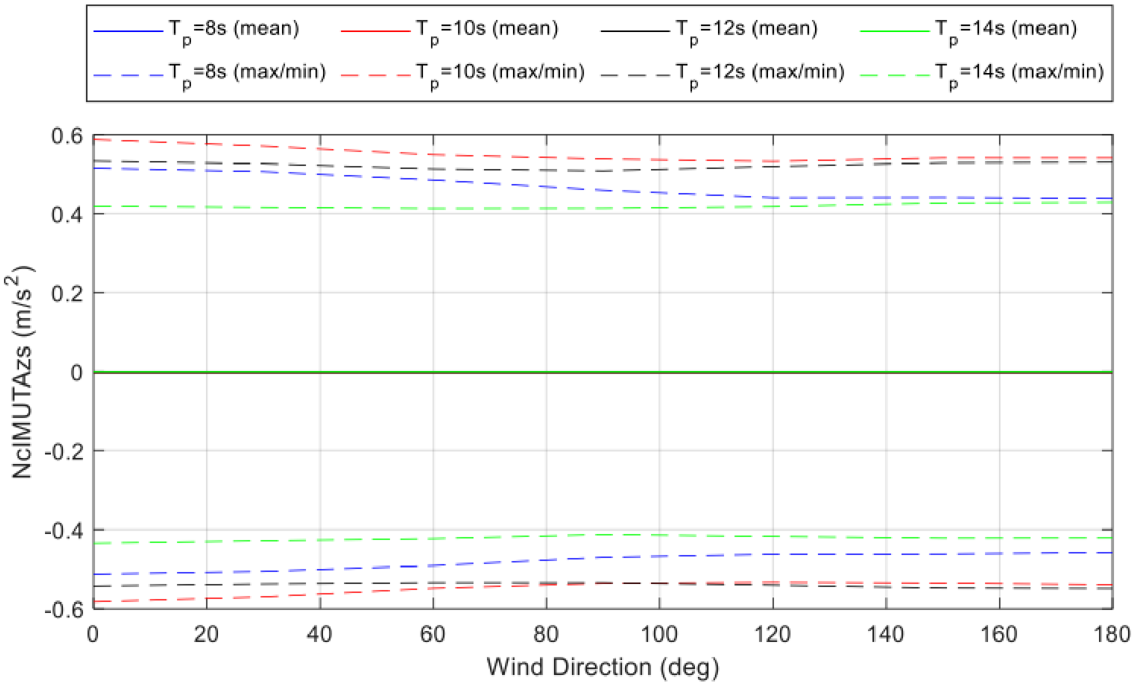


Table 28. Nacelle vertical translational acceleration

Mean and characteristic maximum and minimum nacelle vertical translational acceleration perpendicular to the shaft for transport condition (12m)

Tank testing results - Deliverable 6.2

Motion	File Name	mean	rms	min	max	Perc. 1	Perc. 99
Accel Z $[m\ s^2]$	seakeepingWind_LC01_irregLargeTp14s	0.00	0.12	-0.49	0.46	-0.28	0.28
	seakeepingWind_LC01_irregLargeTp10s	0.00	0.14	-0.65	0.78	-0.33	0.33
	seakeepingWind_LC01_irregLargeTp7s	0.00	0.11	-0.44	0.47	-0.25	0.26

7.6.2. Ballasting conditions: deep water vs. 35m water

As expected, the results obtained during the ballasting operations showed that as the GBS is gradually submerged, its performance regarding motions and accelerations in the WTG improves slightly, so maximum values correspond to the towed transport condition described in the previous section. Figure 49 and Figure 50 illustrate how pitch motions are gradually reduced when the draft of the GBS foundation increases as it is gradually ballasted until touchdown with the seabed.

Figure 49. Pitch motion

Pitch motions during ballasting at intermediate draft with maximum wave and wind conditions (KC01)

Deliverable 6.2

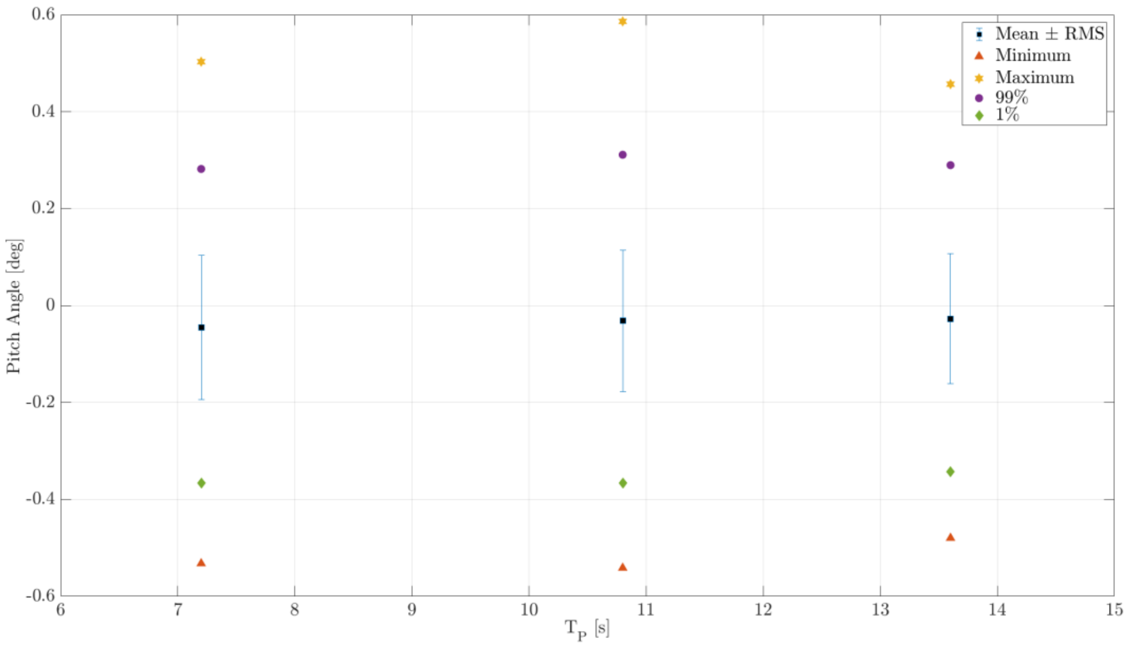
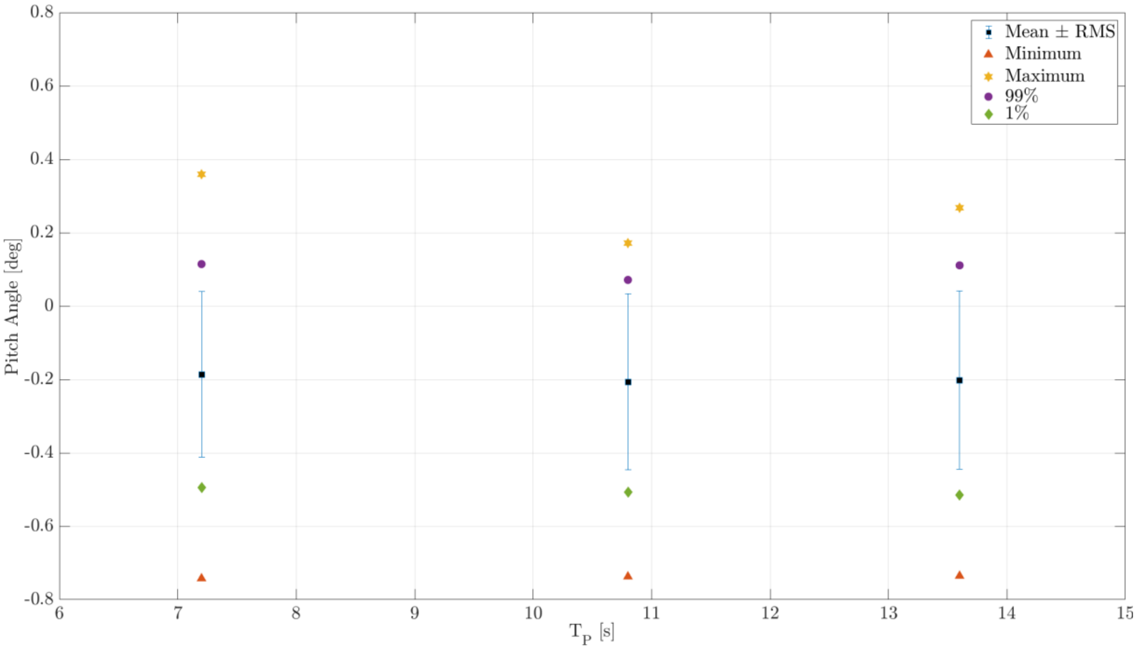


Figure 50. Pitch motion

Pitch motions during ballasting close to seabed with maximum wave and wind conditions (KC04A)

Deliverable 6.2



Tests were performed in two different tanks, one simulating a large water depth condition, and the other one simulating the presence of the seabed at 35m water depth. The intermediate draft condition (LC01) was tested in both tanks to assess the influence of the seabed. It is worth highlighting that, as expected, the presence of the seabed increases damping effects, particularly in heave, even when the GBS is still 12m away from the seabed. When the GBS come close to the seabed, damping also increases significantly for pitch and roll. It is also worth noting that when the GBS is close to the surface, damping also increases for both heave and pitch/roll.

7.7. Task 6 Conclusions

An extensive and ambitious tank testing campaign has been performed covering both the towed transport and the ballasting process on the ELISA GBS Foundation Technology which is towed from harbor to site carrying the pre-installed WTG and wind tower. The test campaign has involved two different tank facilities to better reproduce all relevant conditions regarding water depth and has covered a wide range of meteocean conditions representative of the planned operations to be performed in the US East Coast.

As general conclusions the following aspects can be highlighted:

- Results from the tank tests have been useful to confirm a suitable global performance of the platform during the whole Transport and Installation (T&I) Process. Motions are low and far from the pre-established design thresholds for max tilt or accelerations of the WTG.

- As expected, it has been confirmed that motions tend to decrease as the GBS increases its draft during the ballasting process, in particular when the GBS comes close to the seabed before touchdown due to the influence of the seabed.
- The results have been well aligned with the predicted results derived from numerical simulations by NREL with maximum tilt and accelerations lower but similar to those predicted (results from the numerical simulations have anticipated very well the behavior of the platform and delivered design values for motions and accelerations on the safe side). This confirms that with proper calibration the performance of the system can be adequately and safely replicated by the numerical simulations used for design purposes.
- Maximum tilt observed during the towed transport in the tests remained below 3deg, lower than the maximum 3.6deg predicted in the simulations and comfortably below the pre-established design threshold of 5deg.
- Maximum horizontal acceleration at the WTG observed during the towed transport in the tests remained below 1.1m/s2, lower than the maximum 1.25m/s2 predicted in the simulations and comfortably below the pre-established design threshold of 4.5m/s2, confirming that transport and installation of the WTG on top of the ELISA GBS foundation will generate very moderate and comfortably admissible motions and forces on the WTG components.
- It has been confirmed that proximity to the seabed favorably increases damping and reduces motions prior to touchdown.
- Sensitivity to modelling strategy and pretension of towing lines: Tests were carried out with soft-lines and non-linear lines, and with higher and lower pretension on the lines. It is demonstrated that effects on the overall platform response in terms of tilt and accelerations are not significant.

8. Task 7 –Telescopic joint detailed design for substructures supporting large turbines

The aim of this task is to analyze the horizontal joint of concrete tower in the case of the use of ELISA technology with telescopic tower and its scalability for very large turbines.

8.1. Brief introduction to the potential use of the telescopic tower

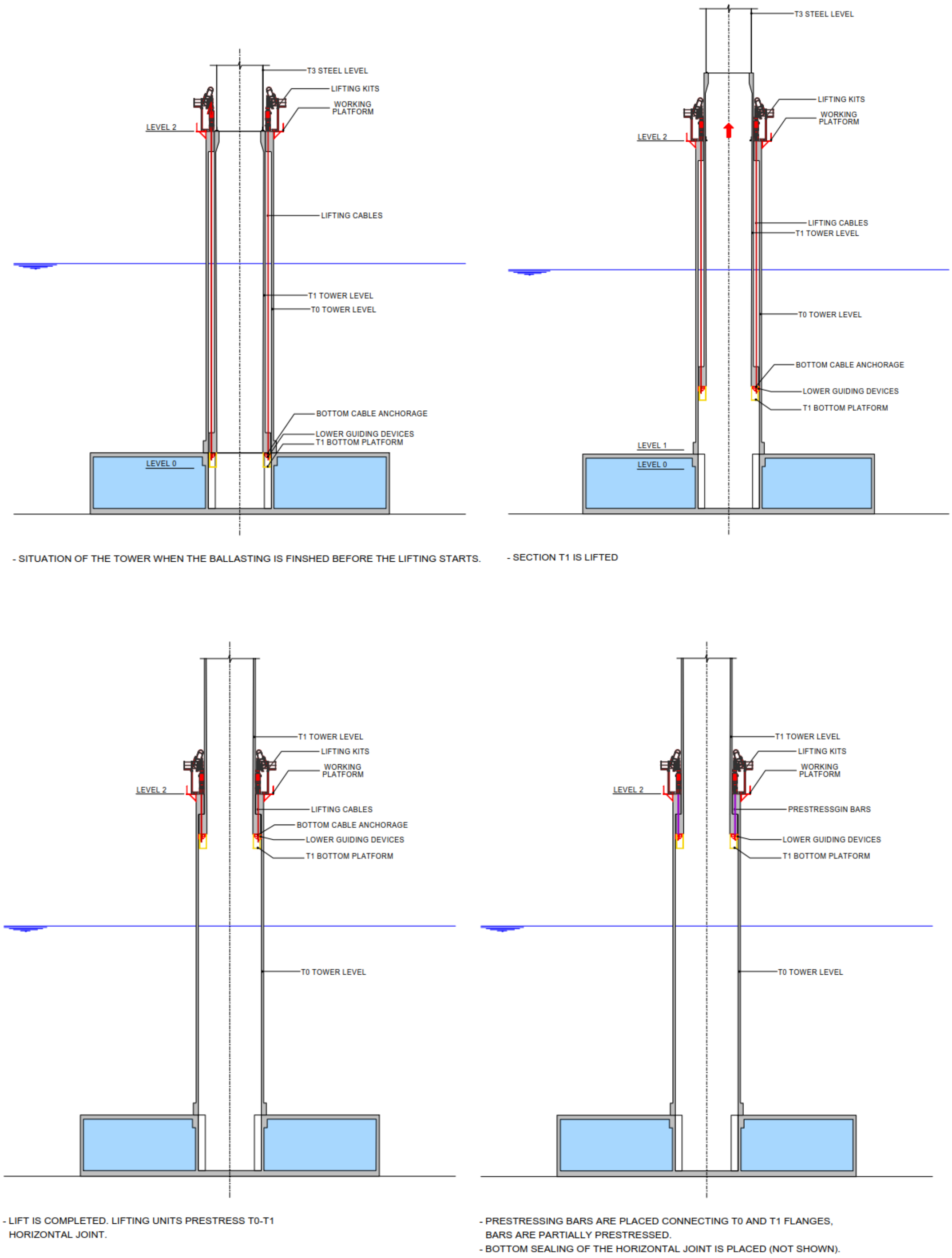
The ELISA technology may use a conventional tower or a telescopic tower which is lifted with reusable heavy-lift strand jacks once the GBS is installed offshore (see Figure 3). If needed, the telescopic tower allows to reduce the RNA installation height at port and lowers the CoG during towed transport. Current base case for WTG sizes up to 22MW and water depths up to 45m (approx.) is a configuration without telescopic tower, since there are commercial onshore cranes capable of performing the onshore assembly of the WTG. For future scenarios with even larger turbine rated power or water depth, the configuration with telescopic tower may be selected to ensure that commercial onshore cranes can adequately perform the onshore installation of the wind turbine.

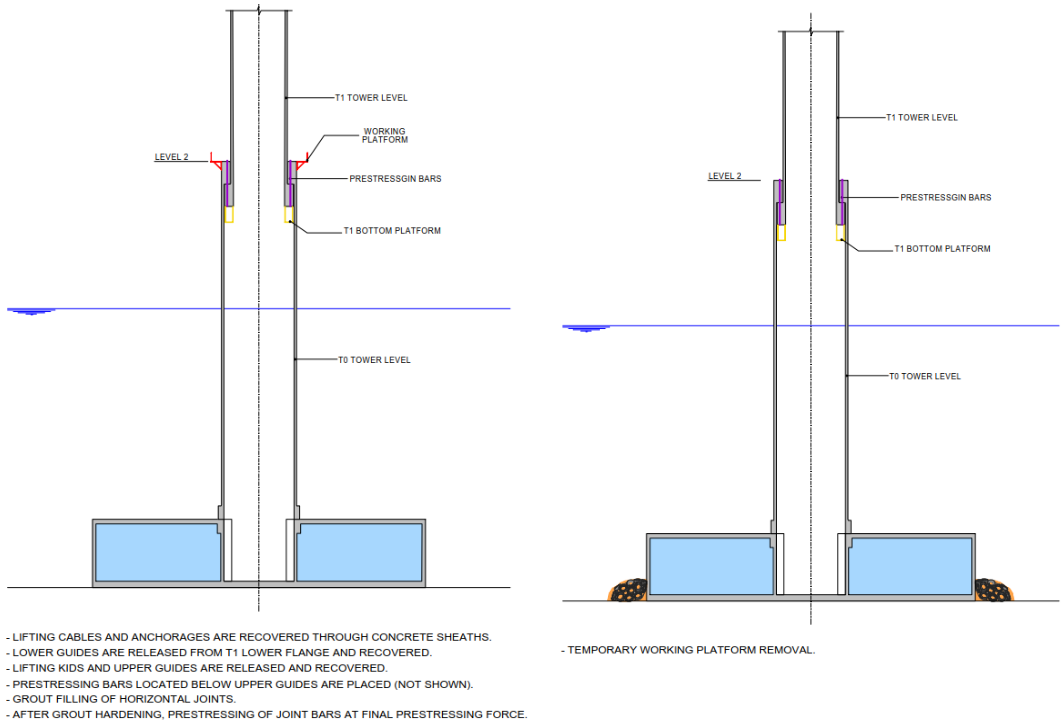
The telescoping joint system allows the tower to be folded for onshore turbine installation and towing to offshore site and erect it once it rests on the seabed.

The lifting process is carried out by means of conventional hydraulic strand-jacks and uses procedures similar to other existing in the civil industry.

Figure 51. General description of the lifting process

Deliverable 7.1





8.2. In-service analysis - Ultimate and Robustness Limit States

8.2.1. Telescopic Joint Design Philosophy

The horizontal joint of the telescopic tower is obviously a key element in the design for an adequate structural performance of the tower. Therefore, it has been analyzed with particular attention and verified with conservative assumptions and comfortable safety margins.

Several more or less complex mechanisms interact in the load transmission through the horizontal joint, which are described next and have been analyzed through detailed and advanced FEM modelling first and through an extensive lab testing campaign of the horizontal joint strength.

Once these mechanisms have been analyzed, quantified, and understood adequately, safe verification methodologies can be derived for design purposes. These methodologies can be simplified by neglecting on the safe side some of the load transfer mechanisms that will somehow increase the joint strength but complicate its analysis and verification, bearing in mind that it is not in these key elements were savings are to be pursued.

Figure 52. Horizontal joints

Horizontal joints cross-sections (Left: at lifting tendons; Right: at prestressing bars)

Deliverable 7.1

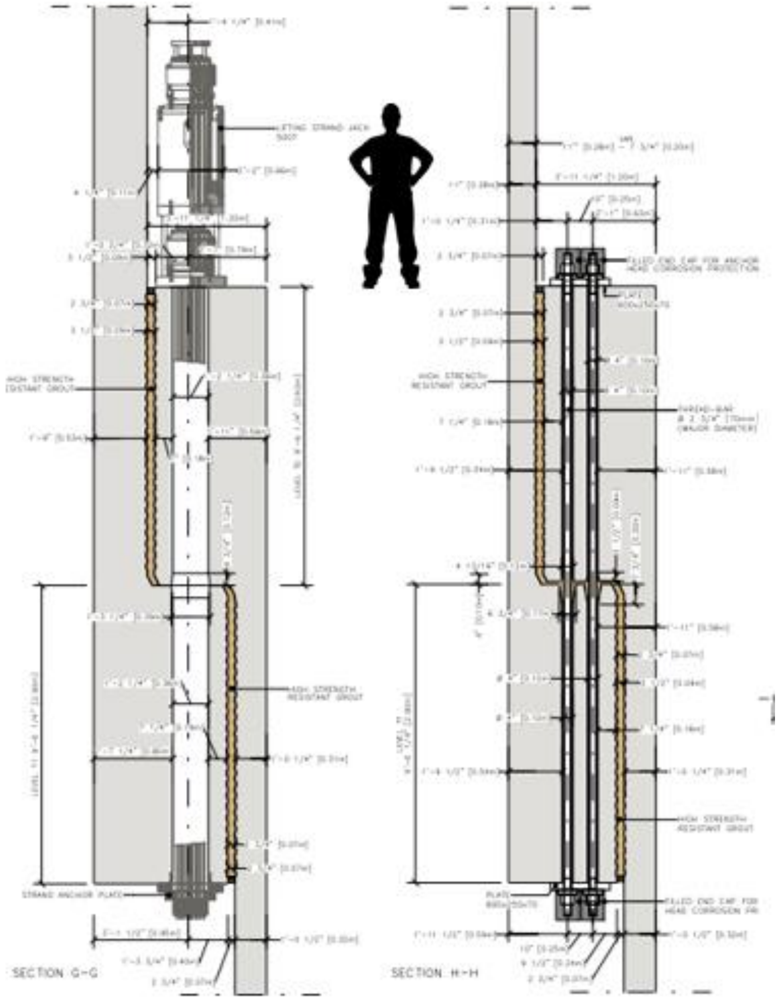
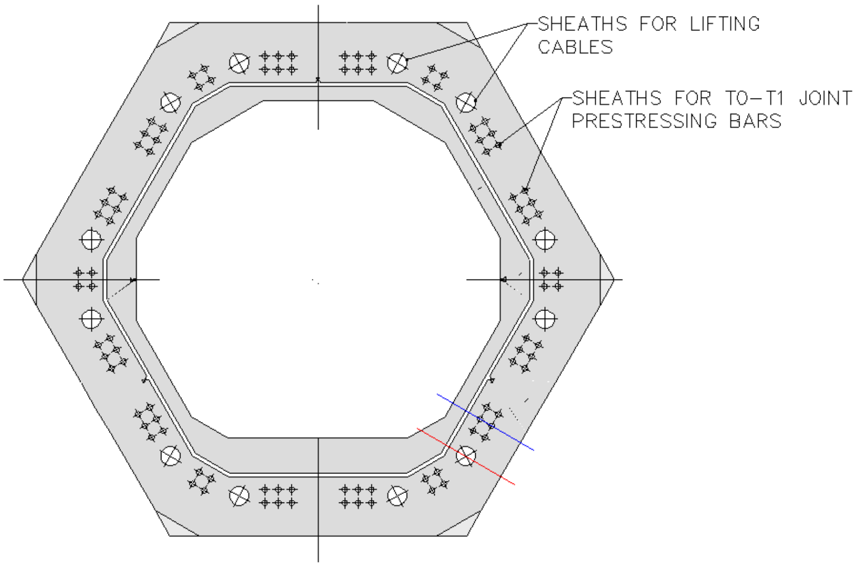


Figure 53. Horizontal joints

Horizontal joints plan view

Deliverable 7.1



In summary, the main two mechanisms which will contribute to the horizontal joint strength are:

- **Indented shear joint contribution**

The indented shear joint has been considered conservatively as a secondary mechanism which will complement the joint strength and will provide robustness to the joint.
Vertical surfaces of contact between levels will be filled with high strength grout without shrinkage and will be provided with shear keys to improve its capacity in the transfer of shear forces.
Shear transfer has been assessed in a conservative way based in Codes and Lab Tests Results. The contribution of adhesive bonding and shear key interlock mechanisms has been neglected, and additional safety factors stated by Esteyco (SF=2) for the contribution of shear-friction mechanism has been considered. That leads to a very conservative estimation of at least 0.5 MPa of shear strength for the indented shear joint. As a reference, that means 3000 KN/m of shear strength for a 6m high indented surface joint.

- **High-tensile prestressing bolts contribution**

The strength prestressing bolts have been designed to withstand by themselves the complete design load (i.e. factored extreme loads).
A linear-elastic analysis of the horizontal joint is performed to define the required strength of the prestressing bolts. In this analysis it is verified that with the compression force provided by the prestressing bolts there is no decompression on the horizontal joint interface not only under service (quasi-permanent) combination of loads but also under factored extreme loads. Also, the bolts strength is verified under the factored extreme loads combination considering no contribution from the indented shear joint.

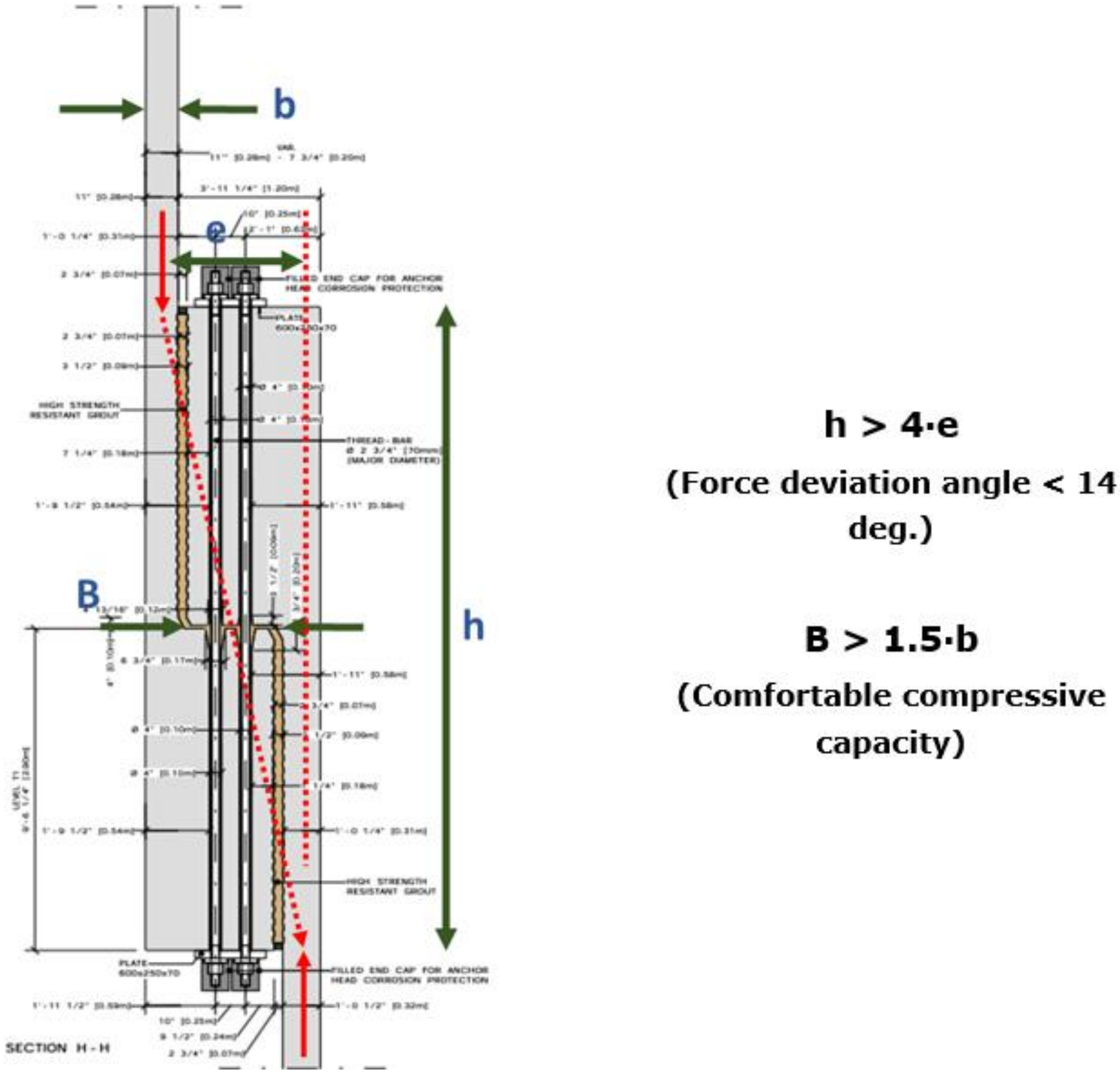
8.2.2. General geometry of the joint (Level 0)

Joint geometry is based on simple principles for robustness and sufficiently smooth force deviations as indicated in next figure:

Figure 54. Telescopic Joint Geometry

General Criteria for definition of Telescopic Joint Geometry

Deliverable 7.1



8.2.3. Mechanisms for transfer of bending moments

The telescopic joint must transfer Bending (Mxy), Shear (Fxy), Torsion (Mz) and vertical load mainly due to self-weight (Fz). Among these, the prevailing and governing force is of course bending (Mxy). Different mechanisms will contribute to the transfer of bending moment:

A) **Horizontal Forces from tube interlock**

B) **Vertical Forces in the vertical connection between flanges**

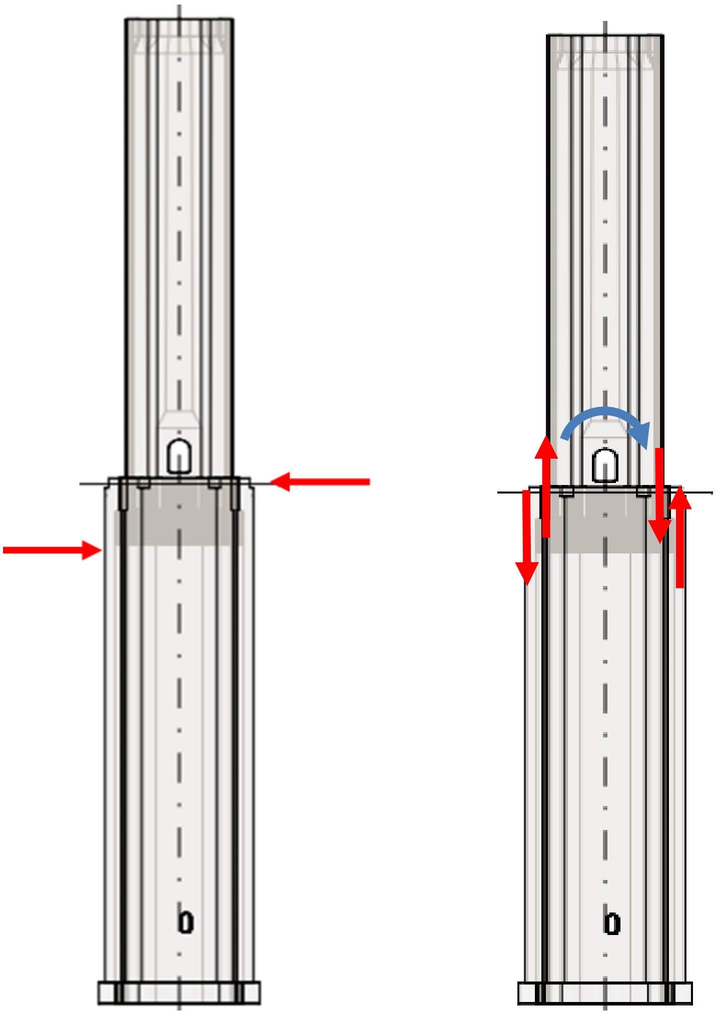
B1. Vertical Shear Transfer through the Keyed Grouted vertical Joint

B2. Vertical prestressing bolts.

Figure 55. Mechanisms for transmitting bending moment.

Mechanism A based on horizontal forces from tube interlock (left) and Mechanism B1 and B2 based on transfer of vertical forces across the joint (right)

Deliverable 7.1



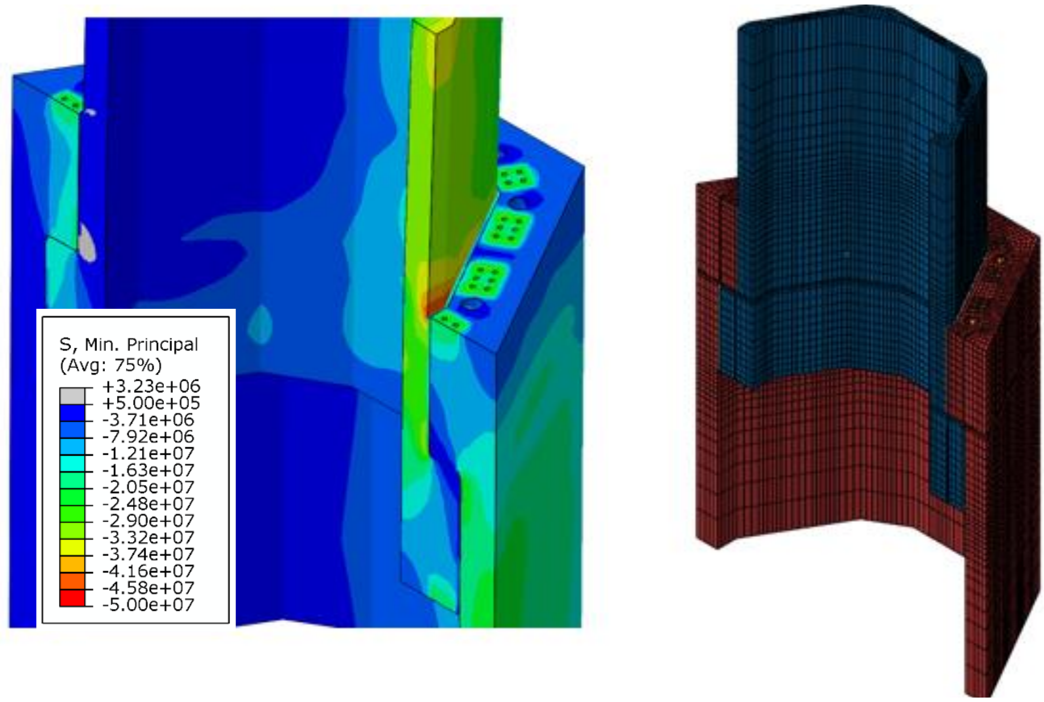
8.2.4. Advanced solid FEM model for complete verification of the joint and validation of previous simplified models and assumptions (Level 2)

A detailed FEM model based on ABAQUS software and solid FEM elements has been developed for final verification of the joint and confirmation of the validity of all safe assumptions and simplified models used in previous stages of the design process.

Figure 56. Advanced solid FEM

Advanced solid FEM model for detailed analysis and final verification of the joint. Extreme ULS Factored (Level 2)

Deliverable 7.1



Main conclusions obtained at are:

- Confirmation of the resisting mechanisms assumed and of the global structural capacity of the horizontal joint.
- Low stresses in concrete. Below 20-25 MPa in SLS. fcd not reached even under Extreme factored Loads.
- Flange interface remains compressed all around even under ULS loads.

8.3. Pre-service analysis – Lifting

Lifting operation is a key aspect of the whole installation procedure of the telescopic tower. In this chapter a general description of the lifting process is included as well as a description of the acting forces and resisting mechanisms. Detailed results of the liftin analysis were performed and included in Task 7 deliverables.

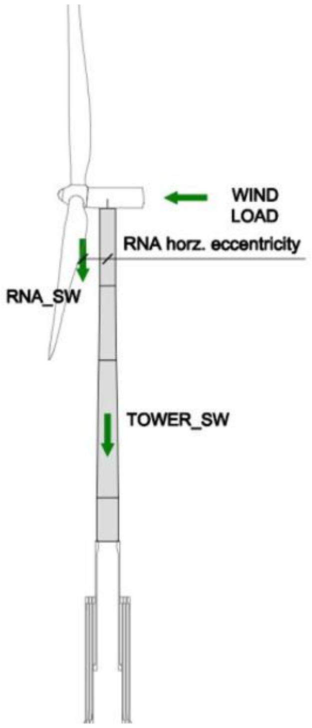
8.3.1. Acting forces

The lifting and guiding systems are designed to adequately withstand all possible forces affecting the hoisted tower sections as they rise. These include vertical forces due to self-weight, and all horizontal forces and/or eccentricities resulting in overturning moments on the tower. The horizontal and/or overturning forces include:

- Wind loading on the RNA and tower.
- Dynamic inertial forces due to maximum movements and/or deflections of the tower.
- Eccentricity from RNA cog to the tower axis.
- Eccentricities resulting from maximum inclinations and/or deflections of the tower.

Figure 57. Lifting maneuver design approach

Deliverable 7.1



The tower lifting is obviously a weather restricted operation that will only be carried out with wind speeds under a given threshold, as are all turbine erection operations. Adequate weather forecast shall therefore be needed, as is the case for the assembly of other components. It is noted that when the joint is closed a safe state is reached and terminates the weather restricted operation.

With average lifting speeds of approximately 6-8m/h, the tower lift will take in average 5-6 hours. However valid weather windows of no less than 12 hours shall be required before starting the tower lift to make room for possible contingencies.

It is important to note that some of the horizontal acting forces, such as wind loads and inertial loads, may be acting in different directions, whereas others such as the seabed inclination are fixed and known (in this case seabed inclination es expected to be nearly zero). There is also the possibility to choose the direction of some other loads such as the RNA eccentricity, in which case it will need to be set to minimize the resulting acting loads.

In order to simplify the lifting analysis, and properly assess the acting loads during lifting operations, it is required to make some simplified and conservative assumptions as well as to define some installation measures regarding the load's direction:

- All forces, except for RNA eccentricity and seabed inclination, are conservatively assumed to reach maximum values simultaneously and acting on the same direction.

- RNA alignment during lifting operations will be set in the opposite direction of the seabed inclination. It is not required to be exactly in the opposite direction to the maximum slope but at least they will need to be acting with opposite sign. It is not intended to subtract loads but to neglect the seabed inclination to simplify conservatively the analysis.
- Different maximum wind speeds to proceed with the lifting operations will be defined depending on the predominant wind direction at the moment when the lifting takes place. The idea is to align the RNA in the opposite direction of the predominant wind direction so that wind loads and RNA eccentricity are acting in the opposite direction when the maximum wind speed takes place.

Considering wind direction and seabed slope the optimum RNA alignment is defined so that the resulting overturning forces are minimized during lifting operation. It is expected that in most cases wind direction will be more relevant since the seabed slope is expected to be small.

All the combination loads are adequately multiplied by the corresponding safety coefficients in order to obtain maximum design forces that may occur on the lifting units, guides and the tower flanges and walls.

8.3.2. Resisting mechanisms

Vertical forces are obviously resisted by the lifting units. As for horizontal loads acting on the rising part of the structure, they will generate overturning moments at its base which are to be adequately resisted. Two mechanisms will contribute to bearing these forces:

- A variation of force on the lifting cables
- The horizontal forces on the guiding devices

Figure 58. Lifting cables

Resisting mechanisms which contribute to resist overturning moments on the tower: horizontal forces on the guides and variation of force in the lifting units.

Deliverable 7.1

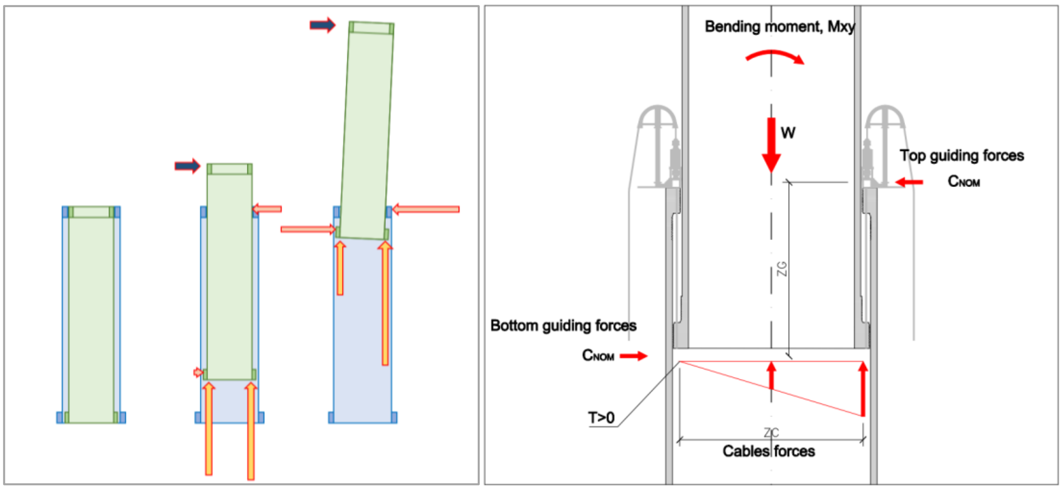
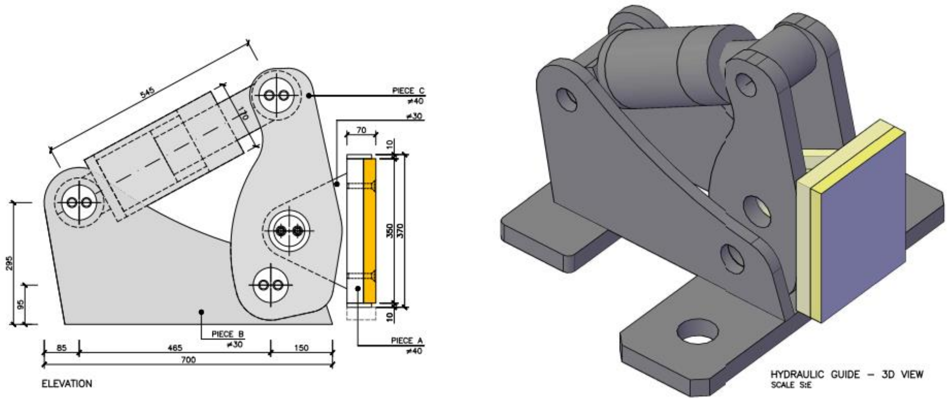


Figure 59. Guiding devices

Upper guiding devices located at corners of T0 top flange to provide stability during lifting operation.

Deliverable 7.1

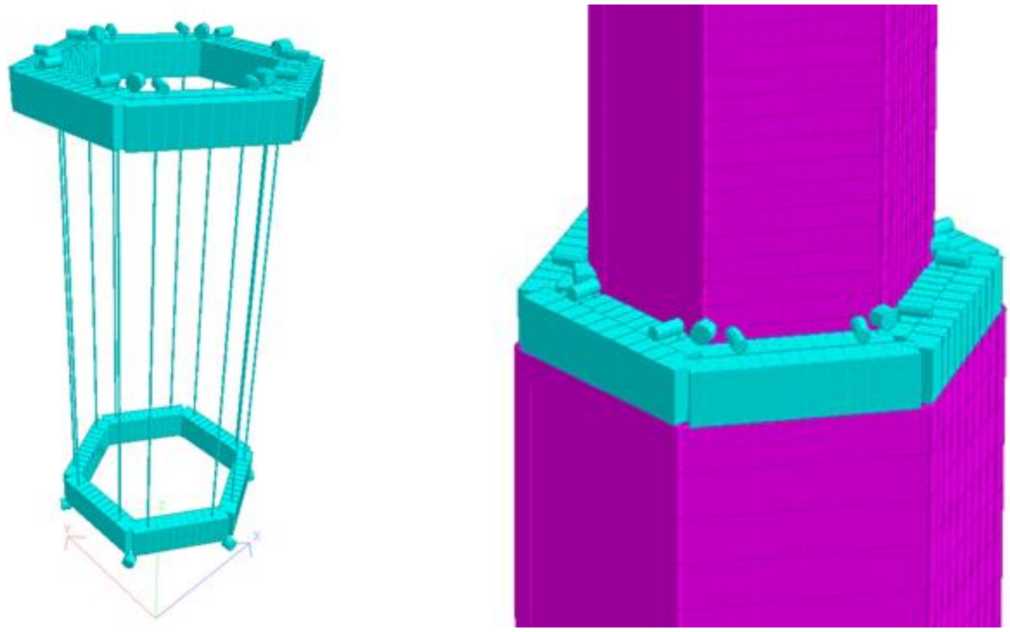


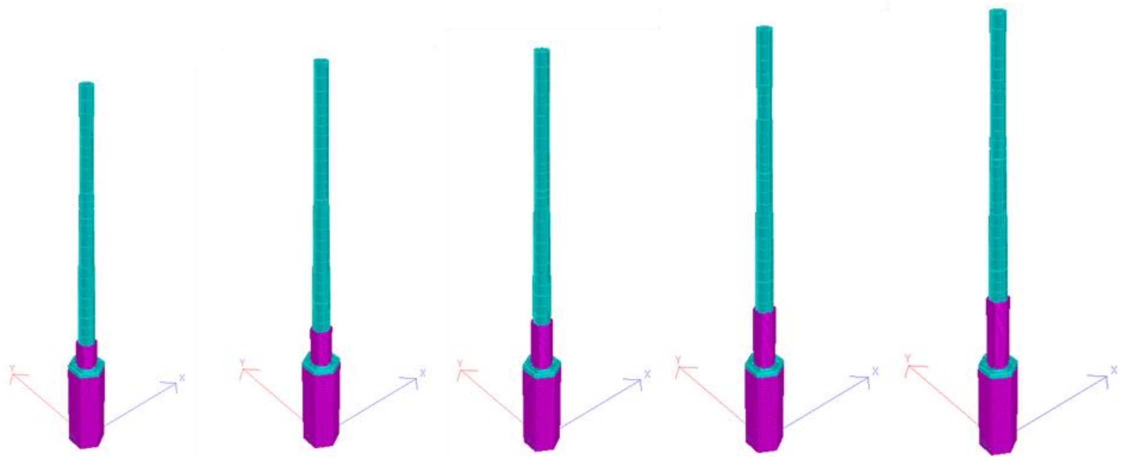
The contribution of each of these mechanisms and the resulting design forces on the lifting units and guides will depend on their relative stiffness and it has been thoroughly analyzed with FEM models that take into account several lifting steps and possible wind direction and force.

Figure 60. Strand jacks and guiding devices

FEM models are analyzed for several lifting heights to evaluate the distribution of the acting moment between resisting mechanisms: strand jacks and guiding devices

Deliverable 7.1





The overturning moment resisted by the lifting units will increase the load on the units on one side of the tower and reduce the load in the units in the opposite side, particularly during the final upper stage of the lift. This is adequately considered in the design:

- On one hand enough overcapacity of the lifting units is provided so that force increments due to acting moments can be resisted.
- On the other hand, it is verified that force reduction on the lifting units in which force decreases will not generate cable slacking (the cables shall maintain a minimum tension force).

Any movements from torsional moments during the lifting operation will be prevented through the bottom guiding devices. The bottom guides will be provided with two different jacks, which will be separated as much as possible in order to provide lever arm to bear torsional loads during lifting operation. That is also included and analyzed in the FEM models used to check every stage of the lifting operation.

Overall, under extreme factored loads, it is verified that:

- Maximum load on any lifting unit is below 500 tn
- Maximum load on any guide is below 300 tn

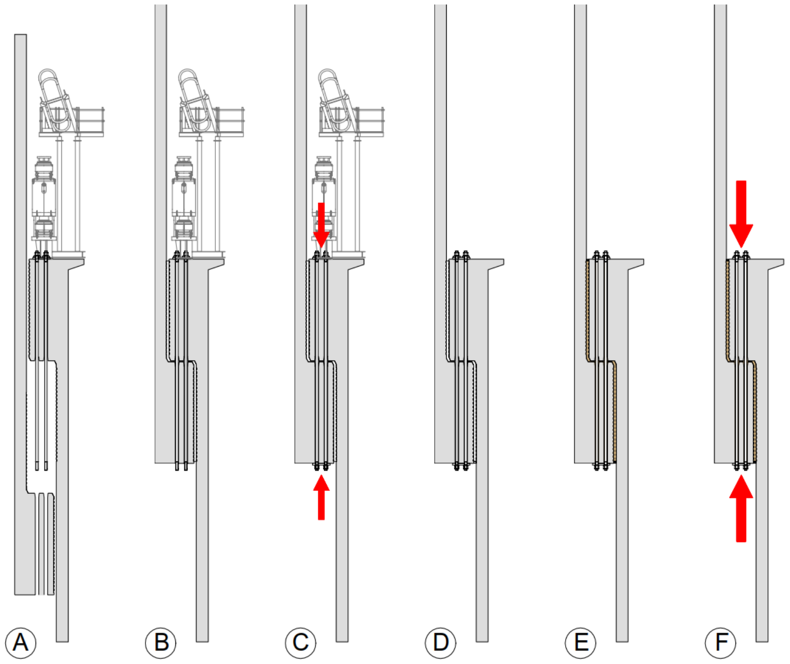
8.4. Pre-service analysis of the horizontal telescopic Joint

8.4.1. Execution process

The lifting operation involves temporary stages for the horizontal joint T0-T1 which need to be properly analyzed and verified. Essentially the idea is that the horizontal interface between flanges will be provided with a few dry contact areas so that the joint can be closed with the strand jacks. Afterwards, the remaining horizontal interface is filled with high strength and non-shrinkable grout. Once it is hardened joint bars are prestressed and the strand jacks can be released. Adequate strength along all these stages has been analyzed and verified as reported in Task 7 deliverables.

Figure 61. Horizontal joint execution process

Deliverable 7.1



8.4.2. Correction procedure in case of misalignments of tower axis

The telescopic joint design allows for correction of verticality if needed. Further details are given in Task 7 deliverables.

8.5. Task 7 Conclusions

The ELISA GBS technology with telescopic tower may be a suitable option for scenarios in which onshore crane availability for WTG integration in harbor was an issue.

Current Commercial onshore cranes (ringer cranes) do provide capacity for installation of 22MW turbines with foundations up to 45-50m water depth. Beyond that, the telescopic tower can be considered as an option to overcome crane availiabilty concerns.

Small pilot and pre-serial projects with a reduced number of turbines may also consider the use of the telescopic tower solution to avoid the high cost for mob-demob of ringer cranes. However, for large commercial projects such as the ones used as reference for the present project, such mob-demob costs can be distributed among a larger number of turbines and mobilizing a large capacity ringer crane is envisioned to be the more cost-effective solution.

This task provides a thorough description and structural analysis of the telescoping joint and its scalability from the 5MW demo unit developed in Spain to very large turbines as the IEA 15MW reference turbine.

9. Task 8 – Adapt the conceptual design to existing supply chain and facilities

One of reference location analyzed is the New York Bight, for which the full local construction of the GBF and assembly of the steel tower and RNA has been assumed in Arthur Kill Terminal (NY).

Arthur Kill Terminal (under planning) has no air-draft restrictions which is a distinctive in the New York region. However, it has a more limited quay length, which makes it recommendable to used foundations with lower diameter, so that the same production ratios (1unit/week) can be maintained using less key length. To that end, an alternative ELISA foundation design which minimizes the required diameter was developed as part of Task 8.

The full fabrication and industrialization process of the foundations was defined to assess the potential production ratios, as described in detail in the following sections.

9.1. Alternative GBS design with reduced footprint

The previous reference configuration (used in Task 3 and Task 4) for analysis of installability and constructability was a foundation ballasted only with water and with no skirts. That configuration was considered as base case on the safe side being the one leading to the largest and heaviest foundation design and thus the one more restrictive and demanding regarding the construction and installation process, therefore acting as an envelope to alternative configurations leading to smaller and lighter configurations of the concrete structure.

In many cases the use of solid ballast within the foundation and/or the use of short skirts may be preferred and lead to reductions in foundation size and concrete weight. This has been the case in the new scenario of Task 8, in which an alternative design with a reduced base diameter has been considered. A reduced diameter base allows maximum use of the port quay and in this case, as will be seen in the following sections, it has allowed optimum implementation at the Arthur Kill Terminal to adjust the manufacturing speed to the desired rate of no less than 1 unit per week.

The reduction of the base diameter has been achieved by means of sand ballast inside the tower shaft (T0).

9.1.1. Description of the alternative GBS design

For the alternative design, a base platform has been sized for the scenario in which the base is initially ballasted with water and additional sand ballast is provided once the GBS is in its final position. The sand ballasting is only located in the central shaft, including the base inner shaft, while the base cells shall be ballasted only with water. This facilitates the ballasting and the decommissioning process.

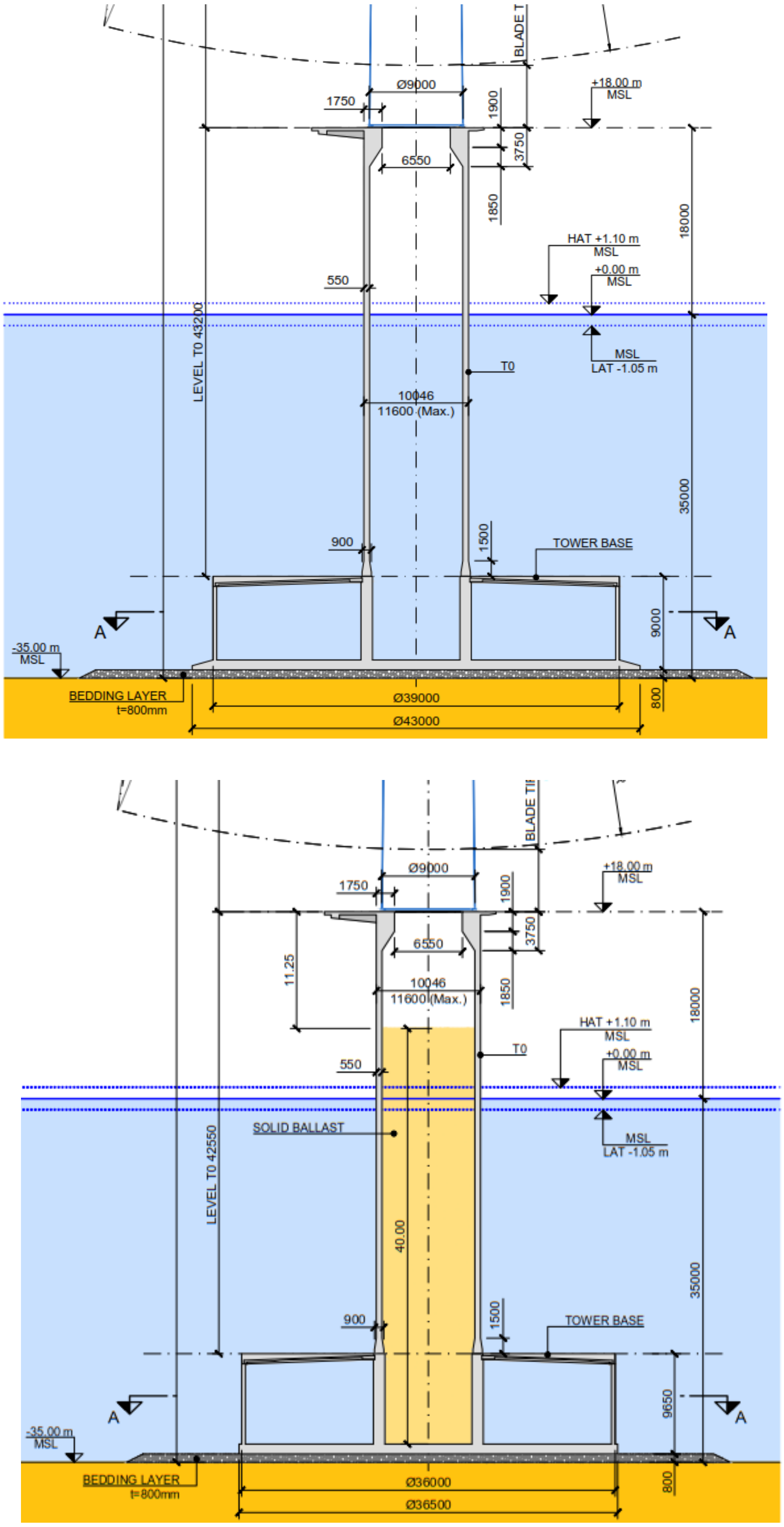
The overall geometry, materials and construction process remain the same as in the previous design developed in Task 3.

The next figure shows the general arrangement of the original GBS in which only water ballast was considered.

Figure 62. ELISA General Arrangement with and without use of solid ballast

ELISA GBS General arrangement without solid ballast (top) and with solid ballast (bottom)

Deliverable 8.1



The following table provides a comparison of the main parameters and quantities for both options.

Table 29. Comparison of main parameters for designs with or without solid ballast

Deliverable 8.1

	ELISA (WITHOUT TELESCOPING)		DIFF	
	W.O. Solid Ballast Task 3	W. Solid Ballast Task 8	ud	%
Depth (mMSL)	35.0	35.0	0.00	0.00
Base diameter at lower slab (m)	43.0	36.5	-6.50	-15.12
Base diameter at walls (m)	39.0	36.0	-3.00	-7.69
Heel slab (m)	2.00	0.25	-1.75	-87.50
Base height (m)	9.00	9.65	0.65	7.22
Base concrete dry weight (t)	6675	5795	-880	-13.19
T0 length (m)	43.2	42.6	-0.65	-1.50
T0 hexagon side (m)	5.8	5.8	0.00	0.00
T0 concrete dry weight (t)	2223	2240	16.65	0.75
Total concrete dry weight (t)	8898	8034	-864	-9.71
Steel tower length (m)	120.6	120.6	0.00	0.00
Steel tower weight (t)	745	745	0.00	0.00
RNA weight (t)	950	950	0.00	0.00
GBS weight during transport w/out ballast (t)	10717	9864	-852	-7.95
Solid Ballast dry weight (t)	0	3518	3518	-
Hub height (mMSL)	144.0	144.0	0.00	0.00
EWP height (mMSL)	18.0	18.0	0.00	0.00
Freeboard Base+T0 (m)	1.8	1.8	0.06	3.25
Draft Base+T0 (m)	7.2	7.8	0.59	8.21
GM during transport/installation (m)	10.2	10.9	0.70	6.84
Tpitch during transport/installation (s)	37.4	39.1	1.65	4.41
Bed thickness (m)	0.8	0.8	0.00	0.00

9.1.2. Influence of diameter reduction on geotechnical verifications

Next table summarizes the geotechnical and stability verifications carried out in the present analysis (refer to Task 3 for detailed description of the verifications), considering two different reference soil profiles which have been defined as representative of expectable conditions.

Table 30. Comparison of geotechnical verifications

Deliverable 8.1

	W.O. Solid Ballast (T3)		W. Solid Ballast (T8)	
SF Overturning	1.72		1.74	
SF Gap Quasi (%)	1.28 (0.00%)		1.33 (0.00%)	
SF Gap Charact (%)	1.63 (13%)		1.70 (11%)	
Cohesionless / Cohesive Soil	φc= 35º	su= 135 kPa	φc= 35º	su= 135 kPa
SF Sliding (factored i.a.t. DNV-RP-C212)	1.00	1.36	1.18	1.01
SF Bearing (factored i.a.t. DNV-RP-C212)	1.50	5.17	1.36	3.00

As shown in the first three rows of the table, stability checks remain almost the same, i. e. the reduction of the base diameter is compensated by the favorable weight of the sand ballast. However, geotechnical verifications do vary significantly being the design with sand ballast favourable for the reference cohesionless soil and unfavourable for the reference cohesive soil.

9.1.3. Bill of quantities of the alternative design

Estimated bill of quantities for the alternative design described in previous sections have been estimated as given in the following table.

Table 31. BOQ

BOQ of the alternative design with sand ballast

Deliverable 8.1

Bill of Quantities for the alternative GBS configuration with sand ballast		
Concrete Volume T0 (fck=10ksi)	896	m3
Concrete Volume Base (fck=7ksi)	2318	m3
Passive Steel reinforcement T0 (Gr. 75 ksi)	161	Tn
Passive Steel reinforcement Base (Gr. 75 ksi)	371	Tn
Prestressing steel (Gr 270 ksi - 0.62" Low relaxation)	55	Tn
Prestressing bars for Connection to steel tower (Gr. 150 ksi)	10	Tn
Sand Ballast (dry weight)	3518	Tn

9.2. Industrialization: supply chain and port facilities

9.2.1. Fabrication and installation procedure

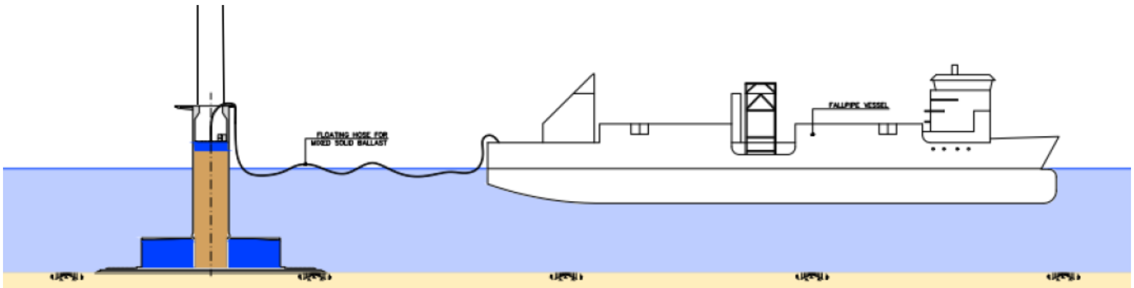
A detailed description of the fabrication and installation procedure was included in Task 4. Next paragraphs are only a summary of the procedure:

- The GBS fabrication is assumed be done in the water, alongside the quay. However, while a commercial semi-sub barge was considered in Task 4, a modular barge has been assumed for this new scenario. The use of modular barges in conjunction with a reduced base diameter leads to a reduced necessity of port quay.
- The ELISA technology permits the installation of the wind turbine on the GBS at harbor. Once the turbine has been assembled onto the GBS, an auxiliary floater (called TIM) is attached to ensure stability during transport offshore and during installation, when the water ballasting is carried out.
- Transport and positioning are performed by simple towing with conventional tugboats.
- Water ballasting takes place by flooding the GBS internal chambers in a controlled manner. The full operation is unmanned, performed from a Control Vessel that accompanies the whole process.
- Once the foundation lies on the seabed, water ingress is completed, the auxiliary floater is decoupled (unmanned operation) and returned to port by towing with one of the tugboats used.
- In the case of the use of sand ballast, as in the current alternative GBS design, the central shaft is filled by means of a floating hose and pumping from a fall pipe vessel.

Figure 63. Central shaft filling

Filling central shaft with sand ballast

Deliverable 8.1



9.2.2. Construction on barges

Construction on barge strategy is based on the vast experience for mass serial production of concrete caissons (see picture below). It minimizes required harbor yard area and upfront investments for yard upgrades or load-out means.

Figure 64. Conventional construction on barges

Conventional construction of concrete caissons on barges

Deliverable 8.1

Semisubmersible barges or floating docks to be used can be foreign (they do not transport anything between two points and are therefore not affected by the Jones Act). Expected water depth at Arthur Kill Terminal quay side will be suitable for their use.

Conventional or sliding formwork can be used for vertical walls, emulating proven and very cost-effective concrete caisson manufacturing processes (concrete caissons are conventionally produced with rates of one unit per week with concrete quantities per caisson often 3 times larger than in an ELISA Foundation Base).

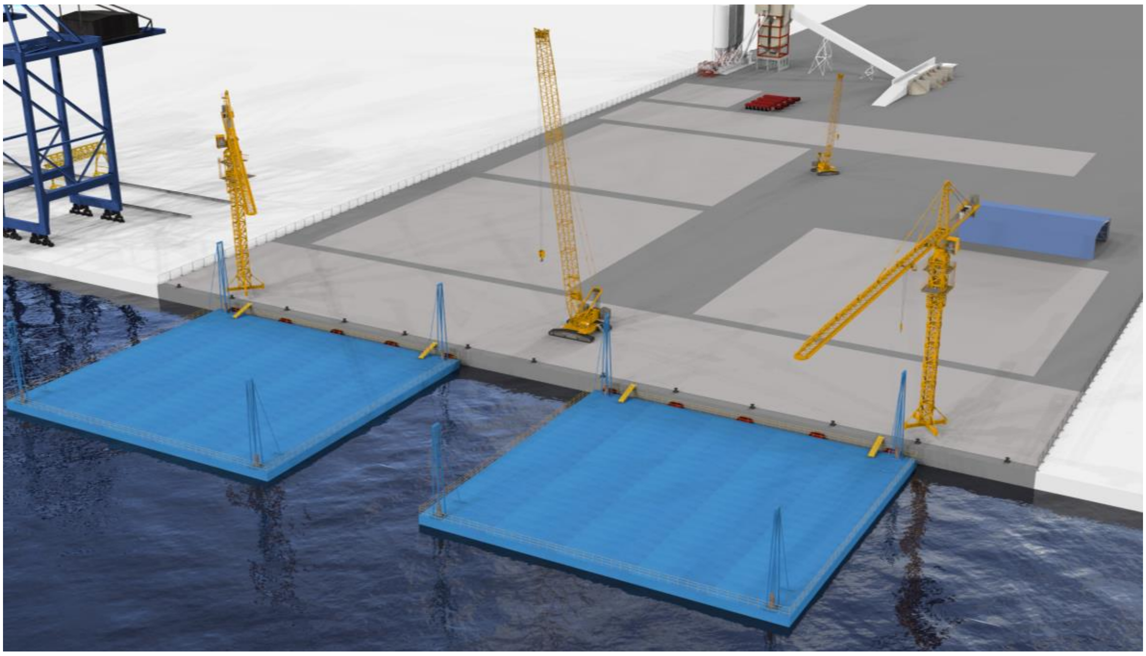
Precast planks are used for the simple concreting of upper slab with no need for formworks or scaffolding (see Task 3 for detailed information).

The tower is cast-in-situ after float-off, working from the quay, with conventional slip-forming or climbing formwork techniques.

Figure 65. Modular barges

Two modular barges proposed for ELISA GBS at Arthur Kill Terminal

Deliverable 8.1



Dimensioning of barges is based on commercial barge modules ranging from 20’x8’x9.5 to 44.5’x11.5’x10’ (LengthxWidthxHeight). In the present study the assumed characteristics of the barge module are the following:

Table 32. Barges modules

Main characteristics of assumed barge modules

Deliverable 8.1

BARGE MODULE		40'x8'x9.5'
P	14.4	t
L1	12.19	m
L2	2.44	m
depth	2.89	m
DL	167	kg/m3

The required modular barge for construction and float-off of the base should be around 49x56x2.89 (4x23 modules 40'x8'x9.5'). The shorter dimension of the barge should be arranged parallel to the quay side for minimum occupancy. The required draft under the barges is around 8.5m (draft of base only plus height of barge).

9.2.3. Manufacturing and assembly activities and strategies

Once analyzed all the project activities (fabrication, transport, and installation), the main requirements to select the port installations are:

- Quay area available for the construction facilities.
- Quay length and draft, deep enough for the base float-off and when the GBS is completely fabricated, steel tower and RNA installed and for the TIM coupling.
- Sheltered water area with sufficient water depth (> 7.80m - 26FT) for GBS wet storage.

The Key points for the fabrication in the future Arthur Kill Terminal are:

- All fabrication and installation onshore activities are located at the same Port.
- No air draft restrictions since there is no bridge downstream of the facility.
- Local content is maximized.
- Reduced heavy marine transport needs but increase of the wet storage units.
- Installation of temporary production plants is not required due to the existence of commercial plants and suppliers of construction materials in the area with sufficient capacity for the required GBS construction rates, reducing the occupied areas on docks.
- Sufficient area at yard (approx. 13 ha) and berth length (approx. 400m).
- Foreseen water depth at the quay is suitable for the base fabrication afloat and for the tower construction on the ballasted base on a gravel bed.
- Available nearby anchorage zone suitable for wet storage of built units.

Figure 66. Arthur Kill Terminal

General view of future Arthur Kill Terminal and possible wet storage area

Deliverable 8.1

9.2.4. GBS fabrication

The GBS Construction strategy to achieve the production ratio of one unit per week is based on the construction afloat. The key points for this construction options are:

- This construction strategy is based on the vast experience in serial production of maritime structures as concrete caissons, so reliable, and cost-effective production rates can be achieved.
- The construction on a semi sub barge or modular barges requires less occupancy of land areas compared to construction on land.
- To fabricate the GBS's base, one semi sub-barges suitable for 2 bases construction at each one will be used, alternatively 2 single semi sub- barges or modular barges can be used.
- The ELISA GBS design allows the construction of the towers afloat or positioned onto a gravel layer, working from the quay. We have assumed the gravel beds to ensure no movements would take place during the tower´s construction.
- Only conventional construction machinery and auxiliary means (sliding or climbing formwork) with high availability in the market are required. No heavy-lift equipment is necessary.
- Low bearing capacity requirements of the yard for the base and tower construction (only conventional cranes and non-heavy transports needed in execution), so port upgrade is not required.
- Only a local reinforced area of the yard is required for the ringer crane needed for the steel tower and RNA assembly.

For a cost-effective production, the objective of the construction procedure is to industrialize the process, optimizing the construction's auxiliary means and the production ratios, while enhancing quality and safety. The construction procedure is based on the construction of the Base (lower slab, outer wall and bulkheads and upper slab) on a semi sub-barge or modular barges and the construction of the T0 outside the barge. To minimize the potential working lost days due to the sea weather conditions and reduce the possible risk in the project schedule, it is foreseen to fabricate the tower (T0) grounded on a reduced temporary gravel bed, specifically prepared for this activity.

Table 33. Activities of the GBS substructure construction

Deliverable 8.1

ACTIVITY	CONSTRUCTION PROCEDURE	SCOPE
Base fabrication	On barge	Lower Slab, Outerwall, Bulkheads core pit, ballasting system and upper slab
Tower construction	From the quay on a gravel bed	T0, internals and equipment

The GBS ballasting system must be installed at the first stage of the construction to allow the T0 fabrication with the base positioned onto the gravel bed.

The future infrastructure at Arthur Kill Terminal will be suitable for the project requirements. The availability of construction, wet storage, and float off areas, have been assumed without any major additional upgrade of the planned facility. Only the mentioned temporary seabed for T0 construction should be additionally considered.

9.2.4.1. Base fabrication

The GBS bases are cellular structures composed by a lower slab, inner and outer walls, bulkheads to divide the bases into cells (12 in this case), the core pit and an upper slab. The lower slab, the outer wall and the bulkheads are made in-situ with concrete. For the upper slab execution, some precast planks are used as false formwork for the in situ cast upper slab.

The construction procedure is based on the use of the modular formwork and the installation of pre-assembled rebar cages previously prepared on yard.

Figure 67. Preassembly

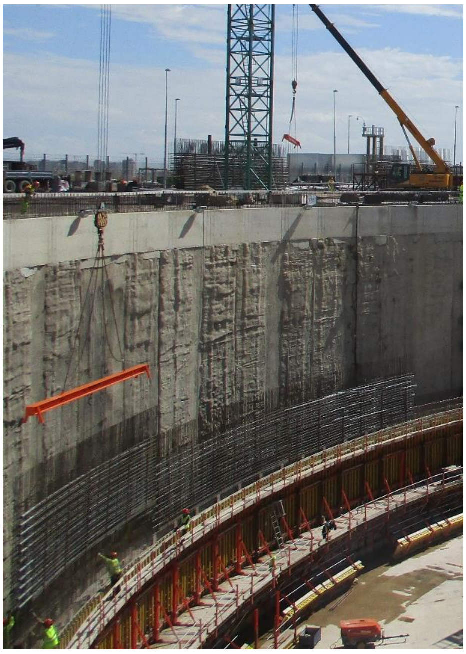
Preassembly and installation of the wall formwork (Left). Preassembly of the reinforcement cages on yard (Right)

Deliverable 8.1

Figure 68. Preassembled reinforcement

Temporary storage of the preassembled reinforcement (Left). Installation of the preassembled reinforcement on the wall (Right)

Deliverable 8.1



The duration of the basic unit cycle is 24 days (see next figure), so at the maximum, the production rate will be 1,25 units/month and per barge. The working hours assumed to achieve this ratio is one shifts per day and 7 days per week (10h/7d). Therefore, with two barges, it is necessary to approximately double the number of shifts per day (20h/7d) so that the production rate of the bases is 1.25unit/month/barge/shiftx2bargesx2shifts= 5 bases/month= 1.25 bases/week.

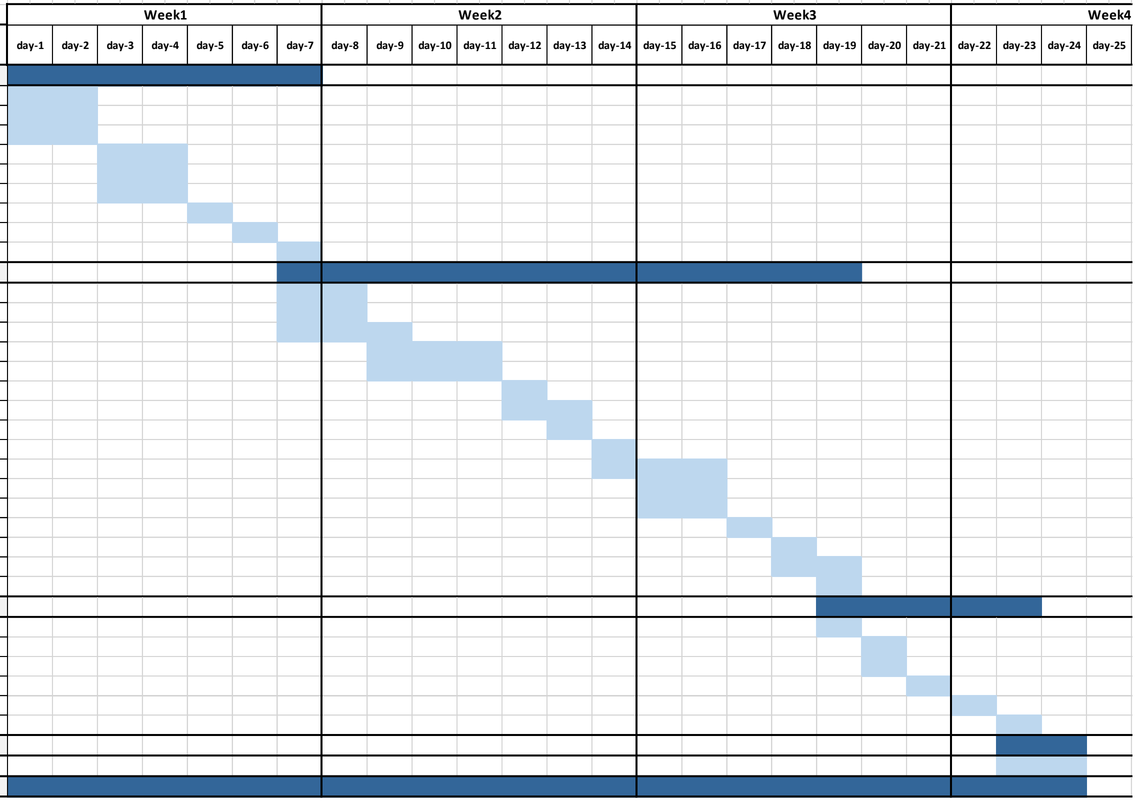
The following schedule shows the anticipated fabrication unit cycle (per barge) including the sequence of activities to be performed for the base and the duration of each one (assuming only one shift per day and 7 days per week).

Figure 69. Base construction unit cycle

Base construction unit cycle assuming 1 shift/day and 7days/week (10h/7d). With double shifts (20h/7d) the duration will be only 12 days (0.58 units/week per barge)

Deliverable 8.1

	BASE UNIT CYCLE	Start shift	End shift	Duration (days)
	LOWER SLAB	1	7	7
1	Preparations, Polyethilene film installation	1	2	2
2	Lateral formwork erection	1	2	2
3	Installation of pre-assembled rebar cages	1	2	2
4	Assembly of reinforcement cages on barge	3	4	2
5	Installation in-situ rebar (walls wating rebars) + Embedded elements	3	4	2
6	Formwork placing	3	4	2
7	Base slab concrete pouring	5	5	1
8	Concrete Curing, Joint cleaning	6	6	1
7	Formwork removal	7	7	1
	CORE PIT, BULKHEADS AND OUTER WALL	7	19	13
1	Core pit: inner formwork installation	7	8	2
2	Core pit: pre-assembled reinforcement cages installation	7	8	2
3	Core pit: Assembly of the reinforcement cages. In situ rebars & embedded insta	7	9	3
4	Core pit: outer formwork installation	9	11	3
5	Bulheads and outer wall formwork installation (alternative sectors)	9	11	3
6	Bulkheads: pre-assembled reinforcement cages installation	12	12	1
7	Bulkheads: Assembly of the reinforcement cages & In situ rebars-embedded ele	12	13	2
8	Bulheads and outer wall formwork installation (alternative sectors)	13	13	1
9	Outer wall: pre-assembled reinforcement cages installation	14	14	1
10	Outer wall: Assembly of the reinforcement cages & In situ rebars-embedded ele	14	16	3
11	Outer wall formwork installation (outer face)	15	16	2
12	Bulkheads and outer wall formwork adjustments previous to pouring	15	16	2
13	Core pit, outerwall and bulkheads concrete pouring	17	17	1
14	Concrete Curing, Joint cleaning	18	18	1
15	Ballasting system installation	18	19	2
16	Formwork removal	19	19	1
	UPPER SLAB	19	23	5
1	Precast slabs installation	19	19	1
2	Lateral formwork installation	20	20	1
3	Reinforcement installation	20	20	1
4	Concrete pouring	21	21	1
5	Concrete curing	22	22	1
6	Formwork removal	23	23	1
	FLOAT OUT	23	24	1
1	Float out	23	24	2
	BASE UNIT CYCLE	1	24	24



9.2.4.2. Tower construction

The tower consists of a hexagonal shaft with constant cross section (T0), except the upper 3,75 m where the section is enlarged to form a horizontal platform and a concrete flange used to anchor the steel tower. The concrete tower is casted in situ and post-tensioned. Secondary steel structures, as handrails, ladders, J-tubes and platforms are installed inside and outside the tower.

The construction procedure is based on the use of sliding formwork and the installation of pre-assembled rebar cages previously prepared on yard.

In this industrialized construction process and due to the importance of keeping the production pace in order not to impact the following activities of the project, it is foreseen to fabricate the tower (T0) grounded on a reduced temporary gravel bed, specifically prepared for this activity, to minimize the possible losses in terms of working days due to sea weather conditions.

The following schedule shows anticipated fabrication unit cycle including the sequence of activities to be performed for the Tower (T0) and the duration of each one.

The duration of the unit cycle is 21 days, so, 14 days for the T0 executed with sliding formwork (2 shifts/day - working hours 20h/7d) and 7 days for the top section, post-tensioning and internals & metallic structures (2 shifts/day - working hours 20h/7d).

The basic production rate will be 1 units/month per construction position assuming a couple of days as contingency. Therefore, analyzing the duration of both unit cycles, base (5 bases/month with two barges) and T0 (1,43 T0/month per working station), to achieve the desired fabrication ratio of 4 GBS/month, 3 positions of T0 fabrication are needed, allowing for contingencies.

The Section Fabrication Sequence includes the organization of the construction workstation.

Figure 70. Concrete shaft (T0) construction unit cycle

T0 construction unit cycle of 21 days (0,33 T0/week), assuming double shifts (20h/7d).

Deliverable 8.1

	T0 UNIT CYCLE	Start shift	End shift	Duration (days)
	T0	1	28	14
1	T0 transicion section	1	4	2
2	Reassembly formwork	5	6	1
3	Sliding formwork (rebars assembly+embedded elements postensioning ducts+concrete pouring)	7	26	10
4	Formwork: stripping and cleaning	27	28	1
	T0 TOP SECTION	29	38	5
1	Formwork installation	29	31	1.5
2	Rebars installation (preassembled rebar cages in conjunction with the formwork)	29	32	2
3	Postensioning ducts and achorages installation	32	33	1
4	Metallic tower anchor bolts and template installation	34	34	0.5
5	Concrete pouring	35	35	0.5
6	Concrete curing	36	37	1
7	Formwork removal	38	38	0.5
	POSTENSIONING	37	41	2.5
1	Concrete handering prior to postensioning	37	38	1
2	Strands pulling	37	38	1
3	Postensioning	39	40	1
4	Injection	40	40	0.5
5	Pockets clousure	41	41	0.5
	INTERNALS AND BALLASTING SYSTEM INSTALLATION	41	42	1.0
1	External ladders and handrails installation	41	41	0.5
2	Internal metallic structures installation	42	42	0.5
	T0 UNIT CYCLE	1	42	21

9.2.4.3. Water ballast system

This system allows the water ingress/egress to control the draft of the GBS during transport and installation at the final site. As previously commented in this section, it also would be necessary to be operated during T0 construction. As described in Task 5, its main features are:

- Full redundant control of ballasting of 6 different cell-pairs.
- Designed for water flows allowing for complete ballasting offshore in less than 3 hours.
- Ballasting through gravity, de-ballasting via integrated pumps (x2).
- Completely unmanned remote operation and monitoring.
- Compact Design of a Central Ballasting Module comprising all main active components (valves, pumps, bilge pumps).
- Quick junction box with connectivity with PLC Control Cabinet (in Platform P1-Door).
- It allows for industrialized assembly and testing of the ballasting system and fast assembly into the Base central shaft (and eventual recovery through the door after offshore installation).
- Permanent tubes in the foundation of PLC for enhanced durability.
- Supplemented with air compressors for water tightness tests during construction and reducing differential pressures during installation.
- The installation of the system will be done in the two stages of construction: embedded parts of the system (mainly in the lower slab) will be installed while fabrication the lower slab and the outer part of the ballasting system will be installed before Base float out from the barge.

For a detailed information of the water ballast system please refer to Task 5 Ballasting System Industrial Design.

9.2.4.4. GBS Fabrication sequence

Analyzing the duration of each unit cycle to achieve the desired fabrication ratio of 4 GBS/month, 2 lines of base production and 3 T0 workstation are needed:

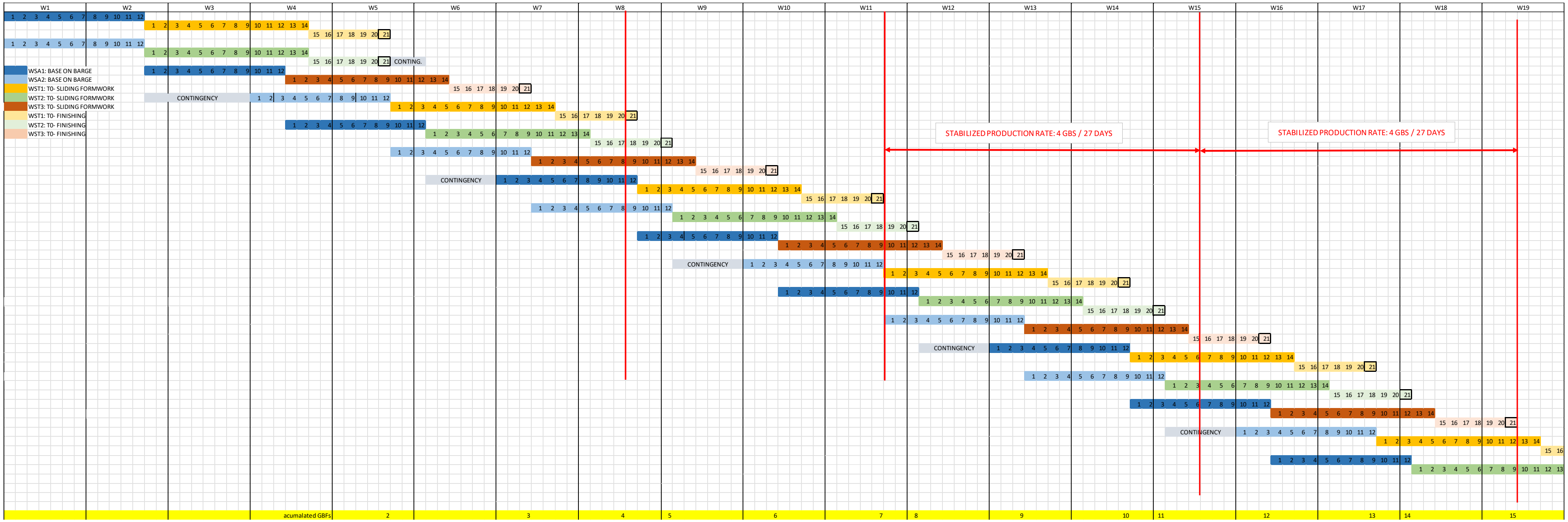
- 2 workstations for base fabrication WSA1 & WSA2 on barges: Lower slab, Outer Wall, core pit, bulkheads, upper slab and ballasting system installation.
- 3 workstations for T0: WST1, WST2 & WST3 grounded: T0 (shaft) and internals & metallics structures.

The following schedule shows the fabrication sequence considering two barges with one production lines each for the bases, and 3 positions for the T0's working in parallel at the maximum production rate.

It is shown in the schedule below that the stabilized production rate leads to 4 GBFs each 27 days, so there are still some available days for contingencies.

Figure 71. GBS fabrication sequence

Deliverable 8.1



9.2.5. Harbor layout for construction and assembly at Arthur Kill Terminal

Based on the previous fabrication methodology and sequence, the construction facilities and its implantation on site is shown in the following figure:

Figure 72. Arthur Kill Terminal

Proposed Harbor layout for construction of GBS and assembly of WTG at Arthur Kill Terminal

Deliverable 8.1

In this configuration it is foreseen the following working areas on the yard:

1. Staff and Employees facilities and parking.
2. Rebars and preassembled reinforcement cages storage and workshop to prepare the rebar cages.
3. Storage for the rebars cages next to the quay.
4. Formwork preassembly area (4a base; 4b tower).

5. Storage and preparation area for posttensioning material.

6. Metallic structures and internals storage and preparation area.

7. Precast planks storage.

8. Corridors for vehicles circulation and tower cranes operations.

9. Storage area for blades, steel tower sections, rotors and nacelles.

10. Area for the ring crane for assembling the steel tower and the RNA.

11. Length of quay for 2 workstations on barges (base construction)

12. Length of quay for 3 workstations grounded on gravel bed (tower & internals)

13. Length of quay for unloading of WTG component from vessels.

14. Length of quay for TIM coupling.

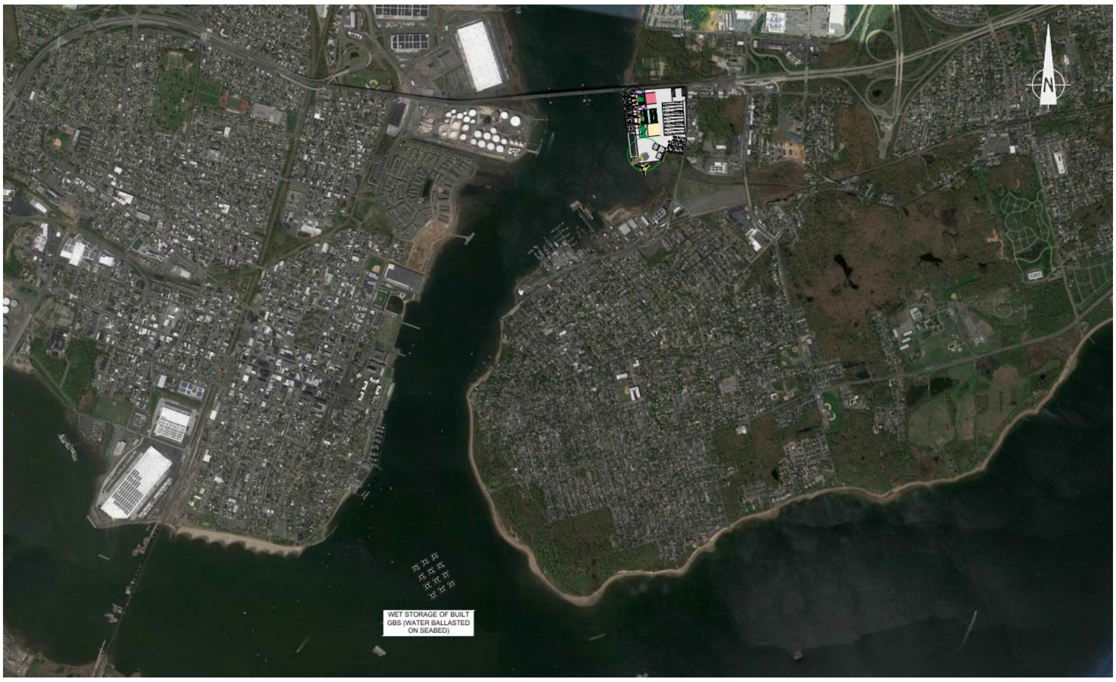
The requirements of the port facilities are:

- Area at Yard: around 14 Ha (34.6 acres) for temporary construction facilities
- Length at Quay: around 500 meters (547 yards)
- Draft at quay: approx. ranging from 8m (26 FT) to 10m (30 FT) depending on the zone.

Figure 73. Arthur Kill Terminal

General plan view of Arthur Kill Terminal harbor and proposed wet storage area.

Deliverable 8.1



9.3. Production rate comparison with monopiles

As it has been justified in detail in the previous sections, in the case of GBF structures, a fast production rate of no less than one unit per week can be achieved with no major upgrades at port facility.

In the case of monopiles, a reference of production ratio achieved in a generic facility may be found in NREL/TP-500-84710.

Table 34. Factory specifications

Factory specifications for a generic monopiles facility

NREL/TP-500-84710 - Deliverable 8.1

Factory Specification	Value	Units
Throughput	100	monopiles/year
Investment cost	410	$ million
Permitting and construction time frame	2–4	years
Laydown area	80–100	acres
Navigation channel depth	8	m
Direct jobs	550	FTE/year

Thus, production ratios of monopiles are around twice of GBS. However, monopiles need the additional transition peace, which requires and additional facility and production line.

Table 35. Factory specifications

Factory specifications for a generic transition piece facility

NREL/TP-500-84710 - Deliverable 8.1

Factory Specification	Value	Units
Throughput	100	transition pieces/year
Investment cost	200	$ million
Permitting and construction time frame	2–3	years
Laydown area	45	acres
Navigation channel depth	10	m
Direct jobs	300	FTE/year

These figures illustrate the very large upfront investment required to set-up high capacity facilities for steel based foundations, which also need longer permitting and construction time frame and large laydown areas at port.

By contrast, the ELISA GBS solution, thanks to its suitability for caisson-type manufacturing aboard floating barges, can deliver fast production ratios of circa 50 units/year with qualitatively lower upfront investments and in many cases making use of existing harbor facilities with no need for any major upgrade.

9.4. Benefits of silent installation of GBS

Underwater noise caused by human activity at sea (prospecting, maritime traffic, etc.) can cause disorientation, stress, malformations, and death of some marine animals, specially, marine mammals that depend on sound to interact each other and with the environment.

Therefore, monopile driving noise assessment as well as its mitigation are thus now a standard part of offshore wind farm permits. Similarly, decommissioning of monopiles can also have a noise impact on marine mammals.

GBFs significantly lower the acoustic footprint during construction and decommissioning (particularly for lower frequencies) benefiting noise sensitive wildlife.

In this regard, a memo elaborated by NREL was included as an appendix on Deliverable 8.1. This memo summarizes several key outcomes from a workshop conducted by the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory to gather input from the offshore wind energy community on noise reduction strategies for fixed-bottom offshore wind turbines (Green et al. 2023). The workshop convened 128 industry representatives, subject matter experts, and regulatory authorities over a 2-day virtual meeting.

9.5. Task 8 Conclusions

In task 8 a reference scenario based on NY Bight Project with full local construction of the GBS and steel tower and RNA assembly in Arthur Kill Terminal (NY) has been analyzed.

Taking advantage of ELISA technology flexibility to adapt the GBS substructure design to meet identified local constraints, an alternative design with reduced footprint has been developed. A reduced diameter base allows maximum use of the port quay and in this case, it has allowed optimum implementation at the Arthur Kill Terminal to adjust the manufacturing speed to the desired rate. The reduction of the base diameter has been achieved by means of sand ballast inside the tower shaft (T0).

As it has been justified along the task, a fast production rate of no less than one GBS per week can be achieved when a proper industrialization sequence is planned, in conjunction with the right means utilization. Moreover, as it has been also detailed, the required implantation yard area and quay length and draft is not a drawback. Note that fabricating steel offshore foundation also required in general larger investments cost for the facilities implantation, longer permitting and construction time frame and bigger laydown area at port that the required by facilities for GBS construction.

A final part of the task is the assessment of local constraints like permitting and impact to mammals. In this regard, a memo on the benefits of noise impacts of silent installation of GBFs has been elaborated by NREL

10. Task 9 – Manufacturing costs and LCOE benefits for the completed design at specific locations

The purpose of this task is to analyze the implementation cost for the ELISA GBS solution in the US and to evaluate how these costs may vary in different East Coast states. The analysis builds on done in Task 8, which provides an industrially compatible design for the gravity base substructure and the corresponding theoretical manufacturing facilities at selected ports. As in Task 4 that considered North Carolina scenario, the analysis is based on ELISA technology and adjusted for the requirements of the IEA 15 MW turbine. However, the option with reduced footprint, designed in Task 8, has been assumed in Scenario 2 (see next section).

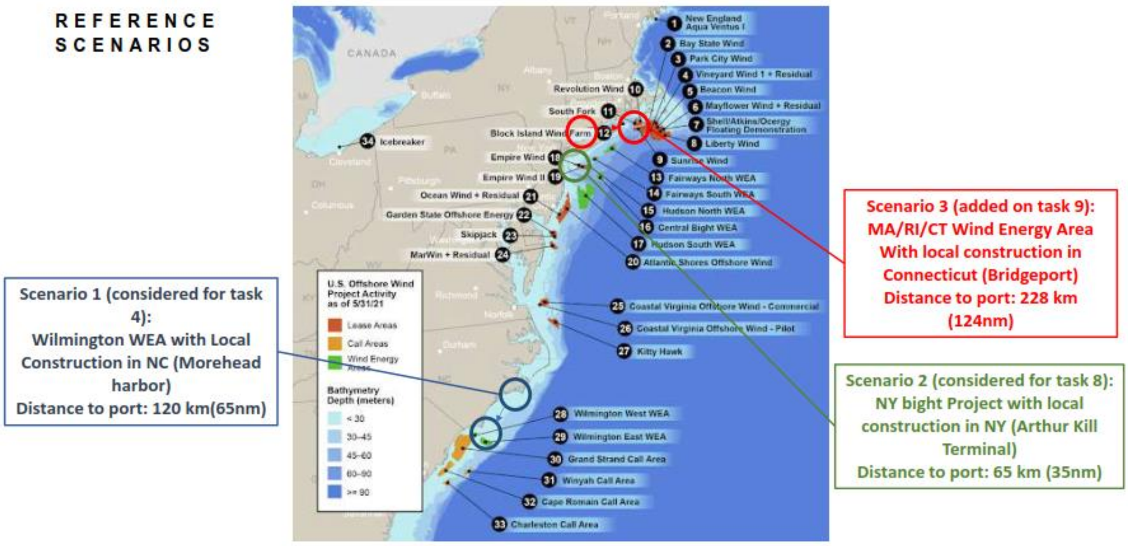
The costs and installation logistics have been modeled for the new scenarios assuming serial production of 50 units in each scenario.

The comparative LCOE analysis has been primarily performed using NREL's Offshore Renewables Balance-of-system and Installation Tool (ORBIT) cost model

10.1. Scenarios analyzed and costed.

Figure 74. Reference scenarios

Deliverable 9.1



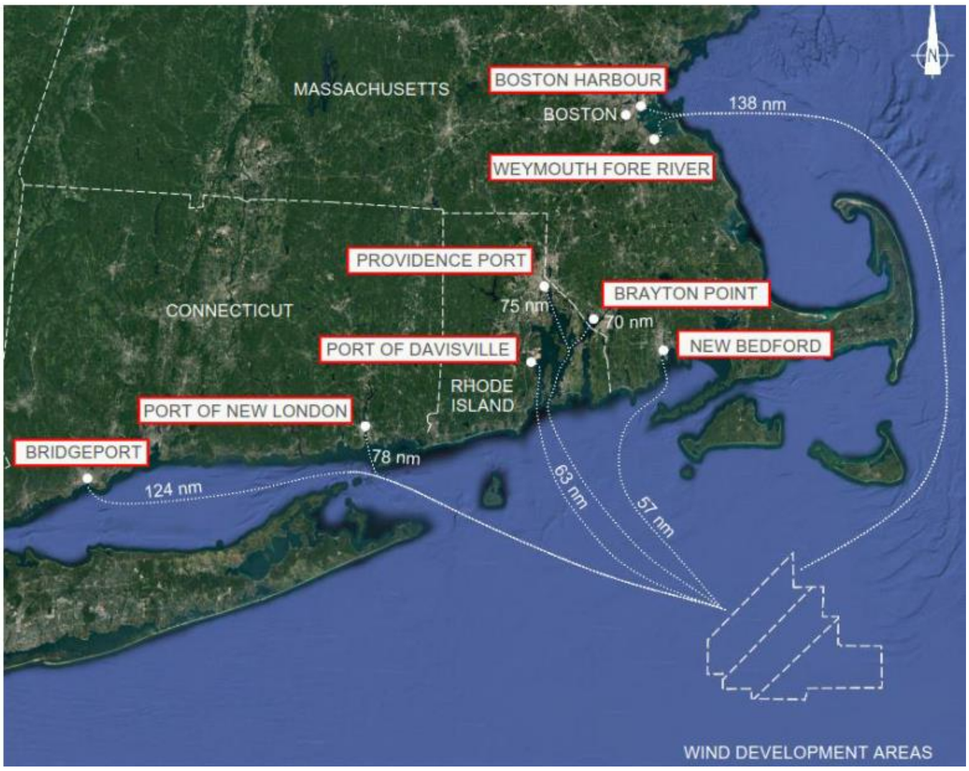
10.1.1. MA/RI/CT wind energy area - Bridgeport

MA/RI/CT Wind Energy Area with local construction in Bridgeport (Connecticut). This location has been selected as per NREL´s recommendations and after having some fruitful meetings with local stakeholders which are promoting the GBF construction in Connecticut.

Figure 75. MA/RI/CT wind development areas.

General view of MA/RI/CT wind development areas.

Deliverable 9.1



The harbor is assumed to be in the Tongue Point of the Bridgeport Harbor. It was an old coal-fired power plant, now involved in a demolition and redevelopment process. Note that the distance from Bridgeport is the second longest of the shown in Figure 75, thus, it is a good opportunity to analyze and cost a longer towing distance for the ELISA technology.

Full local construction and assembly in Bridgeport has been assumed. The distance considered from harbor to the wind farm is around 124 nm. For Bridgeport, the same manufacturing methodology and sequence described in Task 8 for the Arthur Kill terminal has been considered. However, given that the length of the quay and the area of the port yard are greater in the assumed Bridgeport parcels, the GBF option without solid ballast was finally chosen.

The construction facilities and its implantation on site is shown in the following figure:

Figure 76. Bridgeport.

Proposed harbor layout for construction of GBS and assembly of WTG

Deliverable 9.1

Wet storage area could be located in the sheltered area of the port as shown in the next figure:

Figure 77. Bridgeport

General plan view of Bridgeport and proposed wet storage area.

Deliverable 9.1

The ELISA design alternative considered for Scenario 3 (Bridgeport – CT) is the alternative without solid ballast, given that the length of the quay and the area of the port yard are less restrictive than in the case of the Arthur Kill Terminal in NY and can comfortably house serial production facilities for foundations of increased diameter.

10.2. ELISA cost estimates.

10.2.1. Budget breakdown structure and work packages

The ELISA cost analysis has been broken down in five work packages:

10.2.1.1. Site build up / Port adaptation

It includes the items needed to convert an existing port or area into a suitable place to fabricate the GBSs. In the delivered scenario, with floating fabrication and wet storage, preparation of the port is minor. The bedding layers for the turbine assembly positions and some minor preparation to adapt the existing port to the construction layout are considered.

10.2.1.2. Substructure construction

It includes all that is necessary to fabricate the GBS structures. It has three chapters:

1. Site facilities include port fees, mobilization of the needed structure, monthly allowances, indirect costs (general requirements) on site and auxiliary workforce.
2. Machinery, Equipment and Operations include tower cranes, the LR crawler crane and other minor tooling, equipment, and machinery.
3. Substructure construction. Basically materials, direct labor, the necessary formwork and ballasting equipment, secondary steel, and internals. This is the main cost item in the project. Construction of the base and the tower is separated.

10.2.1.3. Logistics

It includes the means needed to handle the substructures, and the special ringer crane to perform the turbine assembly. Main chapters are:

1. Float off mainly includes semi-sub barges for construction of the base and its float-off.
2. Inshore marine operations with the necessary tugs and the lease expenses and preparations for the wet storage. It also covers the expenses for the riggers, tugs and others needed for the float off maneuvers and to send the GBS to the turbine assembly positions.
3. Transport to turbine assembly port. It is zero in this scenario, as the fabrication port is the same as the final installation port. But this technology permits fabrication in a different port, in the US or Mexico, or other places where manufacturing is cheaper. This transport can be made with existing heavy transport vessels that make the loading and unloading operations by Floating on and floating off (they are submersible vessels).
4. Turbine assembly crane. It is only the crane, as the personnel and tooling for the operation is usually in the turbine manufacturer scope.

10.2.1.4. Offshore Marine operations

All expenses related to offshore operations. Main chapters are:

1. Auxiliary floater (TIM) manufacturing. For this cost analysis, two auxiliary floaters have been considered.
2. Seabed preparation. As explained before, for the expected seabed conditions in the area a single bedding layer has been deemed as sufficient. There is no need for dredging and the bedding layer has been enlarged so that it covers the anti-scouring requirements too. Also, the GBS definition has been done so that there is no need for sand ballasting.
3. Transport and installation. Includes the tugboats, control vessel and all the marine personnel to run the whole operation.
4. Sand ballasting at final position (when required). Assumed to be carried out with a fallpipe vessel.

10.2.1.5. Management, Engineering, and others

These are the costs for the EPCM control of the full project, based on separate contracting and handling of the above referred packages. It is estimated at an 8% of the cost.

10.2.2. Prices considered in the analysis.

For the Substructure fabrication chapter and the Port adaptation chapter, costs have been extracted from RSMeans database. Union labor costing is used.

For the North Carolina Region, we identified Kinston in the database as the closest location to Morehead. The scenario was set at mid-2021 prices for Task 4 and has been updated at first quarter-2023 for Task 9. For the Scenario 2 (Arthur Kill Terminal) the reference location in the data base is Staten Island (NY), and for the Scenario 3 RSMeans does include Bridgeport (CT). For these new scenarios first quarter-2023 have also been considered.

RSMeans is the database used by COWI for their reports on necessary investments to adapt the NY ports to the offshore industry, and the best database we have been able to identify. The prices match with some offers we also got from construction companies for former projects in the US.

RSMeans delivers not only unitary prices but also labor efficiencies, so that it defines both hourly rates and amount of steel/concrete/formwork place per manhour.

Other costs such as barges, cranes, marine operations and tugs, manufacturing of auxiliary floaters come from vendor offers for similar projects.

10.2.3. Summary of bill of quantities

Table 36. BoQ

Bill of Quantities for the Envelope GBS configuration (deliverable 9.1)

	w/o Solid Ballast (Task 3)	With Solid Ballast (Task 8)
Concrete Volume T0 (fck=10ksi) (m3)	908	896
Concrete Volume Base (fck=7ksi) (m3)	2670	2318
Passive Steel reinforcement T0 (Gr. 75 ksi) (Tn)	163	161
Passive Steel reinforcement Base (Gr. 75 ksi) (Tn)	411	371
Prestressing steel (Gr 270 ksi - 0.62" Low relaxation) (Tn)	55	55
Prestressing bars for Connection to steel tower (Gr. 150 ksi) (Tn)	10	10
Sand Ballast (Tn)	0	3518
Bedding layer (m3)	1846	1430

Table 37. BoQ

Detailed structural concrete BoQ without solid ballast (up) and with solid ballast (bottom)

DETAILED STRUCTURAL CONCRETE BoQ GBS ELISA W/O SOLID BALLAST								
		CONCRETE MASS (tn)			REINF. RATIO (kg/m3)	PT RATIO (kg/m3)	REINF. (tn)	PT. (tn)
ELEMENT	CONCRETE	EACH	UNITS	TOTAL				
CONCRETE TOWER - T0	70 MPa (10 ksi)	-	-	2270	180	51	163	46
CENTRAL SHAFT	48 MPa (7 ksi)	-	-	888	130	24	46	8
BULKHEADS - AT CENTRAL SHAFT CORNER	48 MPa (7 ksi)	67	6	400	245	-	39	-
BULKHEADS - AT CENTRAL SHAFT WALL	48 MPa (7 ksi)	71	6	429	245	-	42	-
LOWER SLAB	48 MPa (7 ksi)	-	-	2687	125	-	134	-
UPPER SLAB IN-SITU CONCRETE	48 MPa (7 ksi)	-	-	1016	135	-	55	-
UPPER SLABPRECAST PLANKS	48 MPa (7 ksi)	43	12	512	190	-	39	-
PERIMETER WALL	48 MPa (7 ksi)	-	-	743	185	-	55	-
TOTAL BASE	-	-	-	6675	154		411	8
TOTAL GBS	-	-	-	**8945**	**160**		**574**	**55**

DETAILED STRUCTURAL CONCRETE BoQ GBS ELISA W/ SOLID BALLAST								
		CONCRETE MASS (tn)			REINF. RATIO (kg/m3)	PT RATIO (kg/m3)	REINF. (tn)	PT. (tn)
ELEMENT	CONCRETE	EACH	UNITS	TOTAL				
CONCRETE TOWER - T0	70 MPa (10 ksi)	-	-	2240	180	51	161	46
CENTRAL SHAFT	48 MPa (7 ksi)	-	-	965	130	23	50	9
BULKHEADS - AT CENTRAL SHAFT CORNER	48 MPa (7 ksi)	63	6	379	245	-	37	-
BULKHEADS - AT CENTRAL SHAFT WALL	48 MPa (7 ksi)	68	6	410	245	-	40	-
LOWER SLAB	48 MPa (7 ksi)	-	-	1987	125	-	99	-
UPPER SLAB IN-SITU CONCRETE	48 MPa (7 ksi)	-	-	858	135	-	46	-
UPPER SLABPRECAST PLANKS	48 MPa (7 ksi)	37	12	447	190	-	34	-
PERIMETER WALL	48 MPa (7 ksi)	-	-	748	185	-	55	-
TOTAL BASE	-	-	-	5795	156		363	9
TOTAL GBS	-	-	-	**8034**	**163**		**524**	**55**

Table 38. BoQ

BoQ of TIM auxiliary platform

Deliverable 9.1

Element	Structural steel (t)	Heavy concrete ballast (t)
FLOATER	345	278
BEAM	111	-
RING	76	-
TOTAL BRACE	532	278
TOTAL (x3)	**1596**	**834**

10.2.4. Summary of ELISA cost estimates

The following table summarizes the complete budget built in each of the three scenarios, based on the processes, bill of quantities and prices sources described in previous sections. Upon request, Esteyco and NREL may provide further details on the complete costing exercise.

Table 39. ELISA Cost Summary

ELISA GBF COST PER WTG		KINSTON (NC)	ARTHUR KILL (NY)	BRIDGEPORT (CT)
		SCENARIO 1	SCENARIO 2	SCENARIO 3
		$ 8,410,077.94	$ 10,096,005.18	$ 10,063,264.11
01	SITE BUILD UP / PORT ADAPTATION	$ 40,971.34	$ 43,838.47	$ 43,838.47
01.01	PORT ADAPTATION	$ 11,200.00	$ 10,800.00	$ 10,800.00
01.02	MARINE WORKS AT PORT	$ 29,771.34	$ 33,038.47	$ 33,038.47
02	SUBSTRUCTURE CONSTRUCTION	$ 5,369,259.51	$ 6,683,414.78	$ 6,879,449.54
02.01	SITE FACILITIES AND GENERAL REQUIREMENTS	$ 661,577.08	$ 803,765.53	$ 803,765.53
02.02	SITE MACHINERY, EQUIPMENTS & OPERATION	$ 296,004.46	$ 301,003.68	$ 301,003.68
02.03	SUBSTRUCTURE	$ 4,411,677.97	$ 5,578,645.57	$ 5,774,680.33
03	LOGISTICS	$ 646,902.06	$ 604,686.77	$ 615,100.77
03.01	FLOAT OFF	$ 10,000.00	$ 10,000.00	$ 10,000.00
03.02	INSHORE MARINE OPERATIONS	$ 428,720.00	$ 386,504.71	$ 386,504.71
03.03	SUBSTRUCTURE TRANSPORT TO FINAL PORT -	$ -	$ -	$ -
03.04	TURBINE ASSEMBLY	$ 208,182.06	$ 208,182.06	$ 218,596.06
04	OFFSHORE MARINE OPERATIONS	$ 1,730,702.22	$ 2,016,212.92	$ 1,779,448.36
04.01	TIM FLOATERS	$ 572,864.08	$ 566,573.68	$ 572,864.08
04.02	SEABED PREPARATION	$ 702,206.48	$ 567,651.23	$ 702,206.48
04.03	ANTI SCOUR - (NOT NECESSARY IN THIS CASE)	$ -	$ -	$ -
04.04	TRANSPORT AND INSTALLATION (T&I)	$ 455,631.66	$ 455,631.66	$ 504,377.80
04.05	SOLID INFILL	$ -	$ 426,356.36	$ -
05	MANAGEMENT, ENGINEERING AND OTHERS	$ 622,242.81	$ 747,852.24	$ 745,426.97
05.01	MANAGEMENT, ENGINEERING AND OTHERS	$ 622,242.81	$ 747,852.24	$ 745,426.97

10.3. Summary of NREL comparative LCOE assessment of ELISA GBF

NOTE: This section has been produced by NREL

10.3.1. Introduction

Monopiles are currently a 'standard' method for installing offshore wind turbines in shallow waters where the turbine can be fixed to the seafloor. A gravity-based foundation (GBF) that simply rests on the seafloor offers some potential advantages over a traditional monopile and may be a viable option for offshore wind projects in the United States.

A detailed comparison of the levelized cost of energy (LCOE) of a GBF system designed by Esteyco with a traditional monopile has been done. It includes a comparison of the jobs and economic development impact from a GBF versus a traditional monopile for a potential wind energy area (WEA) off the coast of North Carolina. The analysis incorporates outputs from NREL's Offshore Renewables Balance-of-system and Installation Tool (ORBIT) and the Job and Economic Development Impact model (JEDI).

The following sections summarize the LCOE comparison done for three WEAs off the coast of North Carolina, New York, and Connecticut. These results build a previous analysis performed for the same North Carolina site, by updating some of the GBF-specific cost figures, monopile costs, and a comparison to the two other sites located off the coast of New York and Connecticut.

10.3.2. Methodology

10.3.2.1. ORBIT

ORBIT (Nunemaker et al., 2020) is used to compare the LCOE between a traditional monopile and Esteyco's ELISA-GBF. At the time of this analysis, the version of ORBIT utilized the SemiTaut_Mooring_Update1 code-branch. Underlying cost data used by ORBIT is maintained by NREL using historical prices, industry feedback, and market trends. Specific costs and designs provided by Esteyco have been incorporated into ORBIT to describe the ELISA-GBF system. Hourly wind and wave data taken from ERA5 Reanalysis (Hersbach et al., 2020) are used in combination with port, equipment, and vessel constraints to calculate total installation time and project cost. We added an ELISA-specific module into ORBIT to carry out the LCOE comparison.

10.3.2.2. Reference Scenarios

The three scenarios have representative sites in North Carolina, New York, and Connecticut. Each scenario designates a specific port and wind energy area.

1) North Carolina: Morehead harbor to Wilmington WEA
2) New York: Arthur Kill Terminal to Empire Wind WEA
3) Connecticut: Bridgeport Marina to Vineyard Winds WEA

The project characteristics for each scenario are summarized in Table 40. Each wind site assumes a 50-wind turbine grid-layout with fixed turbine nameplate capacity of 15MW, such that the total wind plant capacity is 750MW. The following figures compare the same 750MW wind project at different sites and with different foundation technologies.

Table 40. Site characteristics

Project characteristics for the comparative analysis at each site

Deliverable 9.1

Parameter	North Carolina	New York	Connecticut
Water depth (m)	40	42	42
Distance to shore (km)	120	65	228
Export cable length (km)	50	39	28
Average wind speed at 100m (m/s)	9.2	7.1	9.4
Average significant wave height (m)	1.6	1.3	1.5
Plant capacity (MW)	750		
Turbine rating (MW)	15		

10.3.2.3. Levelized Cost of Energy

The approach to model LCOE is given below. ORBIT is used to calculate the Balance-of-system costs, which are included in the CapEx term. The LCOE is given in $/MWh and is calculated using:

$$LCOE = \frac{1000 \times FCR \times CapEx + OpEx}{NCF \times 8{,}760}$$

- FCR is the fixed charge rate (in %/year) that annualizes the upfront project capital cost, accounting for return on debt and equity, taxes, and the expected financial life of the project,
- CapEx are the capital expenditures (in $/kW), including the wind turbine, balance of system components, som costs, and project costs,
- OpEx are the annualized operational expenditures (in $/kW-year) required to maintain and operate the wind plant throughout its lifetime, and
- NCF is the net capacity factor (in %) that accounts for losses and site-specific wind resource characteristics (scaled by 8,760 hours in a year).

10.3.2.4. Cost Assumptions

The values provided in Table 41 are used to calculate the LCOE of a wind project. Additional cost assumptions made in this analysis are, 1) the turbine CapEx is fixed at $1,300/kW, and 2) the per-unit cost of the manufactured monopile is $4,650 per metric-ton for all references sites.

Table 41. LCOE evaluation

Other cost estimates used in the LCOE evaluation. All values in $2021.

Deliverable 9.1

Parameter	Value	Source	Notes
OpEx	$118 /kW-yr	2020 Cost of Energy Review, Stehly and Duffy (2021)	A 25-year project design life is assumed.
Net capacity factor	0.459	Shields et al. (2021)	Value using 15 MW reference turbine at an East Coast reference site.
Fixed charge rate	0.0582	2020 Cost of Energy Review, Stehly and Duffy (2021)	See Table 3 more details.

10.3.3. Results

We calculated the CapEx and LCOE of both the ELISA-GBF and standard monopile using ORBIT. Each site and technology used slightly different inputs. Those different inputs are found in the NREL's completed report.

10.3.3.1. CapEx for the ELISA-GBF and Monopile Substructure

The ELISA substructure is composed of concrete and steel, whereas the monopile is fabricated steel. ORBIT employs a default value of $3,000/ton for the monopile steel and transition piece. This default value was determined in 2016 internally through market research and industry feedback. Note that the cost of monopile foundations is highly dependent on the cost of commodity steel, which has experienced high volatility in recent years. Between 2016 and 2023, the price index of fabricated steel plate has increased over 50% (225/145) (U.S. Bureau of Labor 2023). Therefore, the monopile steel cost was assumed to be $4,650 per ton in this analysis. Table 42 shows the substructure CapEx breakdown for both technologies at each site. The ELISA-GBF costs included the material, labor, and engineering management cost.

Table 42. Substructure CapEx Breakdown

Substructure CapEx Breakdown of ELISA-GBF and standard monopile foundation.

Deliverable 9.1

Type of System	North Carolina ($/kW)	New York ($/kW)	Connecticut ($/kW)
ELISA-GBF	356	446	460
Monopile	819	837	863

Figure 78 illustrates the CapEx breakdown of the substructure (red) and substructure installation (blue). It is worth noting that with today's high price of monopile steel, the monopile substructure is roughly twice as expensive as the ELISA-GBF system. When comparing the two systems side-by-side the installation processes are handled quite differently. The substructure installation of the ELISA-GBF includes turbine installation and seabed preparation (scour protection), which is accounted for separately for the monopile foundation. Therefore, the ELISA-GBF incurred a more expensive substructure installation phase. Regardless, the ELISA-GBF substructure cost and installation is potentially 30% cheaper than the monopile foundation.

Figure 78. CapEx breakdown

CapEx breakdown of the substructure (red) and substructure installation (blue) between ELISA-GBF and Monopile for North Carolina, New York, and Connecticut.

Deliverable 9.1

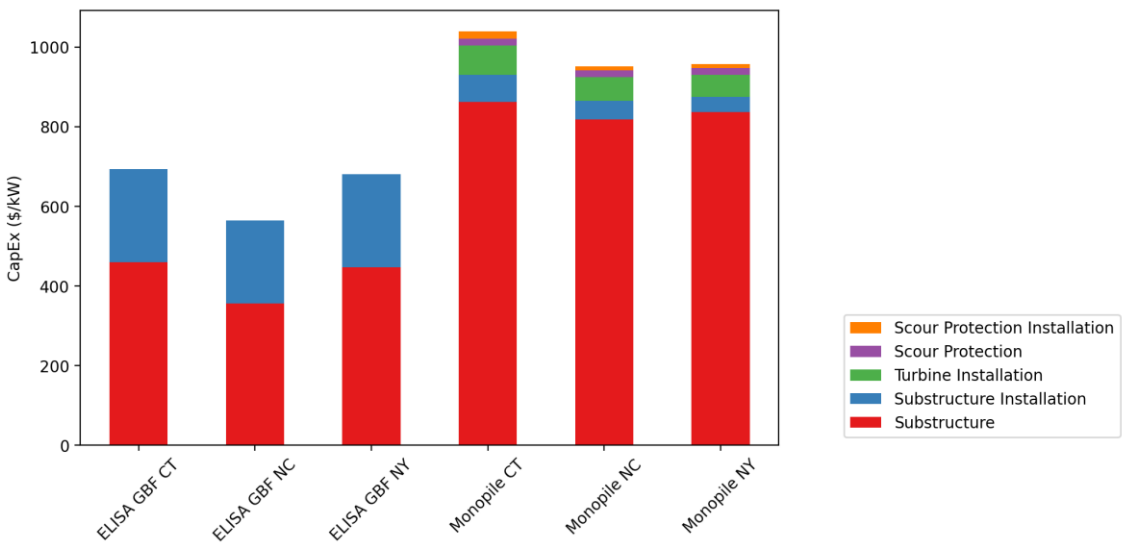
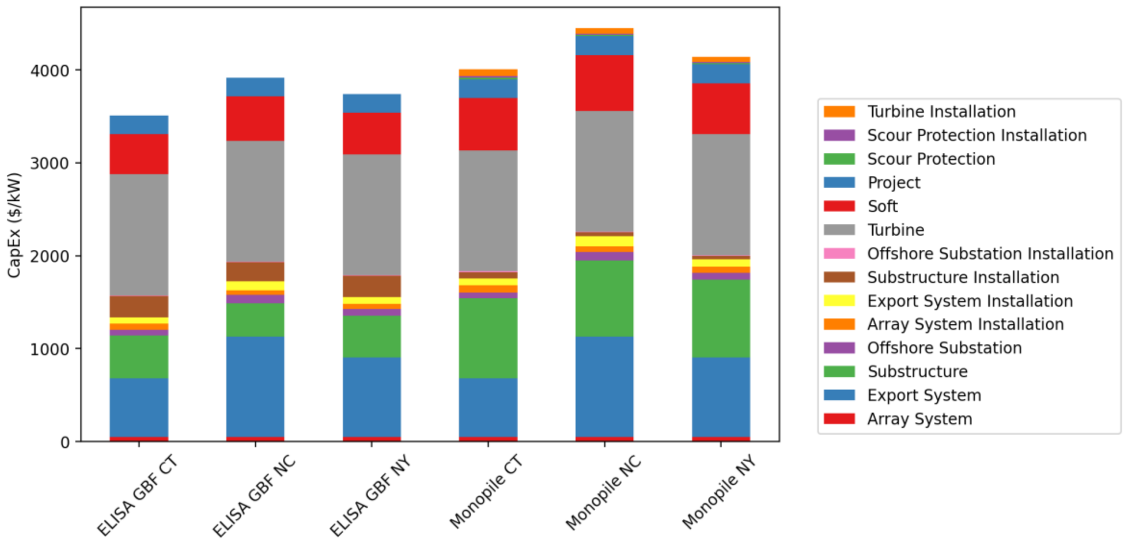


Figure 79. Total CapEx breakdownFigure 79 illustrates the total CapEx breakdown for both technologies at each site. Tabulated values for the CapEx breakdown can be found in the detailed report. The significant cost difference between the structures becomes less apparent when added to the total CapEx. What is shown in Figure 79 is that the total CapEx of an ELISA-GBF is approximately 10% less than a monopile foundation for a given location. What this ORBIT analysis shows is that components or install phases are dependent on the distance from port (I.e. export system, turbine installation, scour protection). Exploring the benefits of on-land construction and installation can potentially mitigate installation, supply-chain, or weather disruptions. ORBIT itemizes many costs such as turbine installation and scour protection when modelling a monopile foundation. However, some processes or equivalent processes are included in the ELISA-GBF substructure. For this reason, some costs exist for a system that uses monopiles that do not for a system that uses ELISA-GBFs.

Figure 79. Total CapEx breakdown

Total CapEx breakdown between ELISA-GBF and Monopile for North Carolina, New York, and Connecticut.

Deliverable 9.1



10.3.3.2. LCOE for the ELISA-GBF and Monopile Systems

The LCOE of each technology is shown in Table 43. Generally, the ELISA-GBF was shown to have an 8-9% lower LCOE than a monopile foundation. The variations in LCOE among the same technology was based on the wind resources as well as the site-specific costs, such as cost of labor and materials.

Table 43. LCOE comparison

LCOE comparison of ELISA-GBF and Monopile

Deliverable 9.1

Type of System	North Carolina ($/MWh)	New York ($/MWh)	Connecticut ($/MWh)
ELISA-GBF	92.97	89.91	86.44
Monopile	102.44	97.23	95.51

10.3.4. Summary of NREL's comparative LCOE analysis

Overall, the analysis performed in this study showed that ESTEYCO's ELISA-GBF had an LCOE 8-9% lower than standard monopile foundations. Since the LCOE of the ELISA-GBF scenarios at each site was between $86/MWh and $93/MWh, the technology has the potential to be cost-competitive to widely used monopile foundation for the United States offshore wind goals.

Depending on the scenario, the ELISA-GBF substructure CapEx varied between $360/kW to $460/kW, whereas the monopile's substructure CapEx varied between $820/kW to $860/kW. The slightly larger variance in CapEx was due to the higher detail in site-specific costs provided by ESTEYCO. An area of improvement is to refine the cost breakdowns of the monopile system within ORBIT to account for more site-specific factors like cost of labor, tooling, and materials. It is worth noting that ORBIT assumes a well-established offshore wind supply-chain that has readily available components, materials, and vessels. A potential research avenue would be to see which technology can withstand supply-chain disruptions.

Lastly, the economic benefits show that an ELISA-GBF would potentially provide more jobs at the port than the monopile due to the port-intensive fabrication (2196 FTEs VS 1090 FTEs). Further investigations should be performed for each site with more refined labor figures to determine economic viability for port-side communities.

10.4. Task 9 Conclusions

The present task consists of an updated version of the work carried out in Task 4, including the characteristics of manufacturing facilities and costs of two new scenarios along the Atlantic Coast. The present task also includes a comparison of project LCOE of the three selected scenarios performed by NREL.

This task describes the fabrication and installation procedure of the ELISA GBS technology, adjusted for the requirements of the IEA 15 MW turbine and for conditions representative of the East Coast of the United States. It also summarizes the material, manufacturing, and workforce requirements of the gravity-based units for the three scenarios and provides a comparison of project LCOE and fabrication/installation logistics between the three selected scenarios and against the conventional monopile solutions. The comparative LCOE study, carried out by NREL, has been primarily based on NREL's Offshore Renewables Balance-of-system and Installation

Tool (ORBIT) cost model.

The cost analysis of GBFs is built off the work done in Task 8, which provides an industrially compatible design for the gravity base substructure and the corresponding theoretical manufacturing facilities at selected ports. The option with reduced footprint, designed in Task 8, has been assumed in the Scenario 2 (NY), while the option without solid ballast has been used for the Scenarios 1 (NC) and 3 (CT).

According to NREL´s study, the ELISA technology had an LCOE 8-9% lower than standard monopile foundations, showcasing that it can be a cost competitive option. The LCOE of the ELISA-GBF in the different scenarios considered ranged between $86/MWh and $93/MWh.

According to NREL´s study, depending on the scenario, the ELISA-GBF substructure CapEx varied between $360/kW to $460/kW, whereas the monopile's substructure CapEx varied between $820/kW to $860/kW. The ELISA GBF consists in a large part of concrete, whereas the monopile is mostly steel, which is more expensive. Note also that the cost of monopile foundation is highly dependent on the cost of commodity steel, which has experienced high volatility in recent years. In contrast cost of commodity materials needed for concrete are much more stable. This allows the ELISA GBF to be cost competitive with the monopile with lower risk due to the market cost of commodity materials. In addition, the GBF substructure installation avoids the use of costly and supply-chain limited wind turbine installation vessels required with monopile foundations.

It is important also to note, that another economic benefit of the ELISA technology deducted from NREL's study is that the ELISA technology would potentially provide more jobs at the port than the monopile due to the port-intensive labor required for ELISA substructure fabrication (2196 FTEs VS 1090 FTEs).

11. Task 10 –Analysis of the opportunity space for ELISA technology in the United States

This task provides a comprehensive analysis of how the ELISA technology addresses gaps and barriers currently faced by the offshore wind industry in the US East Coast. Particularly in the supply of bottom fixed substructures and in the availability of floating foundation installation vessels (FFIVs) and jack-up wind turbine installation vessels (WTIVs).

Current project designs for bottom fixed substructures along the Atlantic Coast anticipate using conventional approaches, such as monopiles installed using WTIVs or transporting major components from Europe.

The ELISA technology provides an opportunity to bypass inefficiencies related to vessel availability constraints, vessel costs, installation restrictions, and a lack of domestic manufacturing.

This task incorporates results from NREL's ongoing NOWRDC award to investigate the readiness level of the supply chain to support East Coast floating wind. Finally, the task identifies how the deployment of current technological solutions focused on XXL monopiles will be constrained by the global availability of wind turbine installation vessels. Based on these results, ESTEYCO and NREL describe the potential opportunities for the ELISA technology to contribute to offshore wind deployment on the East Coast.

This task is divided into five sections, which provide details that support the above assessment summary:

1) Existing U.S. East Coast foundation deployment plans – estimates the U.S. East Coast demand for bottom fixed offshore wind turbine foundations, which are now all planned to be monopiles.

2) U.S. supply chain bottlenecks that constrain existing plans – estimates the amount of monopile demand that cannot be met by U.S. domestic production facilities, as supplemented by surplus European production, and the shortage of suitable large vessels to install monopiles.

3) Ability of the U.S. supply chain to produce and deploy ELISA foundations – identifies U.S. East Coast ports that meet Esteyco's requirements for establishing an ELISA gravity base production facility.

4) Seabed preparation experience with previous offshore wind gravity-base projects – summarizes the difference on the seabed preparations required for the Thornton Bank Project compared to the ELISA's.

5) Limited availability of Wind Turbine Installation Vessels (WTIV) and floating foundation installation vessels (FFIV) - currently global fleet of WTIV or jack-up vessels capable to install 12 MW and larger turbines in waters of 50+m depth is limited to only seven vessels (reference #12).

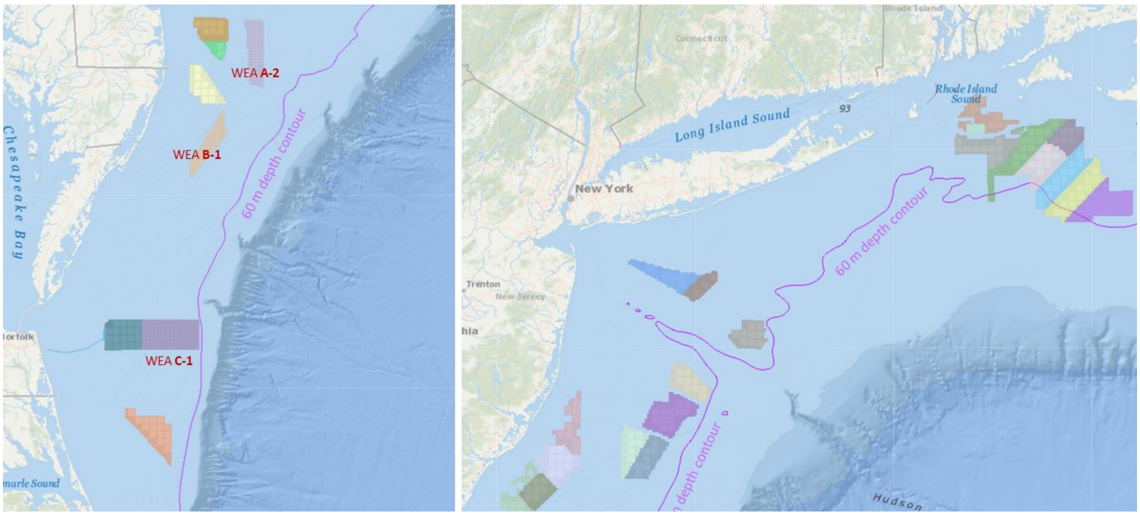
11.1. Existing U.S. East coast foundation deployment plans

It is generally accepted that fixed-bottom offshore wind foundation substructures such as monopiles, jackets, or gravity bases are more economical than floating platforms in water depths less than 60 m. Among the 27 active commercial lease areas on the U.S. East Coast, 22 lease areas are entirely in depths less than 60 m. Small parts of the remaining five areas are in deeper water, as shown in Figure 80, but fixed foundations are planned throughout all these areas. These 27 active leases total 2.34 million acres and if all possible turbine positions were used at 1-nautical mile (NM) spacing, they could hold 2,770 turbines. In addition, the U.S. Bureau of Ocean Energy Management has proposed three new lease areas on the Central Atlantic shelf, which will add a further 356,550 acres that can hold an additional 420 turbines if all positions likewise were used at 1-NM spacing. Thus, a total of nearly 3,200 fixed-bottom foundations will be needed by U.S. East Coast offshore wind projects.

Figure 80. Lease areas

Draft central Atlantic lease areas (3) and planned Central Atlantic WEAs (A-2, B-1, C-1) (left) and active commercial lease areas (25) (right) and their location relative to the 60-meter depth contour. Not shown are the two southernmost active leases, which are off Cape Fear, North Carolina, and these have a combined area of just over 110,000 acres.

Deliverable 10.1



The total fixed foundation demand of 3,200 turbine positions on the U.S. East Coast is an “indicative” estimate, in that some commercial projects are planning tighter spacing, which increases the number of turbine positions within a lease area, while at the same time, environmental and geotechnical considerations are causing some turbine positions to be abandoned. For example, the most densely packed projects, Empire Wind 1 and 2 off New York, have turbines spaced at 0.71 NM, which nearly doubles the number of possible turbine positions within this lease area, as compared with 1-NM spacing, but for geotechnical reasons, approximately 20% of these positions had to be abandoned. In a separate and independent analysis (see ref# 13) of a monopile-only demand scenario, NREL estimates an average annual demand of ~240 monopiles per year from 2024 through 2033, based on more conservative assumptions than used in the above analysis.

With these caveats in mind, NREL’s estimated total foundation demand translates to an average annual supply requirement of 240 to 320 foundations per year over a notional ten-year build-out period from 2024 to 2033, inclusive. The Construction and Operations Plans (COPs) of all 27 East Coast offshore wind projects now under construction (or still in environmental review) indicate XXL monopiles with a bottom diameter of 8.5 to 11 m as their preferred foundation option. As documented in the next section, only half of this demand can be met by existing or announced production facilities in the U.S. and Europe.

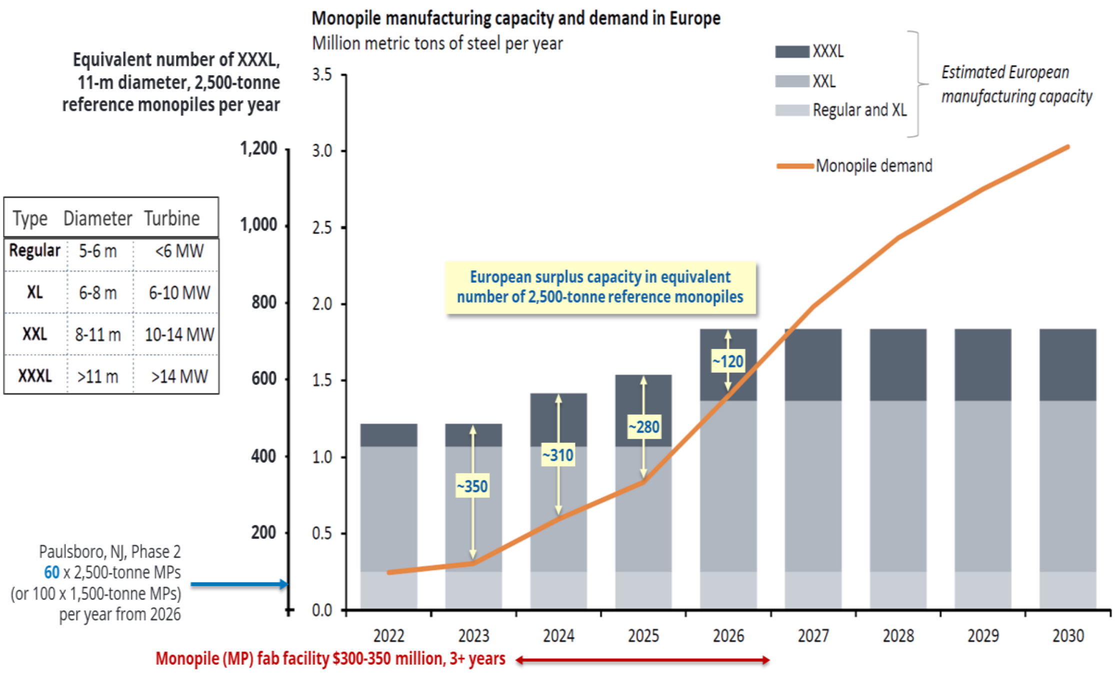
11.2. U.S. supply chain bottlenecks that constrain existing plans

The EEW American Offshore Services monopile Phase 1 finishing plant, in Paulsboro, New Jersey, will be able to fully fabricate 100 XXL monopiles per year in Phase 2, with its first delivery committed to the Atlantic Shores 1 project in 2026. Theoretically, Europe now has surplus monopile production capacity to supplement U.S. monopile supply, but as shown in Figure 81, Europe's surplus monopile production capacity will be incapable of supporting the U.S. buildout beyond 2026.

Figure 81. Monopile production capacity and demand in Europe

Surplus European monopile production capacity will be fully utilized by European demand after 2026.

Deliverable 10.1



A second domestic monopile (MP) production facility has been announced for Sparrows Point, Maryland. Based on its announced steel plate throughput, this would have a production capacity of about 67 1,500-tonne MPs per year. Even when the Sparrows Point, MD plant is combined with the Paulsboro, NJ Phase 2 plant, NREL estimates that there will be a monopile supply shortfall of nearly 150 fixed-bottom foundations per year, which represents a potential U.S. market opportunity for the ELISA GBS.

In addition to the challenge of inadequate monopile supply, NREL and industry analysts predict that four to eight dynamically positioned, floating foundation installation vessels also will be needed, each with a heavy-lift crane capable of upending a 1,500- to 2,500-tonne monopile 80 to 110 m in length. Such vessels would cost around $300 million to build in a U.S. shipyard and would require a lead time of at least four years to finance, build, and commission.

Therefore, if the present U.S. East Coast offshore wind buildout continues to plan for just monopile foundations, it will have to import monopiles from Asia and use foreign-flagged FFIVs with foreign crews, not realizing the promise of new maritime fabrication and mariner jobs. Filling the monopile supply bottleneck with the ELISA GBS “float and flood” foundation alternative would allow using existing US-flagged vessels and create a more credible U.S. shipyard business case for the building of smaller, easier-to-finance anchor handling and tug supply vessels, which also can be utilized in other maritime business sectors such as commercial shipping and coastal infrastructure construction.

11.3. Ability of the U.S. supply chain to produce and deploy ELISA foundations.

The ELISA GBS technology, enables diverse execution strategies, depending on the availability of ports for construction and WTG assembly. Preferably, the same port would be used for foundation construction and WTG assembly activities. However, depending on project circumstances, it is also possible to build foundations in facility and tow them to a different WTG marshalling facility where the WTG can be integrated with the foundation before the whole assembly is towed to the offshore site. As currently in the U.S., large port infrastructure for dry construction and storage of GBSs (at the quay) is difficult to find, without major upgrades/investment, ESTEYCO and NREL have assessed the construction of the GBSs onto semisubmersible means, resembling the extensive use of this methodology in port caissons construction. The following figures show an ideal sizing of the port requirements when such a strategy is used. On a project-by-project basis, this requirement can be fine-tuned to enable the use of available yards.

A dedicated facility to fabricate ELISA GBS foundations with a throughput of 50 structures per year (including foundation construction and WTG integration works) would have the following requirements:

(1) A quayside section length of 300 m and a width of 70 m.

(2) The above plan dimensions have a surface area of 21,000 m2 (or 5.2 acres).

(3) This quayside area should have an average bearing strength of 6 tn/m2.

(4) The quay charted water depth, which corresponds to mean-lower-low-water, must be > 7.8 m.

(5) No overhead restrictions (e.g., unlimited air draft) for towed transport from the WTG assembly facility to the offshore site. Please note that in case air draft restrictions condition the selection of the ELISA technology, ESTEYCO can provide an alternative GBS which moves the WTG integration from port to the offshore site, as is the case with other bottom fixed substructures. This alternative GBS technology is named ELI.

Esteyco and NREL have performed preliminary cost estimates based on fabricating ELISA foundations at Morehead City in North Carolina, the Port of Bridgeport in Connecticut, and at Arthur Kill Terminal in New York. Although these last two port facilities meet the above requirements, they have relatively short quaysides, and any other use of these facilities for other offshore wind manufacturing or for staging might possibly preempt their dedication to ELISA GBS fabrication.

Much longer quaysides exist at Morehead City and at four other port facilities with adequate alongside depth and unlimited air draft. These larger port facilities could accommodate other offshore wind uses and still host a dedicated facility for ELISA GBS fabrication. The key features of these five larger ports are listed in Table 44, together with the key features of Bridgeport and Arthur Kill.

Table 44. Key features of potential U.S. East coast fabrication sites for ELISA

Deliverable 10.1

Port Name (listed north to south)	State	Laydown Area (acres)	Quayside Length (m)	Alongside Depth (m)	Towing Distance (NM) to:		
					RI-MA	New Jersey	Kitty Hawk
Port of Bridgeport	CT	18.3	375	9.8	127-182	231	445
New London State Pier	CT	30	1,244	12.2	77-136	185	399
Arthur Kills Terminal	NY	32	411	10.7	191-223	84	298
New Jersey Wind Port	NJ	70	854	11.5	308-340	104	218
Newport News Marine Terminal	VA	165	1,061	12.2	374-406	196	68
Portsmouth Marine Terminal	VA	287	1,079	13.1	390-422	212	84
Morehead City	NC	128	1,635	11-14	571-603	393	65

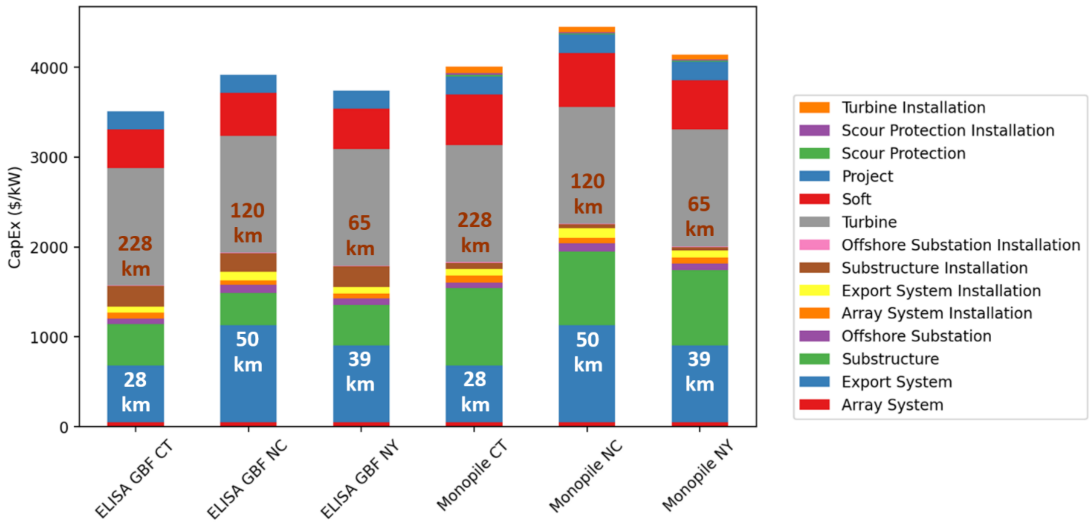
Notes: Towing Distance based on NOAA Office of Coast Survey estimated sea route distances between ports.

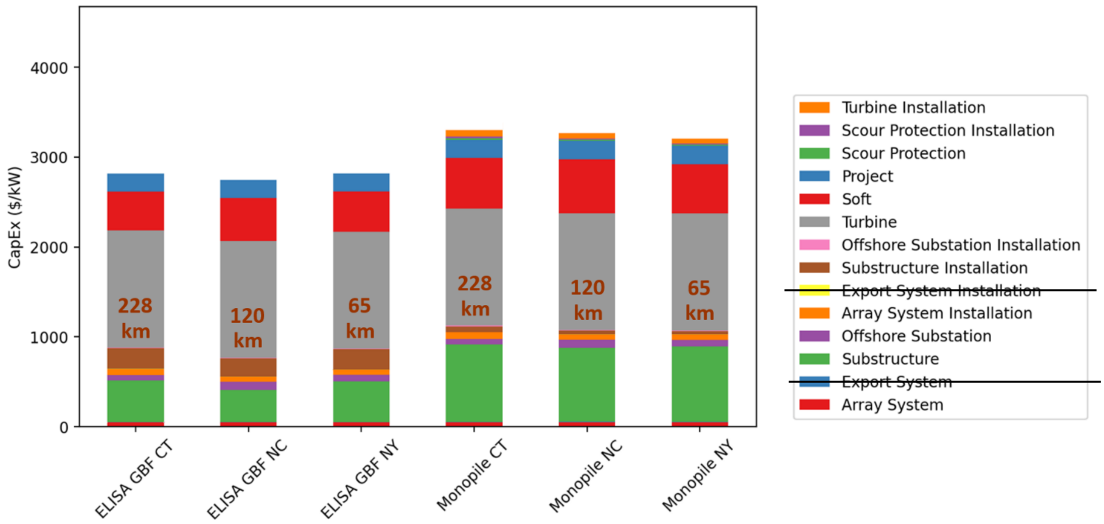
Among the three scenarios that NREL evaluated for the ELISA levelized cost of energy (LCOE), Bridgeport has a towing distance around 230 NM to the MA/RI/CT Wind Energy Area, as compared with Morehead City's towing distance of 65 NM to the Kitty Hawk project site (please refer to Deliverable 9.1 for detailed information). Compared with the two northern ports, however, Morehead City, NC, has a 20-30% lower labor cost advantage for fabrication site preparation, crane mobilization, and concrete fabrication, and this regional labor cost advantage more than offsets the increased towing costs, as can be seen in Figure 82, which compares the offshore busbar CapEx (with export cable removed) among the different scenarios. A similar regional labor cost advantage also would apply to the VA ports. Based on the cost tradeoff between labor and towing-distance and considering other key features in Table 44, NREL recommends that the New London Pier and Newport News Marine Terminal be more closely evaluated in the next phase as a combined two-port strategy for Esteyco's possible U.S. manufacturing footprint for ELISA.

Figure 82. CapEx for the full project & CapEx at the offshore busbar

Top: CapEx for the full project, showing that export cable length dominates the difference among the three project sites. Bottom: CapEx at the offshore busbar (with export system supply and installation removed), showing that while port distance-to-project has a slight governing influence for monopile-based projects, the higher labor content in ELISA gravity base fabrication gives regional labor cost differences the governing influence, more than offsetting the trend in port distance-to-project. White numbers indicate export cable length, and brown numbers indicate port distance-to-project.

Deliverable 10.1





In evaluating the potential business case for ELISA at Newport News Marine Terminal, NREL recommends a study that also evaluates an LCOE scenario whereby the ELI GBF instead of the ELISA GBF is deployed (without the turbine installed in port), with turbine installation by the nation's only Jones Act compliant, U.S.-flagged jack-up wind turbine installation vessel, Charybdis, which will be homeported at Portsmouth Marine Terminal.

11.4. Seabed preparations on previous offshore wind gravity-base projects

The first phase of Thornton Bank, 6x 5MW wind turbines installed offshore Belgium in 2009, using GBSs as substructures, required vast seabed preparations: Thornton Bank seabed preparation included substantial dredging, with nearby deposition of the dredge spoil, which was subsequently used as backfill. Rip-rap stone layers included two foundation bedding layers and two scour protection layers; the latter being installed after the dredge spoil was backfilled into the dredged pit. This implied an important impact to the CapEx and to the carbon footprint.

This particular project has traditionally generated the wrong impression about GBS requiring extensive seabed preparations with the corresponding costs, environmental impact and marine spread requirements. It must be highlighted that this project is in fact the exception rather than the norm. Around 400 GBS units have been installed for offshore wind turbines, and these have as a rule required much lower seabed preparations than the Thornton Bank project. These several hundred units include not only shallow water projects, but also deeper water projects such as the Blyth Project in the UK or the Fecamp project in France. For a majority of the GBS units installed and operating around the world, much simpler seabed preparations have been required, often consisting only of rock armor bedding layers whose impact is not essentially different than that of the rock armor also used typically for scour protection of monopiles.

It is therefore important that U.S. developers and regulators don't consider Thornton Bank as representative case for seabed preparations when evaluating GBS substructures, as it is probably an exception or extreme scenario that is not representative of the usual seabed preparation requirements.

By way of example, ESTEYCO can provide specific details and lessons learned from the demonstrator of the ELISA GBS (5MW Siemens Gamesa WTG) that was successfully installed in Gran Canaria in 2018 and has been operating and performing adequately since then. This substructure did not require any seabed preparation at all; the GBS+WTG was directly installed offshore onto the unaltered seabed. This naturally required natural seabed conditions which were sufficiently flat, horizontal, and capable. Specifically, it was a sandy seabed with ripples of +-15cm and an inclination lower than 1deg. Such conditions may be found in many other offshore projects. The permanent tilt of the foundation resulting from the previously known natural inclination of the seabed was duly considered in the design load calculation and certification and with such proper anticipation was not a limiting or design driving factor for the foundation or the WTG.

In the ELISA pilot unit, scour was prevented by the usage of tyre -filled nets, which where preinstalled in port around the base and therefore required no special vessel for its installation. The WTG is still operating today, and no alteration has been detected in the seabed.

Seabed preparations required for commercial projects studied with the ELISA or ELI technologies, have only required one layer of rock as leveling/bedding mattress and antiscour. In most cases, such layer can act both as bedding layer and scour protection system.

Figure 83. Thornton bank profile sketch

Deliverable 10.1

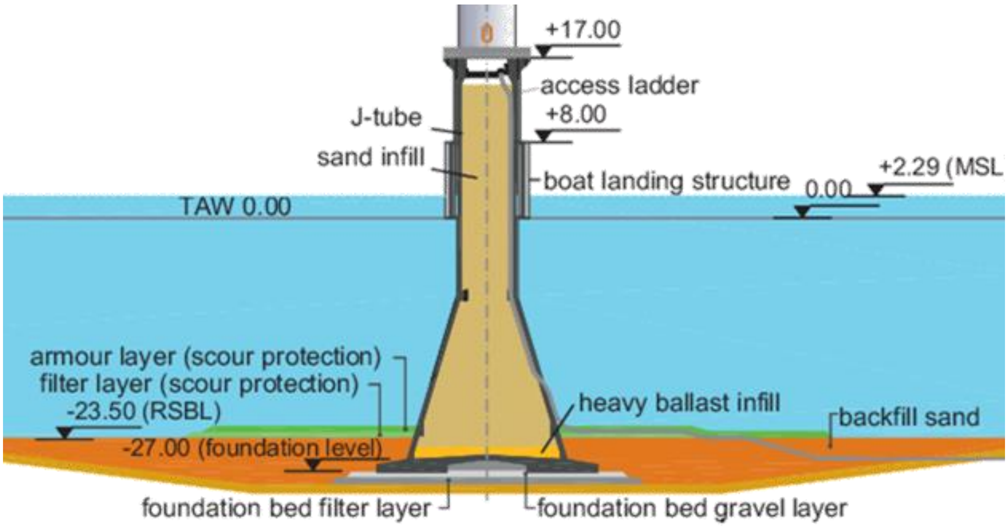
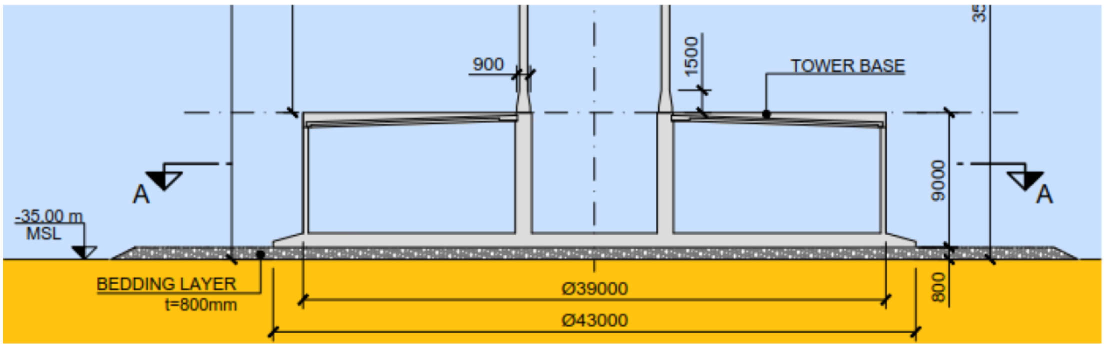


Figure 84. Single rip-rap stone layer

Esteyco's single rip-rap stone layer for both foundation bedding and scour protection

Deliverable 10.1



The usage of a single bedding/armor layer, as is normally the case with the ELISA Technology, would reduce seabed habitat disturbance and vessel emissions concerns and would have the added benefit of enabling the legal use of foreign-flagged subsea rock installation vessels.

The Customs and Border Protection agency defines "pristine seabed" as a point "where there is no installation or device attached to the seabed, and thus where for Jones Act purposes no coastwise point exists" for the transfer of "merchandise". Under the Jones Act, scour protection rock is considered "merchandise."

Delivery of an initial layer of bedding gravel or scour protection to a future turbine position on a pristine seabed is NOT transportation between coastwise points; however, installation of the first layer (such as a filter layer) would create a coastwise point. As such, any future transport of merchandise to the turbine position (including future deposit of additional layers of bedding or scour protection), must be conducted by a coastwise-qualified (Jones Act compliant) vessel.

11.5. Limited availability of wind turbine installation vessels and floating foundation installation vessels.

According to OSPRE-2021-02, the analysis carried out in 2021 by the research team found a shortage of WTIV and FFIV that will impact in the U.S offshore wind energy development. The lack of supply of WTIV is such that, according to reference #12, currently only seven vessels are available in the global fleet with the appropriate height and capacity to install 12MW turbines in waters greater than 50 meters deep depth. If the next generation of 15-20MW offshore wind turbines is considered, the number of capable enough vessels available is even lower. Furthermore, the study also indicates that six of these seven vessels are already booked for multi-year projects in the European and Asian markets.

Therefore, as indicated in the abovementioned study, "the U.S. is about to build the world's largest offshore wind farm, and there just aren`t enough vessels available in the world to handle these projects". However, this major vessel availability constraint does not affect to the ELISA technology.

11.6. Task 10 Conclusions

The foreseen offshore wind farms to be developed in the upcoming years in the US East Coast will require facing the following challenges:

- Limited monopile production capacity in the US.
- Limited monopile production capacity in Europe.
- Nonexistence of US flagged floating foundation installation vessels (FFIVs).
- Nonexistence of sufficient US jack-up wind turbine installation vessels (WTIVs).
- Expected unavailability of foreign vessels and restrictions for their use in US waters under the Jones Act.
- Limited ports ready for offshore wind (without major investments).
- Local content commitments and US supply chain development.
- CO2 emissions.
- Marine life impact.

Gravity Base Structures are a sound and reliable alternative to monopiles and jackets, which can satisfactorily tackle the above-mentioned challenges as:

- Concrete GBSs can be constructed locally, using existing labor from civil, building and energy sectors.
- "Float and flood" GBSs can be towed offshore by using conventional tug vessels, avoiding the need for foundation installation vessels.
- GBSs are silent foundations which do not require piling, and therefore do not negatively impact, during the installation campaign, marine mammals and marine life due to excessive noise.
- Concrete substructures reduce the carbon footprint of the wind farm.

Furthermore, the ELISA technology also tackles:

- Limited yard requirements for construction in port by using semisubmersible means.
- Installation of the WTG in port prior towing the completed windmills offshore, avoiding the need for Wind Turbine Installation Jack-up Vessels (WTIVs).
- Only one layer of material for seabed preparation enabling performing the seabed prep campaign with Jones Act compliant vessels.
- Competitive pricing compared to monopiles and jackets.
- Enhanced cost reliability/stability as compared to monopiles and jackets due to the larger price volatility of steel raw materials.

Project Conclusions

The performed analysis of the ELISA technology for the US market, and for large turbines (>15 MW), has shown that this bottom fixed technology is a viable solution to address key challenges currently faced by the offshore wind industry in the US East Coast.

Along the different tasks of the project, it has been substantiated how the ELISA technology may deliver significant beneficial impacts on the US offshore wind industry as next summarized:

- *Full independence of heavy-lift vessels for installation of both foundations and turbines, qualitatively facilitating compliance with the Jones Act. ELISA allows complete on harbor assembly of the wind tower and WTG on top of the foundation, which can be towed and installed on-site using only local tugboats.*

  Through advanced and complete simulations performed by NREL and an ambitious tank testing campaign for experimental contrast and validation of the expected performance, the project has demonstrated the full applicability of the ELISA self-installing process for a 15MW turbine and substantiated its suitability for efficient scalability for even larger next generation offshore wind turbines (see further details mainly in Tasks 2 and 6).

  Filling the monopile supply bottleneck with the ELISA GBS "float and flood" foundation alternative would allow installing both foundations and turbines based only on existing US-flagged mid-sized tugboats, as documented in section 11.2 and section 11.3 (Task 10).

- *GBSs are silent foundations which do not require piling and avoid the negative impacts on marine mammals linked to the very high noise levels resulting from the piling of monopiles.*

  This key aspect of the GBS foundations is outlined in section 9.4 (Task 8).

- *Direct scalability for the next generation of large wind turbines (15MW+), and suitability to deliver a robust, durable, fatigue-tolerant and maintenance-free concrete substructure*

  The project showed and quantified in detail how the ELISA technology can be adapted to the future generation of 15MW turbines. As compared to the 5-year field-proven 5MW design, the required resizing for the 15MW foundation is moderate and does not require any shift in the design philosophy or in the required implementation means and infrastructure, either for on-harbor construction or for offshore installation. Detailed structural design and verification has substantiated the suitability of the prestressed concrete design which is not governed by fatigue or durability demands (see further details in Task 3).

The project also covered the adaptability of ELISA to different project conditions or circumstances, showing for example how the foundation can be sized to fully avoid the need for any solid ballast (using only water ballast) in regions in which the cost/availability of solid ballasting material or means may be more unfavorable (see further details in Task 8).

- *Suitability of ELISA technology to minimize harbor requirements and adapt to existing harbor infrastructure with no need for large upfront investments for major port upgrades or new ports.*

  Thanks to its suitability for construction of the foundation aboard barges, the ELISA technology can drastically reduce the harbor infrastructure required for large-scale production of foundations, both in terms or yard acreage needed and in terms of required quay bearing capacity. Such well-proven construction technique is backed by decades of very extensive and successful experience in the serial construction of many hundreds of concrete caissons in countries such as Japan, Spain or Brazil, with outstanding cost-efficiency and productivity ratios (caissons often weighting twice as much as the ELISA foundations are conventionally produced with 1 unit/week ratios).

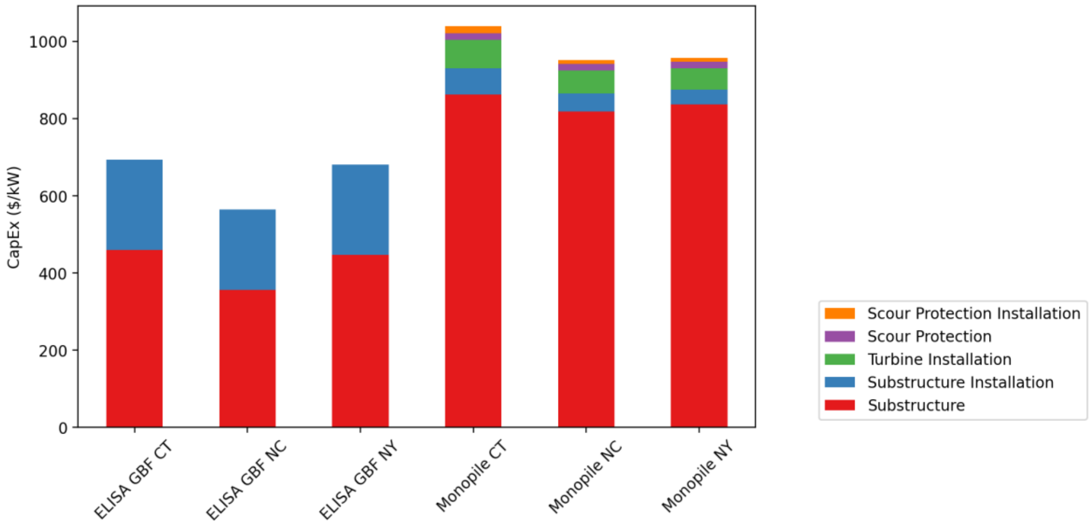
  The project has developed in detail the implementation of such foundation construction strategy in three different real scenarios along the east coast, showcasing how ELISA foundations could be mass produced based on existing harbor infrastructure (see further details in Tasks 4, 8 and 9). For comparison of required upfront investments with monopiles and jackets, refer to section 9.3 (Task 8), where, based on NREL's previous study, it is shown how upfront investments for port upgrade for the ELISA technology can be expected to be one order of magnitude lower than for monopiles or jackets.

- *Significant cost reduction relative to monopiles, due mainly to use of concrete instead of steel and due to the savings in offshore installation means.*

  The study substantiated that the ELISA-GBF substructure cost for manufacturing and installation is potentially 30% cheaper than the cost of the equivalent monopile foundation. This conclusion is demonstrated throughout Task 9 based on a comprehesive cost comparison analysis by NREL. Summary figures may be seen in the next figure, extracted from NREL's contribution to this project:

Figure 85. CapEx breakdown and comparison

CapEx breakdown and comparison between ELISA-GBF and Monopile for North Carolina, New York, and Connecticut. Substructure Installation (blue) for ELISA GBF includes WTG installation in harbor, seabed preparation and scour protection



- *Less risk due to cost volatility of commodity materials in comparison with full steel substructures.*

  This aspect became evident along the cost comparison carried out in Task 9. Monopile foundations are highly dependent on the cost of commodity steel, which has experienced high volatility in recent years. Between 2016 and 2023, the price index of fabricated steel plate has increased over 50% (225/145) (U.S. Bureau of Labor 2023).

- *Full onshore assembly of the wind turbine, avoiding expensive at-sea work. In addition, ELISA technology enables diverse WTG assembly strategies to better adapt to port characteristics and availability in each region.*

  A key advantage delivered by the ELISA technology is making it possible to have full assembly and pre-commissioning of the offshore wind turbines in controlled harbor conditions. No other proven solutions for bottom-fixed turbines can make this possible. This not only avoids the need for expensive heavy-lift vessels, but opens the room for enhanced industrialization and safety levels given the inherently different nature of harbor based activities as compared to offshore operations.

  It has been analyzed and verified that the ELISA self-installing method is fully applicable when using conventional steel wind towers. In addition, the optional possibility to use a telescopic hybrid tower solution has also been covered in the project, as potential means to lower the requirements on the onshore crane needed for on-harbor assembly of the turbines (see further details in Task 7). The cost analysis performed indicated that the use of the telescopic tower solution would only provide a cost advantage for small projects. For large-scale projects it is more cost efficient to mobilize a large capacity ringer crane and use conventional (non-telescopic) steel towers.

Moreover, the adaptability of ELISA for different implementation strategies regarding onshore WTG integration works has been described. Preferably, the same port would be used for foundation construction and WTG assembly activities. However, depending on project circumstances, it is also possible to build foundations in one facility and tow them to a different WTG marshalling facility where the WTG can be integrated with the foundation before the whole assembly is towed to the offshore site; this would open the room for ports that are may be suitable for foundations manufacturing works but not for full WTG integration due to air draft limitations. Furthermore, a complementary strategy, which is not studied in the present project, would be the ELI GBF (GBF transported and installed without the wind turbine). Details on this can be found in section 11.3 (Task 10).

- *Local content promotion, establishing the supply chain of a project almost completely within a state.*

  Throughout Task 1, Task 4 and Task 8, it is described how the ELISA technology is conceived and suited for local manufacturing and thus very intensive in local content of labor, raw materials and construction means. This is mainly thanks to:

  - its concrete based design for which a populated supply chain of capable contractors is available in virtually any region of the US.
  - its construction process onto semisubmersible barges that allows pursuing implementation strategies based on nearby existing harbors.

  NREL’s study carried out in Task 9 shows that an ELISA-GBF would potentially provide more jobs at the port due to the more labor-intensive nature of concrete manufacturing (2196 FTEs of ELISA GBS vs. 1090 FTEs of monopile).