TELWIND- Integrated Telescopic tower combined with an evolved spar floating substructure for low-cost deep water offshore wind and next generation of 10 MW+ wind turbines

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Summary

Levelised Cost of Energy (LCoE) is a main design driver for offshore wind turbines in deeper water. The presented evolved spar floating foundation combined with a Telescopic tower will reduce the costs of offshore wind. The objective is to design a revolutionary integrated floating substructure concept which shall enable a radical step forward for cost–effective and industrially deployable deep water offshore wind. The research and development activities within this project are executed by a strong multidisciplinary team of 8 project partners, funded by the European Commission in a Horizon2020 program.

Introduction

Two main novel and ground-breaking systems unite in the TELWIND floating substructure to generate a low-cost integrated system and its simple, fast and economical self-installing process: the evolved spar configuration with suspended ballast tank, and the self-erecting telescopic tower.

The floating substructure is based on an evolved spar configuration with solidary suspended ballast. It consists of an upper floating body connected by tendons to a heavy lower ballast tank which sufficiently lowers the system's centre of gravity to stabilize the structure.

The telescopic tower system consists of tubular tower levels built of precast concrete elements, one steel section and a tower self-lift using heavy-lift strand jacks.. This system is already developed for onshore and offshore fixed foundation application and is currently being developed from TRL3 to TRL7 in a separate project. The application with a floating system gives added advantages for deep-water application and transportation: A lower wind turbine height for installation and transportation allows for a stable system and the use of existing in-shore infrastructure
A preliminary experimental tank test of the conceptual fundamentals of the TELWIND platform is performed proofing the feasibility of the innovation. Previously a first simulation based on a fully coupled model with a 5 MW reference wind turbine was executed and the results are presented.

This paper describes the system in more detail including the installation procedure. Also the upcoming technical challenges during the design and validation phase of the H2020 TELWIND project are addressed.

Technology and Design principles

Background and Project Description

45 years' experience in the civil engineering sector and more than 10 years and 500 hundred concrete towers in the onshore wind industry is the impressive ESTEYCO´s visiting card. This experience is the solid foundation for an intensive R&D program focused in the design of offshore wind substructures.

The roadmap in the offshore business is initiated in 2010 with the first steps of a revolutionary concept: the TELESCOPIC TOWER which is a proprietary and patented idea developed by ESTEYCO. Since then, an ambitious action plan was carried out. Two projects are ESTEYCO´s flag in the offshore sector:

- Full Scale Prototype of the telescopic tower built in Madrid in 2014 (**Figure 1**-left).
- GBS ELISA/ELICAN with a Gamesa 5MW WTG, to be installed at 30m water depth during the 1Q 2017 (**Figure 1**-right) (www.elisaoffshore.com; www.elicanoffshore.com)

Figure 1. ELISA/ELICAN. Telescopic tower built in Daganzo (Madrid 2014) (left) and GBS under construction in the Canary Islands (Sept-16) (right).

Those efforts were rewarded by the European Commission in December 2015 funding the TELWIND project with 3,8 M€, currently under development in consortium with 8 companies led by ESTEYCO. The final objective is to develop a fully constructive design, certified by an international certifying agent and tested in a reduced scale in the model basin facilities in IHCantabria and CEDEX.

The main objectives of the TELWIND project are listed following in **Figure 2**.

- Study the concept scalability for a 12 MW WTG developed by MECAL
- Build a fully coupled aero-hydro-servo-elastic Floating Wind Turbine model and investigate coupling effects in the overall wind turbine performance
- Model Basin Tests in operating, extreme and installation conditions
- Perform laboratory tests to study the performance of the suspension tendons
- CapEx and OpEx estimate. Viability analysis of a single installation and integration in a multi-megawatt floating wind farm
- Obtain the Certification of the design
- Project dissemination in general and technical forums and conferences
- Design a 5MW WTG from conceptual to detail-constructive engineering.

Figure 2. Main Objectives of the TELWIND Project

TELWIND Platform Fundamentals

The TELWIND floating substructure is based on an evolved spar configuration with solidary suspended ballast (LT). It means the platform is ballast stabilized and therefore the center of gravity is below the center of buoyancy. This configuration implies the uprighting moment which tends to return the structure to the upright position is positive for a wide range of angles and it is not dependent on hydrostatic stiffeness and ship stability principles.

Suspending the LT of vertical cables is not a valid option in general, since the tank would not follow the structure's movement. However, this will no longer be the case if the suspension cables are not vertical, but configured to form a triangular system in which the cables have a given inclination and are prestressed by the LT's self-weight.

In such a case, the LT weight will move rigidly with the rest of the structure. As long as none of the cables reaches a vertical position, they shall remain under tension and behave as rigid bars, which adequately triangularised ensure a rigid solidary connection between the LT and the UT.

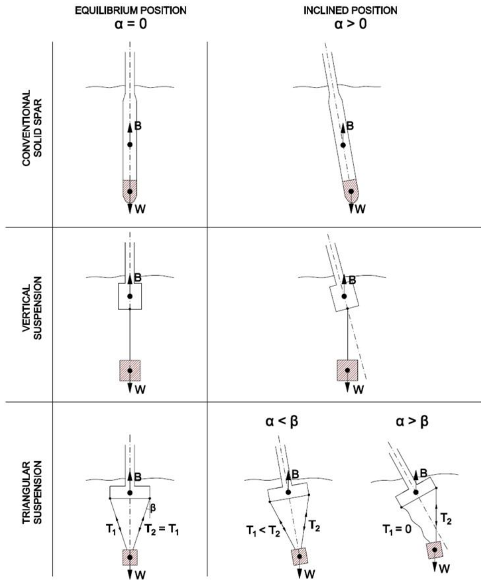


Figure 3. Conceptual fundamentals of the suspended ballast tank.

Based on those elementary principles, the preliminary arrangement has been defined. The TELWIND platform is divided in the following main parts:

- **Wind turbine generator (WTG):** It is a generic 5MW wind turbine with an specific WTG controller designed to deal with the floater motions.
- **Tower (TW):** The telescopic tower system consists of tubular tower levels built of precast concrete elements, one steel section and a tower self-lift using heavy-lift strand jacks.
- **Upper tank (UT):** It consists of an upper concrete floating body connected by tendons to a heavy lower ballast tank. It is compartmented to meet standardized stability requirements, minimize free surface effects, sloshing, allow water ballast transfer to reduce the tilt angle when required.
- **Lower tank (LT):** The suspended ballast lowers the system´s centre of gravity to stabilize the structure. It is filled with a combination of solid and water ballast when it is inplace. The concrete structure is stable during transport partially filled with solid ballast. For installation purposes the lower tank is water ballasted until it gets the final location.
- **Tendon suspension system**: cable connections between the UT and the LT. Tendons may be made of steel of synthetic fibres. For initial design purposes steel cables has been selected.
- **Mooring system**: the mooring system is a traditional free hanging catenary. It is composed by several catenary mooring lines (chain, fibers or mixed systems), anchors and intermediate connectors.

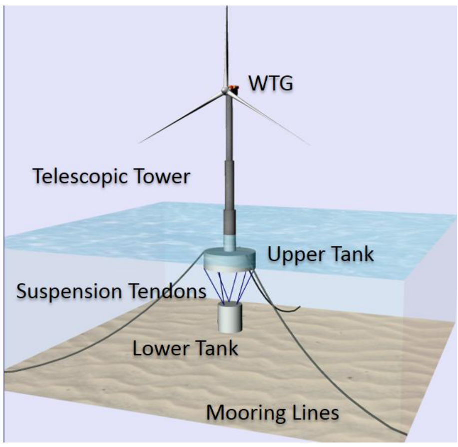


Figure 4. Showing the TELWIND main components

Sizing Methodology and Preliminary Design

This design strategy herein for the TELWIND facility is an adaptation of the general design principles used for the design of floating offshore platforms, specially Spar platforms, in conjunction with structural design principles to cover those specific issues related with the concrete hull.

For initial design purposes, the in-place condition is governed by quasistatic effects due to currents and wind and dynamic effects due to wave excitation. Hence the preliminary sizing is driven by:

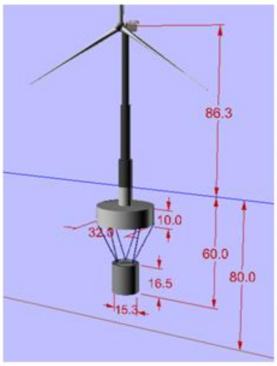
- **the initial stability (GM)** in all design conditions,
- the **tilt static angle (θ_{sta})** in both directions roll and pitch and
- **natural periods (Ti i=1…6).**

The installation process is based on a wet towing of the upper body (Upper Tank+Tower+WTG) and lower body (Lower Tank) connected by towing lines but floating separately. After the Lower tank is ballasted and installed in-place, the mooring lines are installed and finally the Upper tank may be supplemented with water and/or solid ballast (if required). Once stabilised the telescopic lift of the tower is undertaken.

Esteyco has developed a proprietary parametric tool to take into account the main design drivers during **all the design phases** from deployment at sea to the offshore inplace conditions and therefore to carry out the calculations simultaneously. In order to select the right set of dimensions **several design constraints** are imposed. The most important are listed following:

1) Tilt static angle (θ_{sta}) < 10º
2) Natural Periods in heave and pitch (roll)> 25s
3) Initial stability GM>1m (all phases)
4) Large angle stability (Area under GZ/area heeling curve) >1.3

Finally, the initial dimensions are selected. Trade-Offs in the definition of the input variables are adopted as the solution is not unique. The preliminary design is detailed in the figure and table following:



Concept	Value	
Overall Draft	60	m
Upper Tank draft	20.50	m
Upper Tank diameter	32.00	m
Upper Tank height	10-10.5	m
Lower Tank diameter	15.35	m
Lower Tank height	16.50	m
Cable length	26.06	m
Overall displacement	12,003	t
Metacentric height inplace (GM)	3.81	m
Metacentric height transport (GM)	2.50	m
Tilt static angle (θ_{STA})	9.56	º
Overall heave period (T3)	32.66	s
Overall pitch period (T5)	41.13	s

Figure 5. TELWIND preliminary design. Main characteristics.

Marine behaviour and preliminary load analysis

Basic Marine Behaviour and general stability analysis

In order to analyse the basic marine behaviour of the concept and the loads produced on the mooring system and the tendon system for a set of predefined metocean conditions, two different approaches are being developed by the consortium with the intention of validate and control the different results obtained:

- By using IHCANTABRIA “in-house” software, a fully coupled numerical model in time domain which comprises hydrodynamic numerical model, line model for catenary mooring lines (both quasi-static and dynamic model), line model for tendon system (only dynamic model) and wind model for the performance of a wind turbine (both quasi-static and dynamic model) to analyse the hydrodynamic behavior and loads on TELWIND concept.

- By using BLADED, well-known software in the wind industry, which MECAL is using to analyse the dynamic behavior of the TELWIND concept.

IHCANTABRIA fully coupled numerical model (Figure 6) is based in the results produced by two different Software, NEMOH (Babarit & G. Delhommeau, 2015) and WADAM (SESAM, DNV, 2014), both based in potential flow theory (Boundary Element Method, BEM) and Cummins' Equation (Cummins, 1962) for the coupling of all the effects from mooring system, tendon system, wind turbine and metocean conditions forces that produce motions on the platform as it is shown on Figure 7.

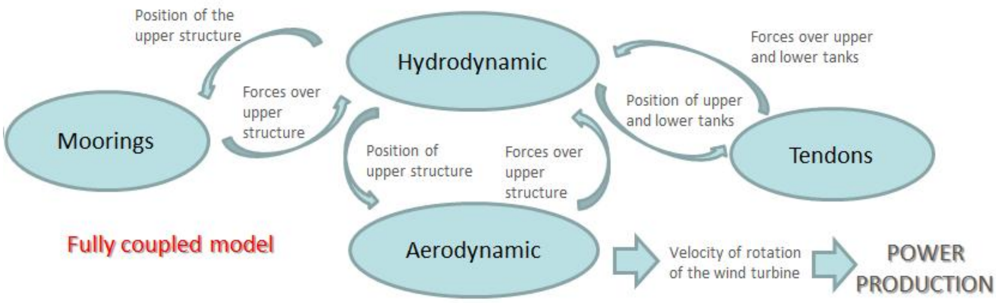


Figure 6 Fully coupled model scheme

$$\underbrace{(M + A_\infty)\ddot{z}(t)}_{\text{Inertia force}} + \overbrace{\int_0^\infty \underbrace{K(t-\tau)}_{\text{Transfer function}}\dot{z}(\tau)d\tau}^{\text{Radiation force}} + \underbrace{Gz(t)}_{\text{Hydrostatic force}} = \overbrace{F_e(t) + F_c(t) + F_v(t) + F_m + F_u(t) + F_f(t)}^{\text{External forces}}$$

Figure 7 Cummins' equation – principal elements of the equation

Considering the geometry of the TELWIND concept, two different configurations have been considered for numerical model analysis:

- The first configuration is a simplification that considers the whole concept as a single body replacing the tendons by rigid bars. In this configuration, the body is stable and in equilibrium, and both potential flow models in the frequency domain, NEMOH and WADAM, can be used, knowing the mass properties of the rigid solid geometry.

- The second configuration is the whole concept with two independent bodies connected by tendons. In this case, individual bodies are unstable and are not in equilibrium (UT tends to go up because of buoyancy force is larger than gravity force and LT tends to go down because gravity force is larger than buoyancy force). Consequently, the independent RAOs for each body are not obtained. Furthermore, WADAM cannot be used in this second case, as the first step when performing a WADAM analysis is to check for equilibrium and stability. On the contrary, NEMOH does not perform any of these analysis, as it computes the added mass, damping and waves excitation forces, which depend on the geometry of the body. Therefore, the second configuration is computed using NEMOH knowing the mass properties of each body considered.

The results obtained with BEM models are presented for both configurations and included in the hydrodynamic model in time domain. The time domain hydrodynamic numerical model includes a damping force (both linear and non-linear) that reduce the motions of the body in an attempt to incorporate some of the physical phenomena that has been neglected when using potential flow theory. Due to tank testing are not perform yet, a sensitivity analysis of the results obtained with different values of the damping forces has been performed.

The results obtained in simulations of the given metocean conditions by means of a design load case (DLC) matrix based on standards (IEC, DNV, etc.), give the impression to be consistent in the absence of tank testing, which is necessary to obtain some important parameters such as damping coefficients for each DOF (Degree of Freedom). The results analysed include the motions of the bodies in the 6 Degrees of Freedom (DOFs), acceleration at the hub's position, thrust, blade pitch angle, forces computed by the mooring model at the fairleads of the body and at the anchors' positions and forces computed by the tendon system at UT and LT.

The scope of the paper limits the number of particular cases and examples that can be cited. Therefore, some brief conclusions are presented considering the first configuration analysis (rigid solid) using the time domain fully coupled model and DLCs. It is important to highlight that results of motions are in global reference system, where metocean conditions from North means a direction of 0 degrees.

- Results are considering hydrodynamic numerical model is used for the motions, quasi-static model for the mooring system and dynamic model with a simple blade pitch controller for the performance of the wind turbine.
- Results present the uncertainty of the hydrodynamic damping force. This uncertainty will remain until the tank testing provides data to calibrate these motions and forces. This tank testing will be carried out at IHCANTABRIA facilities.
- For operating DLCs (from reduced DLCs matrix):
    - For waves and current corresponding to a storm of 10 years return period (Hs5.7m & Tp11.5s) and wind speeds below rated wind speed, the controller is not working and the pitch angle is always zero, being the results feasible. TELWIND platform behaves adequately, with low angles of rotation observed (roll below 3 degrees, pitch below 6 degrees and yaw below 1 degree) for these load cases, low accelerations at the hub (being in every load case less than the maximum value registered as 0.41g) and no vertical forces are registered at the anchors and 34 tons as a maximum force in the fairleads of the mooring lines that face the waves.
    - For similar waves and currents, and stronger winds, as expected, fast changes in blade pitch angle given by the simple controller implemented in the wind model produce large movements on the platform, with maximum accelerations at the hub up to 0.53g. The vertical forces produced by the mooring system at the anchors remain zero and the maximum force registered in fairleads is 86 tons. For these DLCs, because of the large wind forces, the rotations reached resonance, oscillating with natural period of the structure in pitch (close to 34s) instead of oscillating with the irregular waves. This is a problem related with the pitch controller, whose development is in progress.
- For parked DLCs:
    - Current and waves corresponds to a storm of 50 years of return period and the wind is defined in accordance with wind class IIA. Platform angles of rotation have been feasible in all conditions, below 9 degrees (maximum pitch angle observed). However, there are large forces applied to the anchors of the mooring system. For one DLC, mooring line 3 is the one receiving the largest forces on the anchors as waves and wind are coming aligned from North direction. The maximum forces registered for this mooring line are 55 tons at the anchor (vertical force) and so much larger in fairlead than forces in operation conditions It is considered that maybe the used drag coefficients are not appropriate ones for this situation and the mooring system is not long enough to avoid these forces at the anchors.

MECAL and IHCANTABRIA are collaborating and working in parallel in order to improve the accuracy and the consistency of the results of both approaches. Once tank testing campaigns are carried out, these data will give enough information to calibrate the numerical models and optimize performance of the seakeeping of the TELWIND concept.

Interaction with turbine and control system, development of fully coupled model

A fully coupled and integrated approach has been taken to understand the dynamics of this novel floating wind turbine concept. This means turbine (rotor-nacelle assembly) has been integrated with floating substructure (telescopic tower, upper and lower tanks, tendons and mooring lines) in an aero-servo-hydro-elastic coupling environment with inflow of wind, waves and currents. This interaction has been depicted via Figure 8.

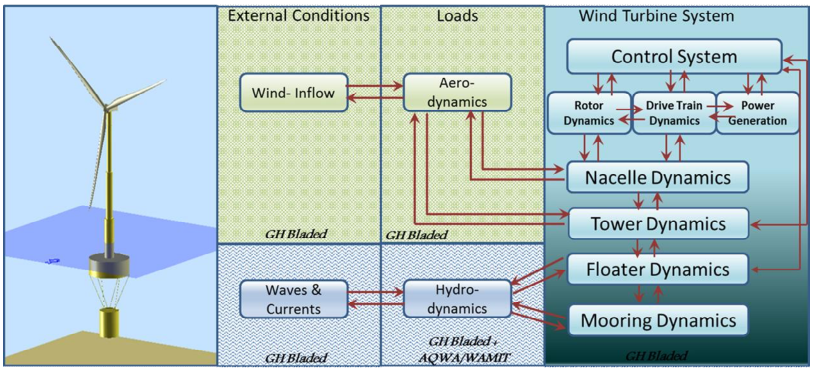


Figure 8.Interface Modules for Fully Coupled Aero-Hydro-Servo-Elastic Simulation

For aero-servo-hydro-elastic modelling and simulation purposes, GH Bladed 4.7 is used. The wind turbine is a generic 5 MW wind turbine with a 132 m rotor diameter.

One design criteria for the floating structure is that the tendons should not become slack, as this would lead to a high transient loading and detrimental to turbine's stability. This slackness can also be correlated to platform pitch angle which is typically high in floating wind turbines (compared to gravity based/fixed foundation system). This slow pitching motion of platform should be damped as efficiently as possible to lessen its impact on loads, especially above rated wind speed, when pitch controller interacts with this motion. The amplification of this pitch motion is due to the phenomenon of 'negative floater pitch damping' when collective pitch controller is activated.

To handle this issue, MECAL has developed a tower top velocity feedback control with rated power set-point variation (PTTF). The basic principle of this strategy is explained in Figure 9. This approach was investigated as it decouples rotor speed and tower top thrust (shown in terms of fore-aft Tower bending moment, My, in Figure 9), thus limiting the rotor speed fluctuations because of the additional feedback loop in pitch control. Platform pitch damping is achieved after varying the rated power around a set-point (eg. 95% of rated power) as a function of tower top velocity. This demands a change in generator torque, thereby, varying the blade pitch angle. So this way, there is a decoupling between floater pitch damping and generator speed control.

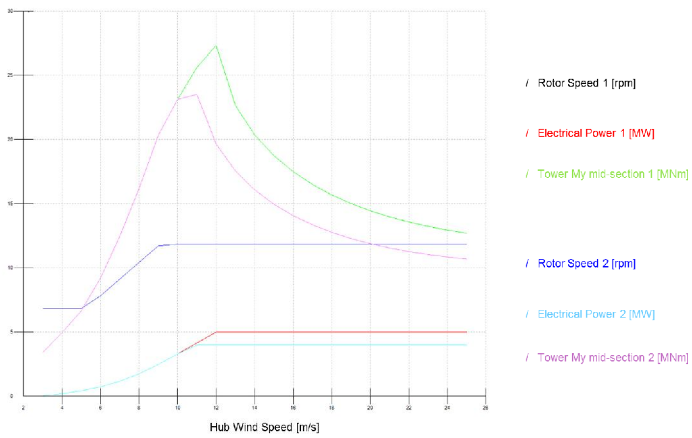


Figure 9. Principle Showing the Decoupling of Rotor Speed and Rotor Thrust

Note that this is different than the ‘typical’ tower top feedback control where blade pitch demand is directly linked to tower top velocity. This strategy is still under consideration and maybe used at a later stage depending upon its feasibility.

PTTF feature works well since the power fluctuation will result in a rotor thrust force fluctuation without affecting the rotor speed. The economic feasibility of this feature depends on the required amount of power fluctuation needed, to add significant platform pitch damping. Note that other control approaches such as shutting down the wind turbine at higher wind speeds, also lead to certain amount of power loss. Also, wave (blade pitch control responds to wave motion) has an impact in power reduction.
One of the preliminary simulation with turbulent wind (20 m/s) along with a fully coupled floater wind turbine model gives promising results for platform pitch damping. This can be seen in Figure 10. The black line plot shows how nacelle nodding can be damped at higher wind speeds using PTTF feature.

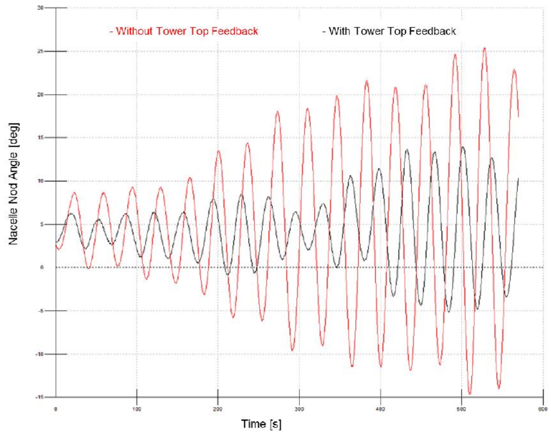


Figure 10. Platform Pitch Motion Damping with Tower Top Feedback at 20 m/s

The tendons behaviour are analysed in case of an extreme gust + grid loss scenario where there is a reversal of thrust loads on the tower due to the blades pitching to feather position. Figure 11 shows the axial forces on extreme upwind (member 19 = C6) and downwind tendon (member 16 = B3). The layout of these tendons are described via **Error! Reference source not found.**. The first thing to be observed from this (Figure 11) is that the tendons don’t go in compression (slack mode).

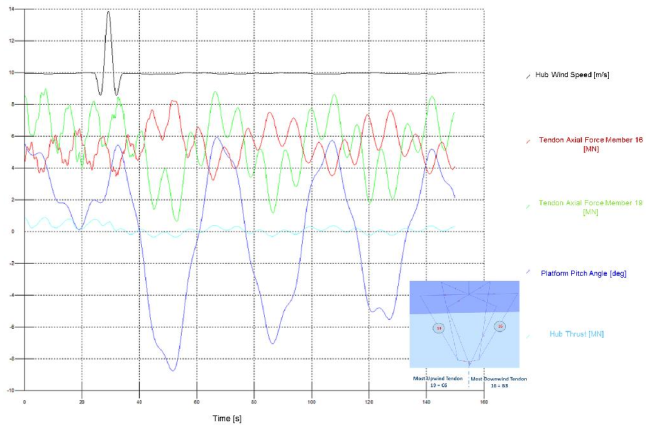


Figure 11. Axial Forces on Tendons Connecting Upper and Lower Tank

Looking at the two tendons, it can be seen that the most upwind tendon (member 19) is most critical considering the slackness. The upwind and downwind tendons forces are 90 degrees out of phase. It can be seen that the gust sets up the platform motion which results in fluctuating axial forces (with frequency of platform pitch motion) in tendons, but since the turbine stops (due to grid loss and rotor speed excursions above a certain level) the platform pitch motion seems to cease (aerodynamic fore-aft damping) over time. Note that this load case is the extreme one, from a set of runs, which considered different worst case scenarios for occurrence of gust, grid loss and maximum wave height at the same time.

The above two results i.e. platform pitch damping using tower top feedback with power setpoint variation and no slack in tendons behavior in the extreme operating gust scenario gives confidence that the design of the floating wind turbine system will meet the required design criteria. Further work is being carried out to optimize the floater design in various aspects like mooring system, introduce more fidelity in hydrodynamic loads modeling (incorporating panel methods to include diffraction and radiation effects while inducing the damping in tank structures).

Impact on Capital Expenditures

The TELWIND platform is engineered to dramatically reduce the capital expenditures of future floating offshore wind farms.
The most important cost reduction is achieved by:

- Using a low cost material: concrete
- Using the telescopic tower implies two main benefits:
    - To improve stability in transport conditions as the overall CoG is lowered,
    - To avoid chartering jack ups and heavy lift vessels

Direct comparison with conventional solutions shall be done taking into account several points:

- Tower costs are already included in the TELWIND solution. Therefore, wind turbine costs are smaller than traditional solutions with steel towers
- Installation costs are substantially lower
- Manufacturing costs are not more expensive than other steel floating solutions. Although it is relatively heavier structure, the concrete is a cheap material.

Current CapEx assessment carried out for the ELISA/ELICAN project (**Figure 1**) are a good reference to build the TELWIND baseline case with actual numbers. Hence it is worth to highlight that ELISA/ELICAN main figures: 5MW WTG+ Concrete GBS +installation (30m Water depth): 3M€/MW.
The preliminary assessment shows that the simple but innovative ideas behind this concept really drive the overall costs down.

Baseline case. CapEx Analysis.

The baseline case has been done based on a single unit, built and installed in the PLOCAN demonstration site, in the Canary Islands (http://www.plocan.eu/) in the following sections a general cost breakdown of the TELWIND platform is also presented. This is a work in progress and only the big numbers are presented below.

<u>Turbine and Site</u>

- Turbine is a generic 5MW WTG with 132m rotor diameter.
- Distance to shore is about 7,5km
- Average water depth is 80m
- Soil conditions are sand

<u>TELWIND platform</u>

- “Hull” includes all structure and outfitting below the bottom tower flange. Cost estimates are done for the “TELWIND platform” (tower + hull)
- Mooring lines: three steel catenary mooring lines
- Anchoring: deadweights, drag anchors, driven piles or suction anchors are potential solutions.

<u>Construction and Installation</u>

- Tower and upper tank are fabricated locally.
- The nacelle is assembled a pre-commissioned atop the telescopic tower using land-based crane before departure to the final location.
- The full system is wet towed from the assembly harbour to the PLOCAN site.
- Mooring lines and anchoring are pre-installed before the arrival of the TELWIND platform
- The power cable is pulled-in after the suspension tendons are inplace, the tower is jacked up and the horizontal joints between the tower sections are grouted.

Electric layout

- The substation is located onshore as the demonstration site is close to the shore line.
- The umbilical and static cable, intermediate floaters, bend stiffeners, etc. are also included in the budget
- Cable burial and/or mechanical protection is also considered

CapEx calculations are based on the assumptions above and later optimized thanks to the lessons learned from the ELISA/ELICAN project.

- The main figures: overall cost per Megawatt in a demonstrator in the Canary Island is about 3,5 M€/MW
- The "platform cost" is about 40% of the total investment but the tower and the installation is already included in this percentage.
- As expected, the mooring system, anchors and its installation are new components in the offshore wind sector. The cost means an important percentage

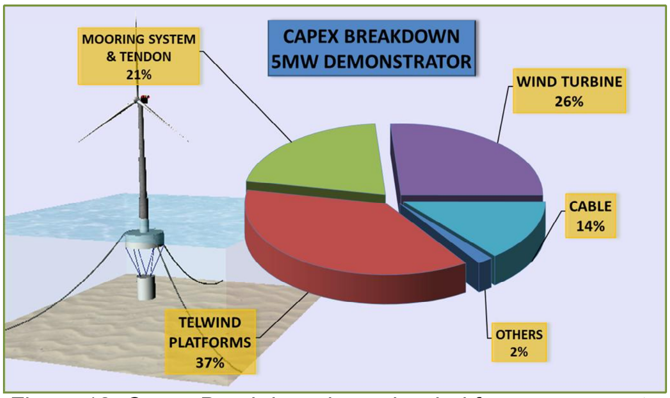


Figure 12. Capex Breakdown by main wind farm components

Conclusions

The presented TELWIND will reduce the Capital Expenditures of offshore wind at deep water. The concept will provide important savings by means of:

- material savings of the floating structure,
- reduce installation costs by avoiding the need for offshore heavy lift equipment
- keep the in-shore assembly works within limited drafts, heights and widths to profit from existing in-shore infrastructure.
- Ease of maintenance
- Reduce decommissioning cost because telescopic operations are reversible and deballasting of LT and UT is also feasible.
- Economies of scale will dramatically reduce the CapEx by using precasting technology in the concrete elements

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