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# Tourist Living on Off-Shore Wind Turbine: Floating Anchorage Design and Wind/Wave – Structure Interaction Study

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**Abstract** This paper aims to show a refurbishment project of an off-shore wind turbine, combining its natural purpose of exploiting the wind resources in the windiest sea areas along the coasts of Italy (Sardinia, Sicily, Abruzzo, Apulia) together with the possibility of using its structure as a tourist accommodation. Therefore, the main purpose of the paper is not to evaluate the wind turbine fluid dynamic response, but to study the interaction between civil architecture and mechanical structure. In this way, an economical contribution to the sustainability of the wind farm is possible. On this basis, a floating wind turbine called ARYA, has been designed as case-study. First of all, the 2 tourist-receptive structures (Hotel and bar-restaurant) around the wind tower have been designed and checked. Later, in order to study the effects on vertical cables fixed to the sea bottom, a detailed analysis of the floating anchorage TLP (Tension Leg Platform) was carried out. TLP consists of a nearly fully submerged cylindrical platform, which supports a 5 MW wind turbine and is linked to the sea bottom by 3 ties which assure stability and limited tilting, even under the worst loads induced by wind and sea. Morison's equation is used to compute the hydrodynamic loading on the TLPs. A numerical model has been implemented and nonlinear dynamic analysis have been performed, investigating both the wind-structure and the wave-structure interaction. The analysis was based on the extreme environmental conditions of the site where it has been suggested to install the system.

***Keywords:*** *wind turbine, off-shore, wave-structure interaction, wind-structure interaction, numerical analysis, refurbishment project*

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## 1. Introduction

Nowadays electricity has become an essential need for humans as much as basic needs like food or water. The demand is growing and the expected trend for the future is not decreasing. Predictive analysis on the uses of electricity forecasts an increase in energy demand of more than 50%, which means that governments have to install new energy plants with a total capacity equal to what is installed today.

Electricity production has the serious disadvantage of causing the emission of pollutants such as "greenhouse gases" which have devastating effects on Earth's climate.

Therefore, the response to an imminent increase in demand for electricity cannot be found in the installation of new "thermoelectric" plants because they would represent a further source of pollution and a rise in energy costs.

In the light of the studies on sustainable development, carried out over the past decade, the only solution is represented by the use of "renewable energy" such as sun, wind, sea currents, etc..

In this work, wind energy is the preferred renewable source of energy, particularly referring to the off-shore wind energy. In the last ten years, the off-shore wind energy has increased thanks to several advantages such as a reduced visual impact and a greater amount of energy produced by a strong and stable wind. Starting from the first off-shore wind farm (few MW of installed capacity) it is now possible to design wind farms of 160 MW, with wind turbines of 2 MW each, while turbines of 5-7 MW are under study.

Today, the countries that have invested heavily in the construction of off-shore wind farms are the USA, Denmark and the United Kingdom. Although the northern seas and oceans in general benefit from a greater availability of wind, also Italy has begun to exploit its great wind potential, to reach the targets imposed by the Kyoto Protocol and achieve, by 2020, the energy goals promoted by the European Union (EU) energy policy. In fact, the EU has set for 2020 a 20% reduction in emissions of greenhouse gases, 20% energy savings and 20% increase in the consumption of renewable energy sources as reported in [1,2].

In 2014, Europe fully connected to the grid 408 offshore wind turbines in nine wind farms and one demonstration project with a combined capacity totaling 1483 MW. A total of 536 turbines were erected during 2014; 2488 turbines are now installed and grid connected, making a cumulative total of 8045.3 MW in 74 wind farms in 11 European countries. Once completed, the 12 offshore projects currently under construction will increase installed capacity by a further 2.9 GW, bringing the cumulative capacity in Europe to 10.9 GW. In regards to the foundations, the average water depth of completed wind farms, or partially completed ones, in 2014 was 22.4 m and the average distance to shore was 32.9 km [3].

On this basis, through the design of a wind turbine of 5 MW of rated power with a floating TLP (Tension Leg Platform), placed inside a completely floating Wind Farm, this paper aims to contribute to the development of deep water off-shore wind turbines, proposing an architectural reuse project which combines a tourist-receptive structure with a wind turbine. This way, there is an economical contribution to the sustainability of the wind farms. The project is based on a literature review about additional uses/functions systems for recreational/touristic activities on the off-shore platforms such as [4,5] and about the main types of support structure for offshore wind turbines [6,7]; on numerical calculation for the foundation system pre-sizing and on an architectural and structural design of two buildings around the turbine tower (a hotel at +10m and a bar-restaurant at a depth of -10m). The chosen Tension Leg Platform (TLP) (see section 4) consists of a nearly fully submerged cylindrical platform, which supports a 5 MW wind turbine and is linked to the sea bottom by 3 ties which assure stability and limited tilting, even under the worst loads induced by wind and sea.

## 2. Wind Farm

With the aim of designing a floating wind turbine and after a feasibility study, it was decided to locate the Wind farm in the Italian waters between Pescara and Vasto (Adriatic Sea), placing it at a distance of about 30-35 km from the coast in a depth between 50 and 100 meters (Figure 1). The Wind farm, in its final position, will consist of 22 units production with a rated power of 5 MW each, for a total capacity of 110 MW, which is necessary to meet the needs of the Abruzzo region.

The bathymetry of the Adriatic Sea (Figure 2) is characterised by strong transverse and longitudinal asymmetries. It is divided into three sub-basins along its main axis NW-SE based on their different morphological characteristics: the Northern Adriatic Sea, the Central Adriatic Sea and the South Adriatic Sea.

The central sub-basin, which is the area where the Wind Farm will be located, is a transitional zone between the north and south of the basin. Its average depth is around 140 meters, and is characterised by the presence of two depressions in its northern area, the pits of Pomo, which reaches a maximum height of 270 meters and by the presence of a submarine mountain at the center of the sub-basin, which rises up to the depth range of 60 meters under the sea level; the central sub-basin ends with the Palagruza Sill. The bottom of the Adriatic Sea, particularly near the coast, is characterised by a modest thickness of the Plio-Quaternary succession and a vertical tectonic. The sediments of the sea bottom consist of clay, silt, sand and gravel.

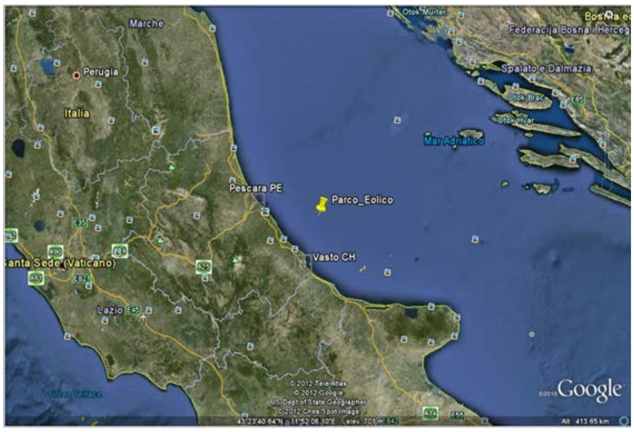


**Figure 1.** Wind Farm location

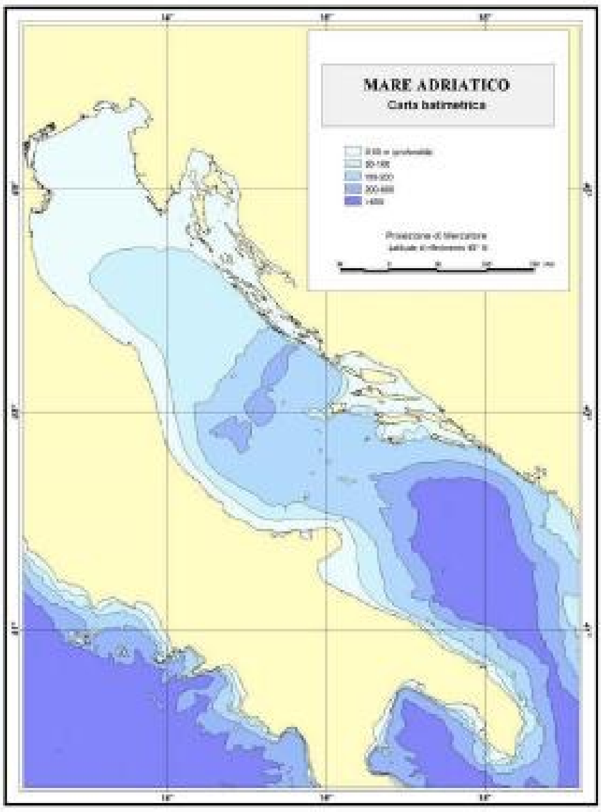


**Figure 2**. Adriatic sea: bathymetric map

## 3. REpower 5 MW

The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL), through the National Wind Technology Center (NWTC), sponsored concept studies to evaluate the best off-shore wind technology in superficial waters but also in deep waters off the coast of the United States and in other off-shore sites around the world. The DOE and NREL have identified REpower 5 MW as the best blade for off-shore installation in deep water thanks to its power (5 MW) and its dimensions. More details about REpower 5 MW can be found in [8]. In Table 1 the main characteristics of REpower 5 MW are summarized.

**Table 1. REPower 5MW**

| **Design** | **Rotor** | **Rotor blade** |
|---|---|---|
| Rated power: 5000 KW<br>Insert speed: 3.5 m/s<br>Rated wind speed: 13 m/s<br>Off speed: 25 m/s | Diameter: 126.0 m<br>Swept area: 12469 $m^2$ | Length: 61.5 m<br>Structure: Monocoque GFK/CFK |
| **Tower** | **Foundation** | **Design loads** |
| Structure:<br>Steel tube tower or steel-concrete hybrid tower<br>Hub height: 90 m<br>Bottom diameter: 6 m<br>Top diameter: 3 m | Structure: Depending on the location | Machine and tower weight: 8000 KN<br>Operating condition thrust: 1700 KN<br>Overturning moment at the base of the tower: 187000 KNm |

## 4. Foundation System

Initially, the research focused on the study of the wind turbine system foundation with REpower 5MW wind turbine and floating foundations (Figure 3). Other studies of floating anchorage TLP can be found in [7,9].

The floating structure is formed by a cylindrical steel body, with a radius of 14 meters and a height of 14 meters. At the bottom of this structure there are 3 big, 25 meters long metal rods (square profile of 1x1 meter). The buoyant force produced by the volume of water displaced by the floating structure is much greater than the weight of the platform and it is balanced by 3 vertical ropes (TLP). In the case of floating structures stabilised with tension cables, in fact, the cables have to stabilise the floating structure and also ensure that the floating structure maintains its position. The metal cables are anchored to the sea bottom through deadweights, often filled with concrete or gravel, which are placed on the sea bottom and thanks to their weight they can contrast the load produced by the mooring lines.

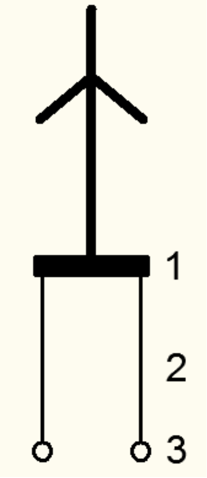


**Figure 3**. Adopted system foundation: 1. Floating tank, 2. Vertical ropes, 3. Mooring lines anchorage system.

## 5. Case Study: Off-shore Wind Turbine Anchorage Design (ARYA)

### 5.1. Structure & Architecture

The ARYA design includes the installation, around the turbine tower, of two structures in the form of big-octagons. The first one is immersed in the sea at a depth of -10 meters (bar-restaurant) (Figure 4) and the second one is located at +9 meters above the sea level (hotel) (Figure 5). These structures are connected through a steel cylinder where lift and stairs are located. This idea is justified to use the turbine not only for the energy production but also as a “tourist destination”.

Both the octagonal steel structures are equipped with huge windows, offering a view of the sea allowing tourists to interact with it, even if only visually format with a space of 1.93 characters between columns.

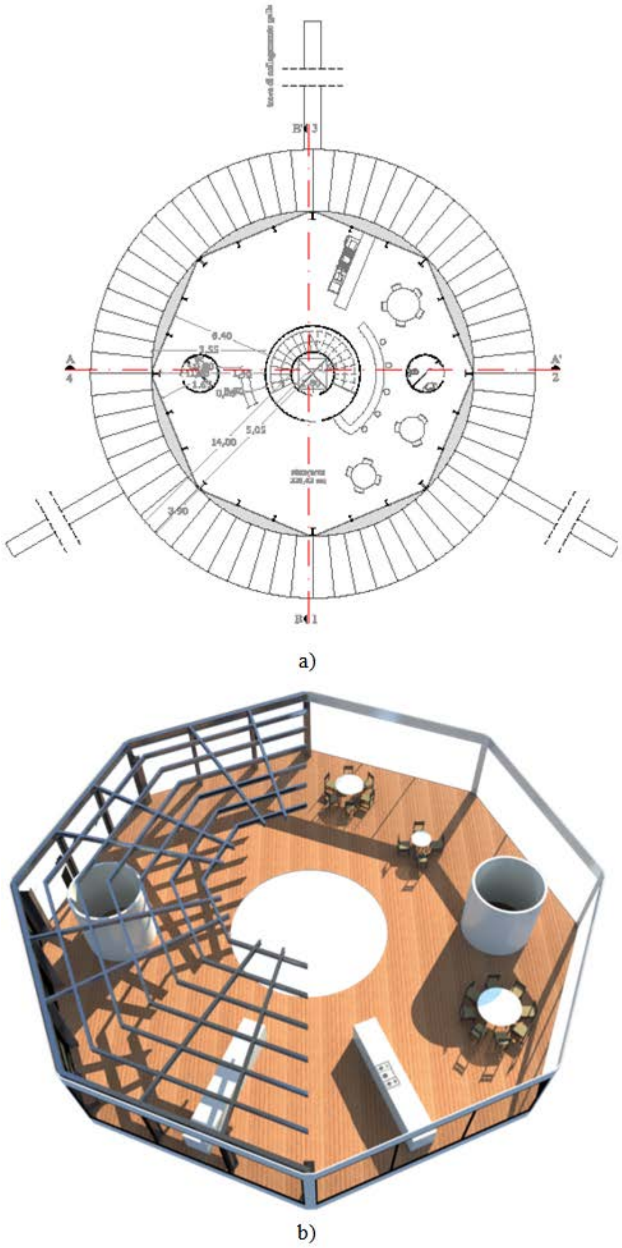
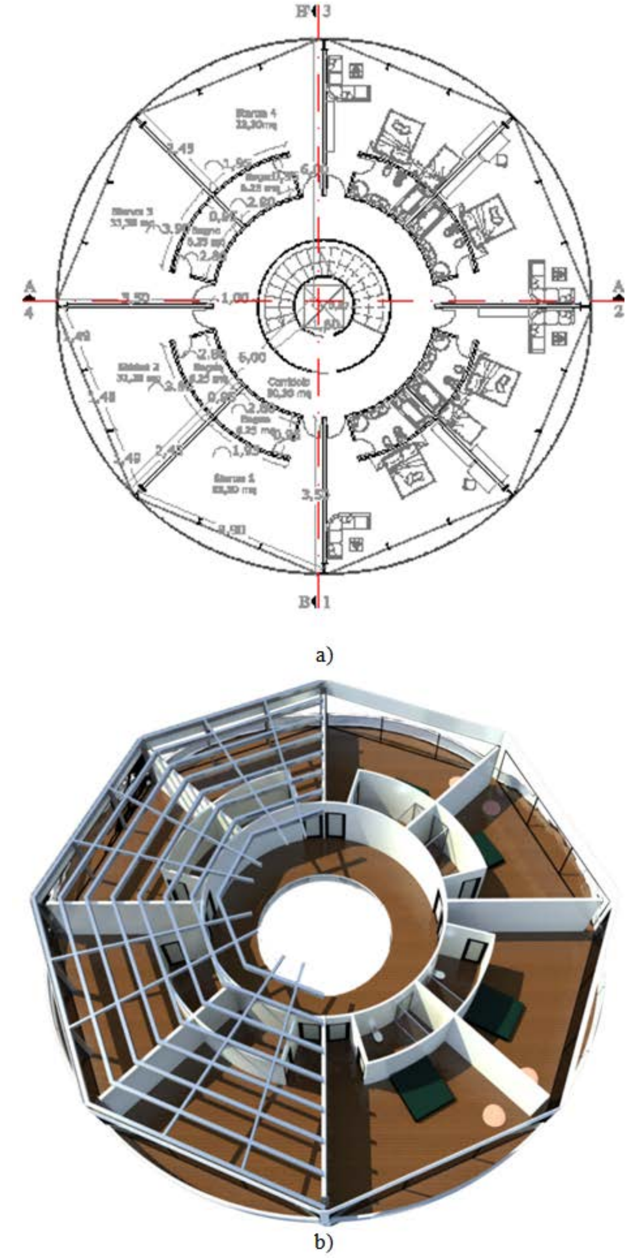


**Figure 4**. Level -10m: Bar-restaurant a) Plan; b) 3d virtual view



a)

b)

**Figure 5**. Level + 9m: Hotel a) Plan; b) 3d virtual view

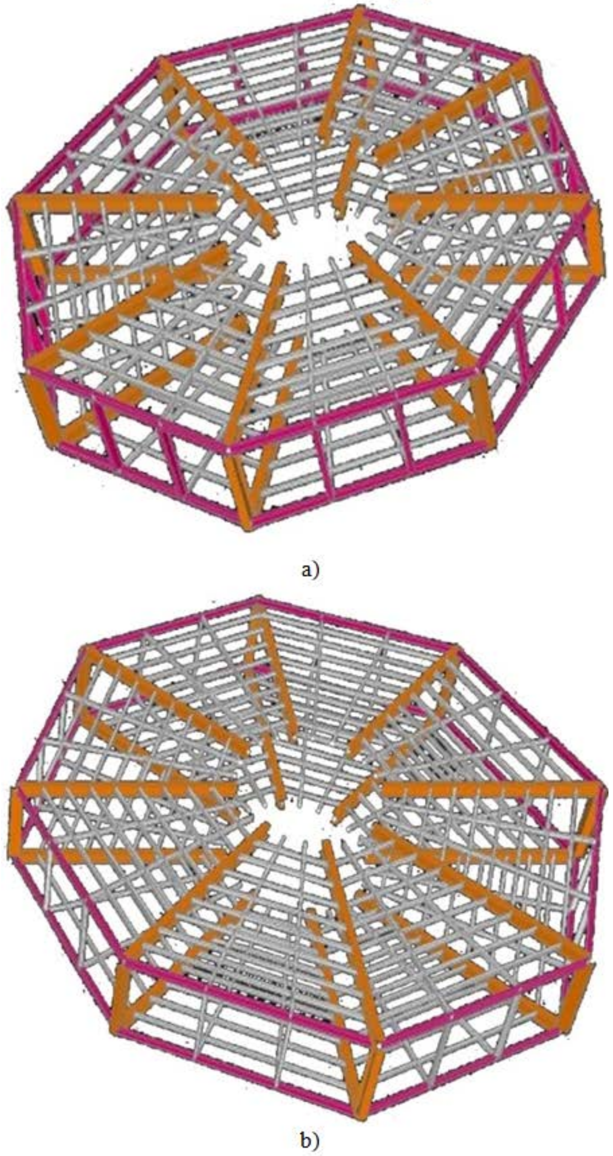
The materials used were chosen according to the specific needs and the location of the Wind farm. The marine environment, in fact, makes it essential to use anti-corrosion materials and materials resistant to the high pressures at different depths. For these reasons, the structure will be made of stainless steel and laminated glass. An important role is also played by anti-corrosive paints that are applied on materials.

The software SAP2000 (educational version) is used to size the octagonal structures and to perform the structural analysis.

The two analysed octagonal steel structures are characterised by different columns and beams. The structure located at -10 meters (bar-restaurant) consists of columns with a height of 3 meters and beams of 10,10 meters of length. The structure located at +9 meters above sea level (hotel), is made of 4 meters long columns and 12 meters long beams.

Thanks to the help of the software all beams and columns have been tested using elastic and plastic theory. All tests are satisfied. For the construction, steel S355 and the following structural elements (Figure 6) were chosen:

- Columns: HEA500 = 🟨
- Main beams: HEA 500 = 🟨
- Secondary beams: IPE 200 = ⬜
- Perimeter beams: IPE 300 = 🟪



a)

b)

**Figure 6**. Structure a) Bar-restaurant (-10m); b) Hotel (+ 9m)

## 5.2. Floating Tank & Vertical Ropes

The load analysis was carried out considering the weight of the REpower 5MW wind turbine and its components such as rotor, nacelle, tower and blades, and the additional octagonal structures bonded to the tower.

A summary table of all the weight forces acting on the wind turbine is reported below (Table 2). These are important to size the floating tank and, subsequently, to choose the right vertical ropes.

The buoyant force (Equation (1)) is a very simple concept which has allowed, in a very elementary way, to size the floating tank and thus, to calculate the hydrostatic pressure exerted on the blade in order to make it float:

$$S_a = \rho \cdot V \cdot g \tag{1}$$

where $\rho$ is the seawater density; $V$ is the volume of the cylindrical floating tank; $g$ is the gravitational force. In this way, it was possible to estimate the buoyancy exerted on the floating tank and to compare it with the weight forces constituting the entire structure.

**Table 2. Weight forces acting on the wind turbine. *g* is the gravity acceleration**

| **REpower 5 MW masses [6]** | | |
|---|---|---|
| Rotor mass | $1079.100*10^3/g$ | Kg |
| Tower mass | $3408.583*10^3/g$ | Kg |
| Nacelle mass | $2354.400*10^3/g$ | Kg |
| Blades mass | $522{,}0882*10^3/g$ | Kg |
| Hub mass | $557.0118*10^3/g$ | Kg |
| **Total mass** | $\mathbf{7921.183*10^3/g}$ | **Kg** |
| **Floating tank weight force** | | |
| Dimensions (r.14 m; h=14 m) | 676368.56 | KN |
| Cavity (r.13,95m; h=13,90) | 666749.23 | KN |
| Radial rods (1m x 1m) | 810.00 | KN |
| **Total weight force** | **10429.33** | **KN** |
| **Load analysis (for ex. Structures, materials, lift, stairs, etc.)** | | |
| Load analysis: | 64274.54 | KN |
| **Total weight forces** | **82610.31** | **KN** |

ARYA receives a buoyancy equal to 17137 KN, the difference between the weight forces and the pressure that is due to the size of the floating tank (Figure 7a).

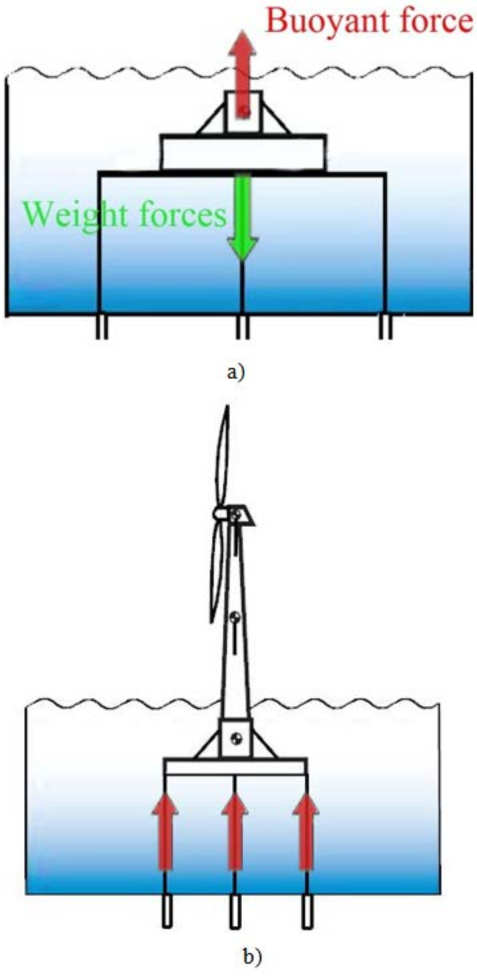


**Figure 7**. a) Buoyant force; b) In red the reaction forces of the system named TLP (Tension Leg Platform)

The proposed Tension Leg Platform has 3 ropes. This means that each rope must resist to a static load of about 5710 KN (Figure 7b).

Dead weights made of concrete and steel were chosen as anchoring devices. This way they are able to contrast approximately 2 times the value of forces. In order to support a vertical force of about 5700 KN, a deadweight with the following characteristics and dimensions was chosen:

- Concrete outer edge of 7x7x4 meters;
- Steel inner cavity of 6x6x3 meters.

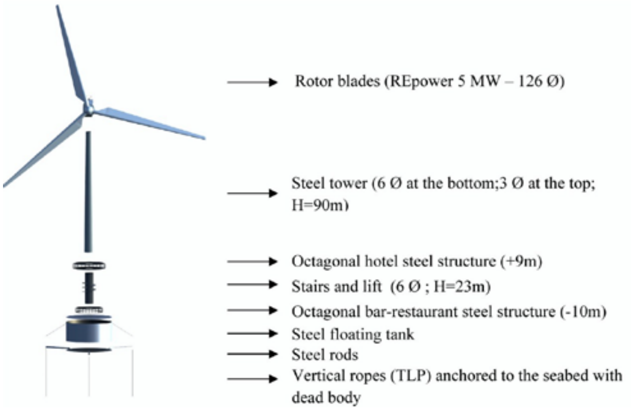


**Figure 8**. ARYA main components

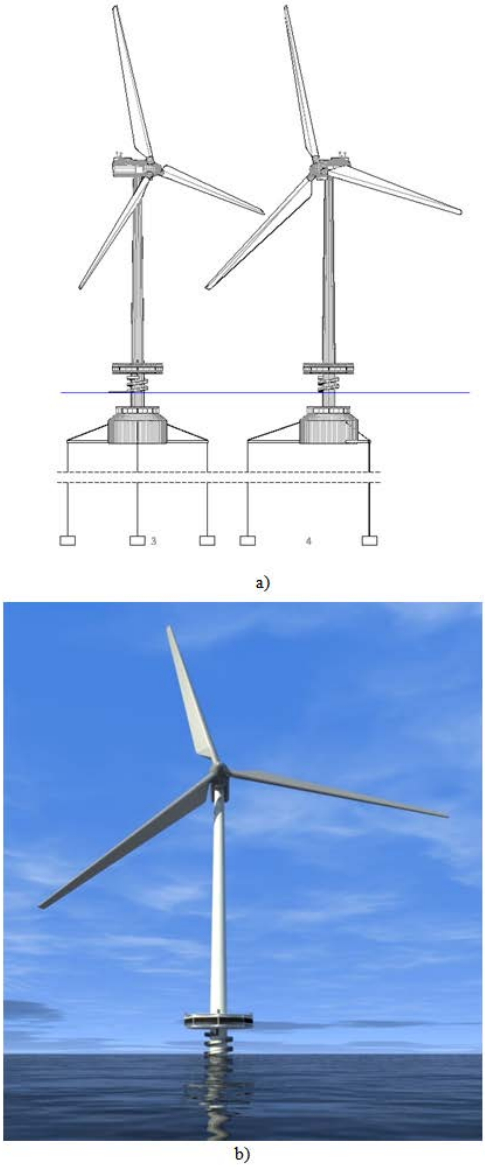


**Figure 9**. a) ARYA elevations; b) ARYA three-dimensional virtual view

Simply calculating the volume of each structural element and multiplying it by its specific weight, it was possible to estimate the weight forces of each deadweight corresponding to about 10800 KN.

In Figure 8 the main components of the wind turbine ARYA are shown. Figure 9a reports the two main elevations while in Figure 9b a three-dimensional virtual view is proposed.

For ARYA design also Standards report in [10,11,12,13,14] are taken into account.

## 5.3. Wind-structure Interaction

The wind action has been calculated to evaluate the wind pressures and, consequently, the wind forces acting on the octagonal hotel steel structure located at +9 meters above the sea level and those acting on the remaining wind turbine.

Pressures and static forces are evaluated by reference to [15], where the wind pressure is given by Equation (2):

$$P = q_b \cdot c_e \cdot c_d \cdot c_p \tag{2}$$

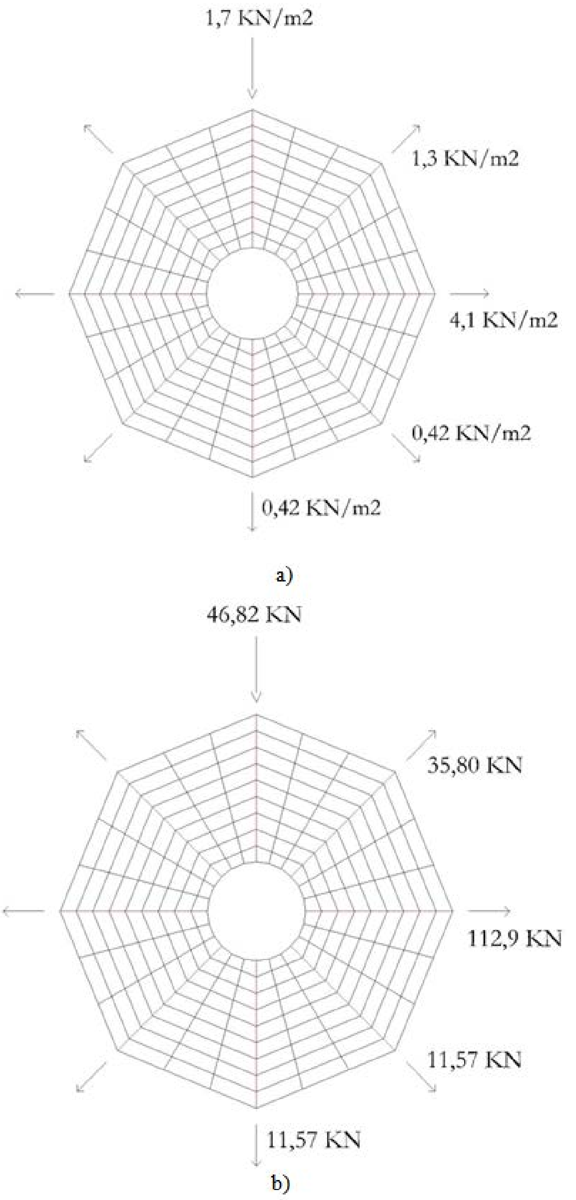


**Figure 10**. a) Maximum local wind pressure acting on columns; b) Wind force acting on columns

$1{,}16$ KN/m$^2$ is the value of the wind pressure acting on the hotel structure located at +9 meters above sea level. In the case of a circular-octagonal structure, local maximum pressures are calculated using the “local” pressure coefficient $c_p$ assuming the values given in the Italian standard of 02 February 2009 n.617, paragraph C3.3.10.8 (Maximum local pressure), respectively for the various angles (Figure 10a). This document is an applicative circular of the Italian NTC 2008 [15]. Then, the forces acting on the columns were calculated by multiplying the pressure for the areas of influence of each column (Figure 10b).

The wind static analysis [16,17] was performed both in the front direction of the rotor, considering the wind acting on the blades of the wind turbine (turbine scheme with wind speed $V_b$ = 25m/s – Figure 11a), and in the direction perpendicular to it (turbine not in scheme with speed $V_b$ = 31m/s – Figure 11b). In order to estimate the wind forces acting on the wind turbine, its total height was divided into 5 parts identifying 6 nodes as shown in Figure 11.

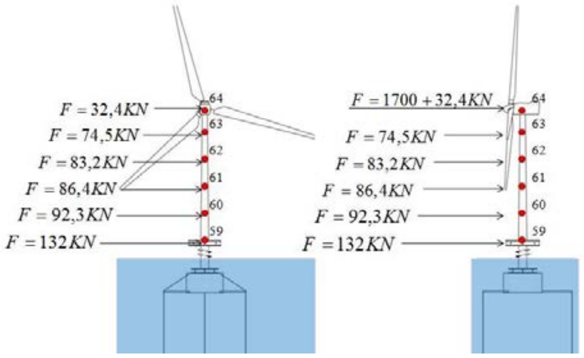


**Figure 11.** a) Turbine NOT in scheme; b) Turbine in scheme

## 5.4. Wave-structure Interaction

In order to investigate the waves-structure interaction [18-22] it was necessary to find measures of waves motion to understand the exposure of the wind farm site.

For this purpose, it was possible to refer to the recordings of the station of Ortona in the period from the 1st of January 1998 to the 1st of January 2008. This station is managed by the SIMN (Servizio Idrografico e Mareografico Nazionale).

In order to design the so-called “wave design” in deep water (Figure 12) it was necessary to perform a statistical evaluation of the major wave heights related to the historical series of reference. According to historical data, the maximum height ($H_{max}$) of waves in the Adriatic Sea is about 13 meters with a period ($T_p$) of about 18 seconds.

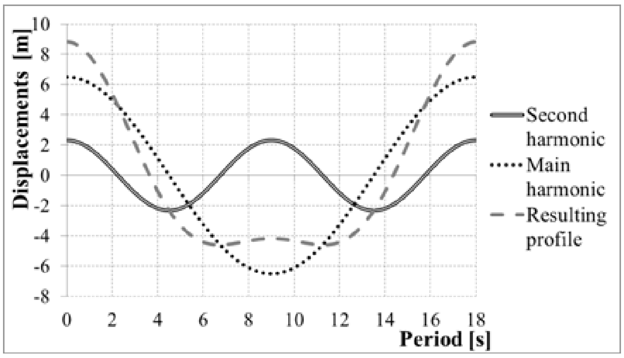


**Figure 12**. Harmonic components profiles and resulting wave design profile

Given the characteristics of the “wave design” ($H_{max}$; $T_p$), evaluated through the use of the second order approximation of the Stokes theory within the domain of Le Mehaute, it was possible to calculate the horizontal and vertical speed of a water particle that are necessary for the determination of dynamics forces (Morison Equations).

The Morison equations (Equation 3) were used to evaluate the wave loads:

$$\vec{f}(t) = \vec{f}_m(t) + \vec{f}_d(t) \tag{3}$$

and in explicit form (Equation 4):

$$\vec{f}(t) = C_m \rho \pi a^2 \vec{a}(t) + C_d \rho a \left| \vec{v}(t) \vec{v}(t) \right| \tag{4}$$

where $\vec{a}$ , $\vec{v}$ are respectively the projections of the acceleration vector and the velocity vector in the plane of the section of the cylinder of equivalent water.

Also Fulton, Malcolm, and Moroz [23] used Morison’s equation to compute the hydrodynamic loading on the TLPs.

Figure 13 represents the wave load graph every 50 cm in height for a period equal to 20 times the wave period (18x20=360 seconds), from +9 meters above the sea level to -24 meters, where the structure ends with the floating tank.

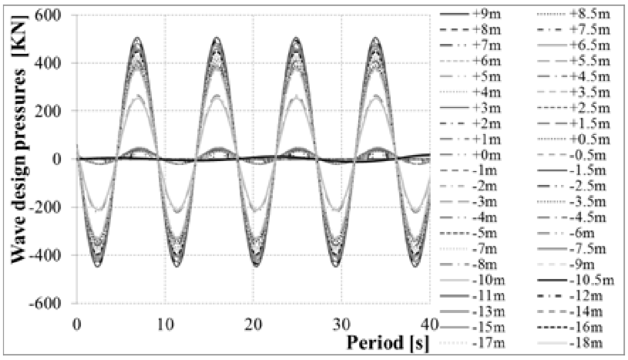


**Figure 13**. Overlap of wave design pressures over the entire structure

## 5.5. Results

Defined the wind pressure, evaluated as a static force, and the time history of the wave design, it was possible to estimate the size and characteristics of the tension leg platform (TLP) and to evaluate the displacements of the wind turbine (particularly some node) through the implementation of a numerical model (Figure 14) and then, the structural analysis using the research open source software *Tenso* developed by the Department of Engineering and Geology of the University of Chieti-Pescara (Italy). Dynamic analysis are performed for 360s.

In Table 3 the wind turbine structural behavior after the modal dynamic analysis are summarized. Maximum and minimum displacements (δ) in the three direction (x,y,z) for nodes 10,11,12,13 and 64 (with reference to Figure 14) are reported. Node 64 is at the top of the tower.

Defined the maximum operating conditions of the wind turbine, wind at 25 m/s and wave design, the main results obtained from the analysis are summarized in Table 4. They are in good agreement with the result published in [6].

Finally, the deformed shape of the wind turbine, both in the x and y-direction are reported below (Figure 15).

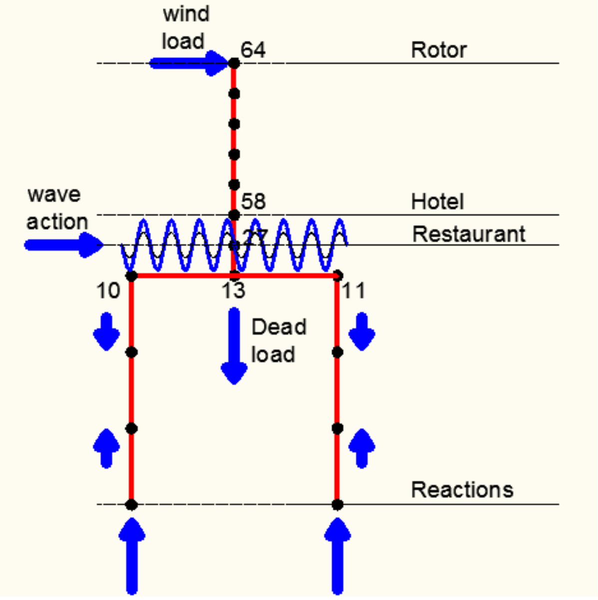


**Figure 14**. Overlap of wave design pressures over the entire structure

**Table 3. Nodal displacements**

Δt = (0-360s)

| | $\delta_x$ (m) | | $\delta_y$ (m) | | $\delta_z$ (m) | |
|---|---|---|---|---|---|---|
| **Node** | min | max | min | max | min | max |
| 10 | ~0 | 0.255 | -9.768 | -9.771 | -0.189 | -0.191 |
| 11 | 0.0943 | 1.314 | -9.047 | -9.604 | -0.735 | -0.832 |
| 12 | -0.094 | 1.136 | -9.598 | -10.15 | -0.832 | -0.948 |
| 13 | ~0 | 0.9099 | -9.765 | -9.768 | -0.626 | -0.630 |
| 64 | -0.117 | 0.0001 | -21.54 | -21.55 | -1.183 | -1.191 |

**Table 4. Results**

| | |
|---|---|
| Floating tank maximum gradient: | **7.8°** |
| Floating tank maximum displacement in *y*-direction: | **~10 m** |
| Hub maximum displacement: | |
| - component due to the translation of the floating tank: | **10 m** |
| - component due to the gradient of the floating tank: 93 m · sen 7.8º = | **12 m** |
| - total: | **22 m** |
| Floating tank maximum displacement in *z*-direction: | **0.9 m** |
| Hub maximum displacement in *z*-direction: | **1.19 m** |

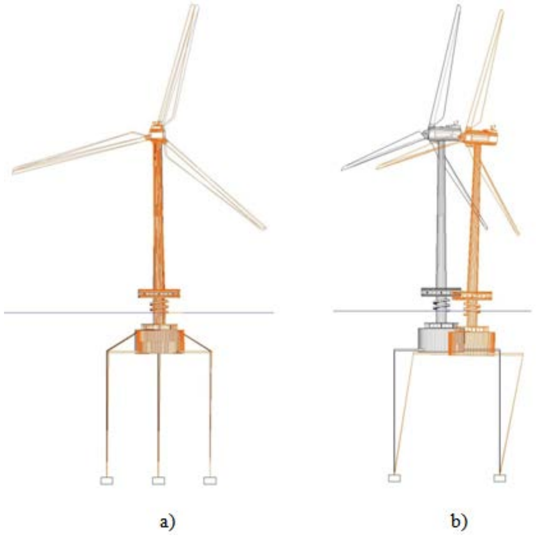


**Figure 15**. Wind turbine deformed shape under static and dynamic loads a) in x direction b) in y direction

## 6. Conclusions

The results obtained from this research are very important because, starting from a numerical model of an off-shore wind turbine, it can be seen that solutions for floating wind turbines are possible together with additional structures for recreational/touristic activities. It is desirable, therefore, to continue the research in this direction to identify solutions that are technically and economically more valid. Moreover, all the values reported in Table 4 are acceptable for a proper design.

## Acknowledgement

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