Preliminary feasibility study of a floating offshore wind plant along italian coastal area

R. Capata[a], A. Calabria[a], M. Di Veroli[a], S. Sangiorgio[a]
[a]*Department of Mechanical and Aerospace Engineering, University of Roma "Sapienza", Italy, roberto.capata@uniroma1.it*

Abstract
Nowadays, wind technology can be considered mature and widespread technology, and its diffusion is strictly connected to the availability and accessibility of windy sites. The specific orographic configuration considered has to be capable of developing the diffusion of wind farms, and suggests the use of these alternative system configurations. The paper intend to analyze the feasibility of a floating offshore wind plant along the coast. Once all existing technologies has been studied, a proposal plant configuration has been analyzed and preliminary designed from technical and economic point of view. Moreover, the floating device has been simulated and the results deeply discussed and analyzed. Finally the possibility of a prototype construction has been investigated.

Keywords
Offshore Floating, Wind Farm, Economic Evaluation, Technical Feasibility.

1. Introduction

Off-shore wind technology has mostly been developed for shallow sea bottoms, typically in Northern Europe [1]. The first plant to be built at sea, was to Vindeby (Dk), located in the Baltic Sea, and released in 1991. the facility is located at a distance of 15-3 km from the coast of the island of Lolland, near the village of Vindeby [1-2]. The "farm" is constituted by 11 wind turbines of 450 kW each, for a total of nearly 5 MW of installed power, with an annual power production of approximately 20% higher than that obtainable from similar on-shore facilities; it also has to install two anemometers to study wind conditions and in particular the turbulence. A few years later, in 1995, was built the Tuno-Knob (Dk) wind farm, in the Kattegat sea, 3 km offshore from the Tuno island, and 6 km offshore from the Jutland peninsula, with 10 wind turbines of 500 kW, for a total capacity of 5 MW. After these semi-experimental early works, other wind farms were built: 40 MW Middlegrunden plant, with 20 wind turbines of 2 MW, Samso farm with 23 MW installed with 10 turbines by 2.3 MW, Horns Rev installation with 160 installed MW with 80 turbines, 2 MW each [1-2], and 165.3 MW Nysted plant, consisting of 72 turbines of 2.3 MW. The wind power plant of Nysted, created in 2003, is located 10 km south of the Nysted town (island of Lolland), with 70 m tall wind turbines and more than 82 m rotor diameter; the total installed power of 165.5 MW, consisting of 72 turbines of 2.3 MW. Without a doubt Denmark is the country with largest offshore power installed worldwide, but there are other plants, Bockstingen (Sweden) with 2.75 MW wind farm, Utgrunden (Sweden) 10.5 MW, Yttrenstengrund (Sweden) 10 MW, Northhoyle (UK) with 60 MW of installed power, Arklow Bank (Ireland) with 25.2 MW of installed power, and others. Offshore installations, at the present state of technology, are made with high unitary power wind turbines, making it possible to better exploit the best wind resource offered by the offshore environment. However, in the last generation, the power range varies from 1.5 MW to 2.3 MW per turbine. These wind turbines are characterized by a tower height up to 70-80 m (at rotor), and rotor diameters of 70-80 m, with a maximum of 104 m to 3.6 MW machine; the wind farms, are built in such a way as to prevent aerodynamic interference effects between the wind turbines, arranged a reciprocal distances at least 2-3 rotor diameters. The offshore plant installation has the advantage of providing better wind resource and therefore a better energy production, a lower wind turbulence and therefore durability of mechanical parts, and better availability of sites, being on-shore sites subject to saturation, even for the not easy acceptance by the populations involved in the areas of installation. On the other hand, there is a different situation to static and dynamic loads on the foundation and on the turbine, both for the sea currents that greater wind resource. Offshore Installation involves transport procedures, mounting and installation/commissioning, very different from those on the mainland; It is inevitable that time and equipment are of other orders of magnitude, and especially from the structural point of view assumes great relevance the foundation structure. In this work, the sites used for offshore wind farm have deep seabed (about 100 meters), because all the areas nearby the coastline have to be excluded for the needs of beach and touristic and economic activities or because they are part of natural protected areas. Consequently, it is necessary to choose offshore floating wind farm. In this way, it is possible to exploit the biggest wind resources in different coastal area around the world, [2] installing wind turbines farther from the coast. In this paper, floating structures for single commercial turbine (5-6 MW) will be analyzed, in order to verify their technical feasibility.

2. Wind turbines on floating structures

Floating wind turbines are intended to be installed in deep sea bottom areas, being not convenient to set foundations directly on the seabed. These turbines are composed by two main parts: floating structure, with its mooring and anchoring equipment, and the wind turbine, bolt connected to the floating structure. Currently, many kind of floating structures for wind turbines are in the planning and experimental phase [3],[4]:

- Semi-submersible with three arms catenary mooring lines;
- Barge with catenary mooring lines;
- Semi-submersible with single vertical pole, and catenary mooring lines;
- Semisubmersible “Tension leg”.

Generally speaking, a floating support structure for wind turbines has to guarantee these functions: remain stable, despite the strong lateral forces; maintain the geographical position; allow flexible movement around the project position set; have lowered inclinations with wind turbine in operation; allow a valid alignment of the turbine to the wind; allow easy access for maintenance personnel; have the greatest possible cost effectiveness; allow unmooring, disassembly and transfer to the mainland of the structure for maintenance or late-life operations.

Floating structures supporting the turbines, can be divided basing on the adopted method to ensure stability in the waterline, as shown in Fig. 1:

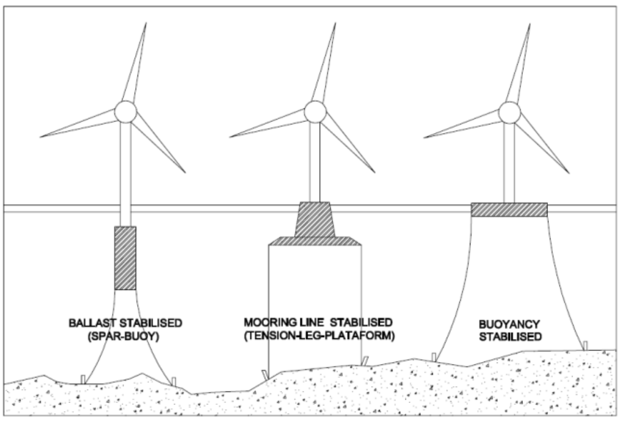


Fig. 1: floating structures for offshore wind turbines [5]

- stability of weight ("Ballast Stabilized"), the pitching moment to counter the forces of wind and waves is provided by a large ballast, positioned in the lower end of the floating structure, vertical and elongated, and anchored by catenary mooring lines to the seabed;

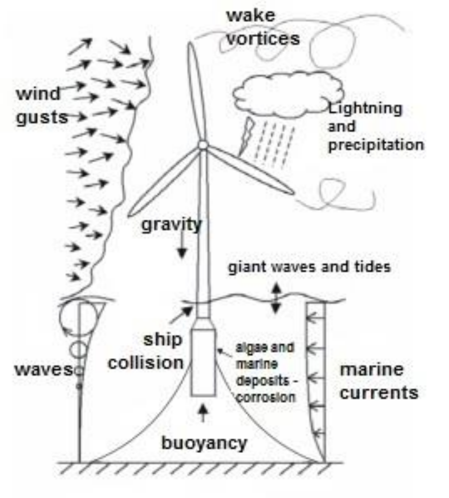
- stability of constraint ("Stabilized Mooring Line" or "Tension Leg Platform"), the pitching moment to counter the forces of wind and wave power is entrusted to vertical rods anchored to the seabed and acting at the top of the floating structure, with long horizontal arms;
- stability of form ("Buoyancy Stabilized"): in this case the pitching moment, to counter wind and sea forces, is due to the shape and to the horizontal extent of a wide floating barge, anchored with catenary mooring lines on the seabed.

3. Choice of the prototype floating device

Below, it will be examined a generic site for a wind farm in deep sea water, using turbines installed on single spar floating structures.
It is necessary to pick out the floating device to install big wind turbines (6 MW), very far from the coast (between 10 and 30 km) and with very deep water (from 130 to 700 m). The choice is a ballasted floating structure that ensures the stability and an intrinsic safety.
In this case study, the following aspects will be considered:

- Technical feasibility;
- Phases of construction in the inshore building site;
- Transport, towing and mooring (anchoring) the floating structure in the high seas,
- Final assembly of the turbine on the float positioned in the high seas;
- Electrical connection to the mainland and activation;
- Regular in situ maintenance on the high seas;
- The eventual disassembly and return to the inshore site for maintenance;
- Decommissioning, at the end of life of the turbine.

Design of the floating body is the basis for the preliminary design of an offshore wind farm. The system must be able to ensure the balance between the various forces involved and withstand the numerous stresses [5][6]. In Fig. 2, forces and stresses that affect the structure are represented. Fig. 3 shows balance of moments in two positions: 7.6° Tilt, referred to the nominal operating conditions (wind power, wave, etc.) and 30° Tilt, referred to the limit operating conditions, highlights the angles and the useful arm between central hull and the centre of gravity of the entire system.
The ballast, 13,700-ton weight, was built using wet sand: it is very cheap and low-maintenance. The horizontal thrusts (wind, sea currents, etc.), compared to the total weight of the structure equal to approximately 17,000 t, are of one order of magnitude lower (Fig. 3).



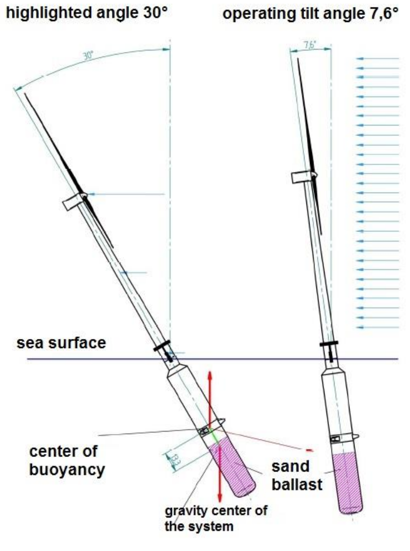


Fig. 2.(left) Forces and stresses on the structure.
Fig. 3.(right) Balance of moments in limit and normal operating conditions.

A 6 MW turbine with a diameter of 154 m has been considered in this case study [7]. Fig 3 shows the distance between the centre of gravity (CG) and the centre of buoyancy (CB) is essential to generate the pitching moment which is necessary to balance the overturning thrust of the wind. It can be noticed that the attack of the anchor lines is at about half the height of the float, in correspondence with the centre of buoyancy. In this way, the forces generated by possible marine currents compensate each other. Furthermore, the triangle-shaped mooring system near the structure is essential to allow the system to direct yaw into the wind turbine (limiting the rotation of the float and the tower around the vertical axis).

4. The Design of Floating System

Design of the floating system is based on the following technical data related to a 6 MW wind turbine and boundary operating conditions [7].

Table 1: Wind turbine data

Rated power	6 MW
Rotor Diameter	154 m
Blades Number	3
Number of laps	5-11 rpm
Control	variable
Rotor tilt	6°
Tower height	110 m
Diameter	
at the base of the tower	8 m
at the head of the tower	4,5 m
Weight	
nacelle and rotor	360 t
tower	770 t

Design of floating system gave the results presented in Table 2 and shown in Fig. 4.
In Table 3 the results of simulation, considering the dimensions, vertical heights and water pressure (from the outside) and ballast (sand) from the inside, are presented.

Table 2: Design specifications[7]

Maximum draught	-101,5 m
Diameter	15,0 m
Depth of the docking point of the mooring lines	-52,3 m
total displacement of the system	17.295 tons
of which ballad (weight and %)	13.717 ton – 79%

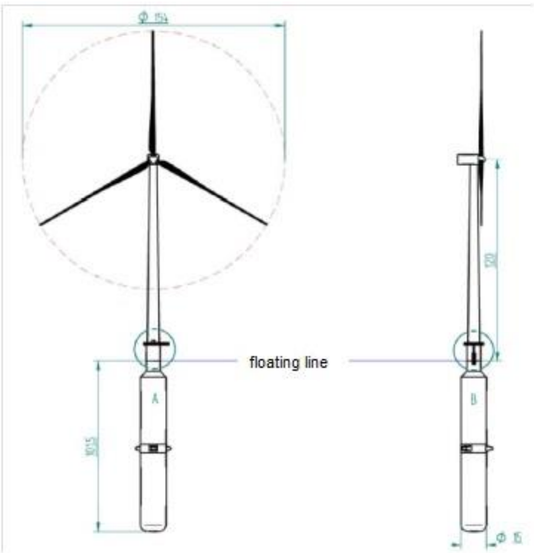


Fig. 4. Floating system design.

Table 3: Results of simulations

Section	height of the section	Diameter		Layer thickness	Vertical axis vs waterline (height / depth)	Pressure		
		external size	internal (empty)			external (water)	internal (sand ballast)	Δp
	m	m	m	mm	m	bar	bar	bar
1 Nacelle + rotor		4,5			120,0	-	-	-
2 Tower	110,0	8,0	7,924	38,0	120,0	-	-	-
3 Intermediate section over waterline	10,0	9,0	8,924	38,0	10,0			*mooring line*
4 Intermediate section below waterline	6,0	9,0	8,924	38,0	-6,0	0,6	-	-0,6
5 Junction conical section	3,0	junction		38,0	-9,0	0,9	-	-0,9
6 Floating section, empty	52,7	15,0	14,900	50,0	-61,7	6,1	-	-6,1
7 Floating section, with	35,8	15,0	14,900	50,0	-97,5	9,6	7,0	-2,5
8 Half elliptic bottom	4,0	15,0	14,900	50,0	-101,5	10,0	10,1	0,1
9 Mooring system (anchor)	-	-	-	-	-	-	-	-
TOTAL	**222**							

The calculation for evaluating the centre of gravity of the entire structure and the centre of buoyancy of the submerged volume (needs to quantify the length of the pitching lever arm), is essential to quantify the pitching moment generated from the total weight of the structure as a function of the angle of inclination caused by the wind thrust. To balance any tilting moments generated by ocean currents, the mooring lines will be fixed to the structure at the centre of buoyancy. The calculations and checks have led to the determination of the distance between the centre of gravity and centre of buoyancy which is equal to 13.2 meters. The tests involved the following aspects referred both to equilibrium, and to the mechanical strength[8]:

- Quantification of the lateral wind thrust;
- Calculation of the maximum turbine inclination;
- Calculation of the lateral thrust from any sea currents;
- Verification of allowable stresses.

4.1 Lateral wind thrust calculation

For calculating the wind thrust on various part of the turbine, the following two formulas were used:

- For the thrust on the operating rotor (production system):

$S_R = 0{,}0064\ V^2 A,$ (1)

- For the load on all the other parts of the turbine including rotor if stationary (not moving – safe conditions) the equation of the aerodynamic resistance was used , applying the coefficient of friction of the cylindrical body:

$S_c = \frac{1}{2}\rho \cdot V^2 \cdot C_D \cdot A,$ (2)

Where:

S_R total thrust of the wind on the rotor;
S_c wind thrust on the cylindrical element;
V wind speed;
C_D friction coefficient for the cylindrical body = 1.17;
A frontal area of the rotor.

The calculations were performed considering different wind speeds and operating conditions; the results are reported in Table 4.

Table 4. Operative condition.

nominal wind speed	12 m/s
extreme wind speed (on survival)	50 m/s

	operating wind speed (12 m/s)		Safety conditions (with stationary turbine and flag blades)	
	t	kN	t	kN
Rotor lateral thrust	172,4	1.691	53,7	527
Tower lateral thrust	7,1	69	123,0	1.207
Lateral thrust on intermediate section over the	0,9	9	16,1	158
Total lateral wind thrust	180,4	1.769	192,8	1.892

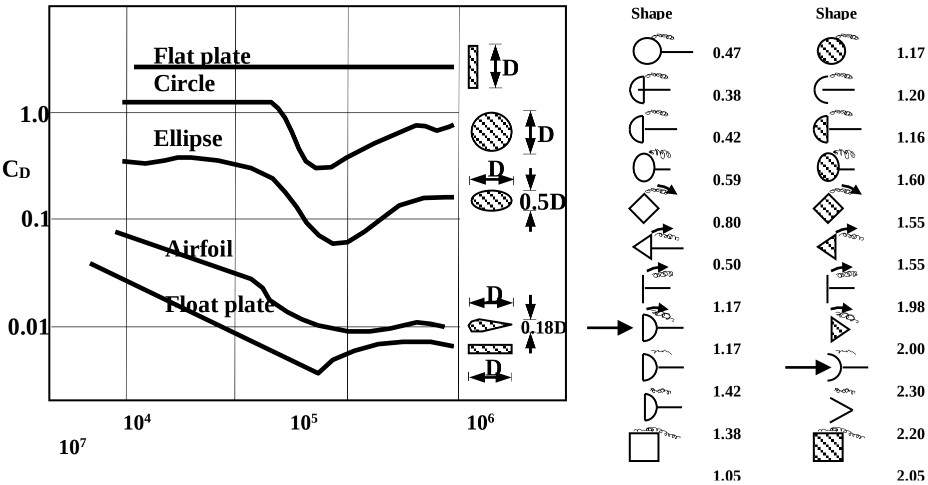


Fig. 5: Actual friction coefficient value in different operating conditions

4.2 Maximum allowable Turbine inclination

To quantify the maximum inclination, associated with the overturning moment generated by the total lateral thrust, the following calculation procedure was used:

Balance of forces in x- direction:

$$S_R + S_T + S_I + T_h = 0, \quad (3)$$

$$T_h = -S_R - S_T - S_I \quad (4)$$

Balance of forces in y-direction:

$$P + S_G = 0, \quad (5)$$

$$S_G = -P, \quad (6)$$

Balance of the moments referring to centre of buoyancy:

$$S_R B_R \cos\alpha + S_T B_T \cos\alpha + S_I B_I \cos\alpha - P B_P \sin\alpha = 0, \quad (7)$$

$$\alpha = tan^{-1} \frac{S_R B_R + S_T B_T + S_I B_I}{P B_P}, \quad (8)$$

Where:

S_R rotor thrust;

S_T tower thrust;

S_I thrust on intermediate Section;
S_f floating thrust;
T_h horizontal component of cables tension;
P total system weight (including mooring lines);
B_R rotor arm;
B_T tower arm;
B_I arm of the intermediate section;
B_w weight force arm.

Table 5 reports the calculation results for the maximum inclination quantification of the turbine, caused by the overturning moment, generated by the lateral wind thrust on all the structures above the waterline. The result of the calculation shows that the maximum thrust of the wind is not in safe conditions (with wind speed of 50 m/s), in operating conditions, with nominal wind (and power) rating, with wind speed equal to 12 m/s. This result may appear unexpected, but can be explained by the fact that, in safety conditions, the brake stops the rotor and the blades move to the "flag" position, minimizing the surface exposed to the wind.

Table 5: Turbine maximum inclination

	arm to the thrust pole	Thrust			
		operating (wind speed 12 m/s)		safety conditions wind speed = 50 m/s (stationary turbine and flag blades)	
	m	t	kN	t	kN
Lateral thrust on the rotor	172,3	172,4	1.691	53,7	527
Lateral thrust on the tower	117,3	7,1	69	123,0	1.207
Thrust on intermediate section over the waterline	57,3	0,9	9	16,1	158
Total weight of the structure	-13,2	17.295	169.661	17.295	169.661
Inclination angle		7,6 degrees		6,1 degrees	

The maximum 7,6 degree inclination from the vertical axis can be considered technically acceptable; further analysis should be made for individual commercial turbines.

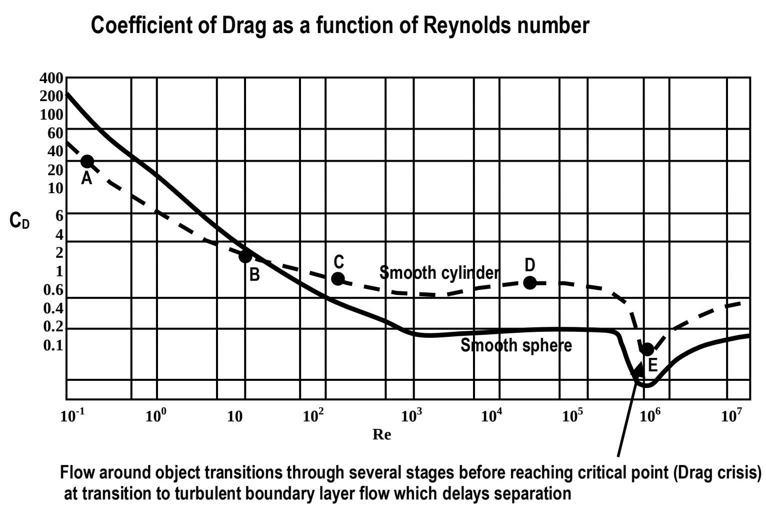
4.3 Calculation of lateral thrust generated by possible sea currents

Even the action of the currents was considered in the verification; Table 6 shows the results of the calculation to quantify the lateral thrust generated on the float from a possible 0.26 m/s sea current (0.5 knots). The result of this calculation shows that the highest stresses suffered by the structure are not those caused by the wind, but those generated from the sea current which exceeds by far (10-fold) the thrust of the wind [10], [11]. The calculation of the Reynolds number has established that the flow regime of the water (current) around the float is an “E” type or it has turbulent boundary layer and restricted wake, so the coefficient of friction (drag coefficient) is lower than normal.

Table 6: Calculation lateral thrust of the sea current maximum design

Maximum draught of the float			101,5 m
Float diameter	base		15,0 m
Density of sea water			1.030 kg/m^3
Kinematic viscosity of seawater			1,50 mm^2/s
Maximum speed of sea current			0,26 m/s
		or	0,94 km/h
		or	0,50 knots
Reynolds Number			2,6x 10^6
CD (cylindrical body)		[9]	0,57
Lateral thrust on the float		(*)	29.900 kN

(*) Rayleigh formula



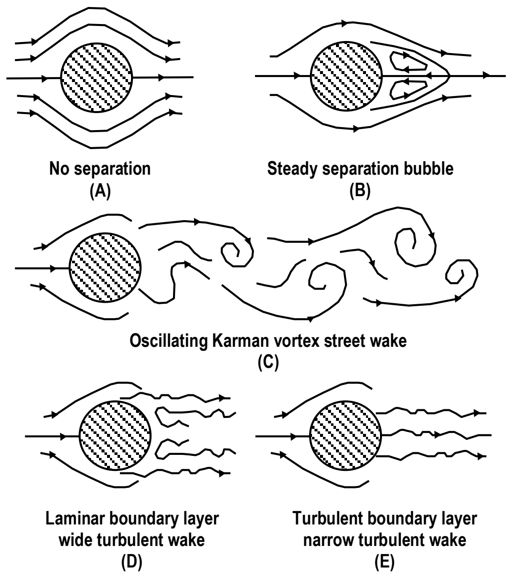


Fig. 6: Drag coefficient in function of Reynolds number

4.4 Stress verification

Table 7 and Table 8 show the calculations to find the stresses in the most stressed sections considering the turbine in the worst conditions (nominal conditions with 12 m/s wind and a 0.26 m/s sea current in the same direction of the wind). From the verification of the allowable stress it is evident that the most stressed point of the whole system is located in the mantle of the float in correspondence of the point of attachment of the mooring lines to about half the height (depth = 51.7 meters). For this reason its cable cuffs supporting the forces in question are located on a wide strip of reinforced mantle. Also, the major stresses are caused by the tide

The most stressed sections, represented in Table 8, also shows the calculation of the equivalent stress according to the criterion of von Mises:

$$\sigma_{eq,v.M.} = \frac{1}{\sqrt{2}} \cdot \sqrt{(\sigma_c - \sigma_a)^2 + (\sigma_c - \sigma_r)^2 + (\sigma_a - \sigma_r)^2}, \quad (9)$$

$$\sigma_r \cong 0 \ (for\ thin\ layers), \quad (10)$$

where

$\sigma_{eq.v.M.}$ = equivalent thrust according to von Mises;

σ_c = circumferential thrust;

σ_a = axial thrust;

σ_r = radial thrust.

After stress examination, it is proposed to use high resistance hull steel, with impact test at 0 ° C, named Fe E 355 A KN EU 156 with a breaking strength of 620 MPa.

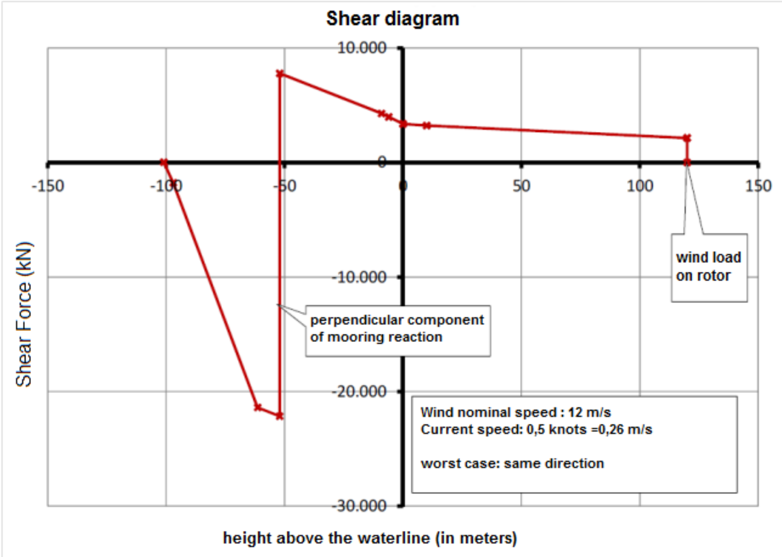


Fig.7: Shear diagram

5. Mooring systems

Mooring systems have to maintain, in pre-defined geographical position, a floating structure that would, would tend to drift and to freely move under the action of the wind and marine currents, till aground on the coast or on a shallow water.

In general these anchorage systems consist of mooring lines, which connect the floating structure to an anchoring device bound to the seabed. The docking mode of floating structures are particularly important since they must be such as to ensure that the same structures remain in place even in extreme conditions (maximum wind, highest waves etc.). Some solutions of realization of floating structures (tension-leg type) ensures, in these extreme conditions, the stability of floating structure, i.e. prevent capsize. Mooring lines are according to the size and mass of floating structure, maximum wave height, sea currents, of maximum wind force, and the depth of the water. Starting from the seabed, a mooring line typically consists of:

- anchor: creates a fixed constraint on the seabed;
- first section of mooring line: formed from a large chain, whose purpose is to ensure a strong connection can withstand wear caused by friction of the inevitable first stretch of the line on the seabed;
- mooring line itself;
- mooring system of mooring line on floating structure in question. The mooring line may consist of a synthetic fiber rope, steel cable or chain, or any combination of the three. Environmental factors, as well as the wind, waves and currents, and the depth of the seabed, determines what materials compose the mooring system;
- chain: is the most common choice for permanent moorings in shallow water or up to 150 m deep relative to the point of attachment to the frame. Despite being rigid, the chain ensures a good flexible response to the mooring line through its weight;
- steel cable: is lighter than the chain and has a higher elasticity. Is generally the best choice for intermediate water depths, typically in excess of 300 m;
- synthetic fibre rope: it is characterized by a good elasticity and represents between 3 alternatives, the solution with lower weight. So it is the solution for moorings on very deep seabeds, where the weight of a chain or a steel cable would be prohibitive.

Table 7. Calculation of thrusts and internal moments (values refer to the upper end of the section)

Section	Height of the section	external diameter	FORCES ON A SINGLE SECTION: Wind/sea current forces: horizontal	vertical	normal	axial	weight forces: horizontal	vertical	normal	axial	floating forces: horizontal	vertical	normal	axial	Total forces: horizontal	vertical	normal	axial	TOTAL SUM OF THE FORCES: shear	axial	Moment
	m	m	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	10^6 Nm
																			-		
1 Nacelle + Rotor	-	4,500	1.691	-	1.676	224	-	- 3.532	467	- 3.501	-	-	-	-	1.691	- 3.532	2.143	-3.277	2.143	-	
2 Tower	110,0	8,000	69	-	69	9	-	- 7.554	999	- 7.487	-	-	-	-	69	- 7.554	1.068	- 7.478	2.143	- 3.277	-
3 Intermediate section above floating line	10,0	9,000	9	-	9	1	-	-982	130	-974	-	-	-	-	9	-982	139	-973	3.212	- 10.755	295
3 floating line	-	9,000		-	-	-	-	-	-	-	-	-			-	-	-	-	3.351	- 11.727	327
4 intermediate section below floating line	6,0	9,000	1.062	-	1.053	141	-	-589	78	-584	-	3.857	-510	3.823	1.062	3.267	621	3.379	3.351	- 11.727	327
5 Conical link section	3,0	connection	708	-	702	94	-	-460	61	-456	-	3.500	-463	3.469	708	3.039	300	3.106	3.971	- 8.348	349
6 Float – Upper empty section	43,3	15,000	12.780	-	12.668	1.691	-	- 9.339	1.236	- 9.257	-	77.335	- 10.232	76.655	12.780	67.996	3.671	69.089	4.271	- 5.242	362
6 Mooring connection	-	15,000	- 30.834	-	- 30.562	- 4.080	-	- 3.347	443	- 3.318	-	-	-	-	- 30.834	- 3.347	- 30.120	- 7.397	7.942	63.847	626
6 Float – Lower empty section	9,4	15,000	2.770		2.746	367		- 2.024	268	- 2.006		16.763	- 2.218	16.615	2.770	14.738	796	14.975	- 22.177	56.449	626
7 Float –section with ballast	35,8	15,000	10.564	-	10.471	1.398	-	-132.893	17.583	-131.725	-	63.922	- 8.457	63.360	10.564	- 68.972	19.596	- 66.968	- 21.382	71.424	422
8 Semi elliptic bottom	4,0	15,000	1.180	-	1.170	156	-	- 8.939	1.183	- 8.861	-	4.285	-567	4.248	1.180	- 4.654	1.786	- 4.457	- 1.785	4.457	7
	-		-	-	-	-	-		-	-	-		-	-							
TOTAL	**221,5**		0	-	0	0	-	-169.661	22.448	-168.169	-	-	- 22.448	168.169	0	0	0	0			

Table 8. Verification of allowable stresses

Verification section	Section diameter	Cover thickness	Difference with external pressure	Flexural resistance module	Section area	Axial force	Momentum	Thrust				
								axial			circumferential	equivalent von Mises
								axial	bending	total		
	m	mm	bar	m^3	m^2	kN	106 Nm	MPa	MPa	MPa	MPa	MPa
Tower base	8,0	38,0	-	1,883	0,950	- 3.277	295	- 3,4	156,4	153,0	-	153,0
Connection of the middle section on the float (6 m depth)	9,0	38,0	- 0,6	2,387	1,070	- 8.348	349	- 7,8	146,3	138,5	- 7,0	142,1
Connection of the mooring lines on the float	15,0	50,0	- 5,3	8,748	2,348	63.847	626	27,2	71,6	98,8	- 80,0	155,1

5.1. Catenary mooring

The catenary mooring system is the most commonly used system in shallow waters. Takes its name from the shape of the mooring line, while at the seabed, the mooring line is in horizontal position. For this reason, the length of the mooring line must be higher (and significantly) the depth of water. Increasing the length of the mooring line also increases its weight. Since with increasing water depth increases even the weight of the line, therefore decreases the work load (floating line) of the considered structure. For this reason in deeper water, it is tend to use ropes of synthetic fabric (polyester, Nylon, polyethylene, etc.) because lighter than chains and steel cables. This solution is generally constituted by an upper section with steel cables attached to a floating structure, and a lower section with a long chains, normally resting on the seabed for much of their length. Moreover, the chains are linked to an appropriate anchor device. This type of mooring has the characteristic to allow large movements to the floating structure and is used basically to maintain it on the desired geographic and pre-defined position. In particular, each mooring line consists of a higher section, connected to the platform, consisting of a steel cable, a lower section consisting of a chain, and an anchor device fixed on the seabed.

The steel cables of high quality have a diameter of not less than 160 mm, while the chains are at least 150 mm. Mooring lines are generally pre-loaded with a 300 kN traction thrust, to reduce the movement of the floating structure. Typically the anchoring devices are "naturally aspirated", i.e. made up of a hollow cylinder sucked in soft mud on the seabed through the suction of the inner water. Such a type of devices were also used for the prototype of the Hy-wind, in Norway.

The sizing of mooring lines for the studied floating turbine, depending on the maximum thrust generated by marine current is shown in Table 11 below. The results show that, to support the thrust of a marine current of modest entity (0.5 knots) requires at least 6 mooring lines with many large anchors (40 tons each) capable of withstanding (UHP = Ultimate Holding Power) to a 1700 tons traction. Calculations distinguishes two cases — the first with minimum depth of the seabed still acceptable and equal to 130 meters deep, and the second with depth about 700 meters maximum.

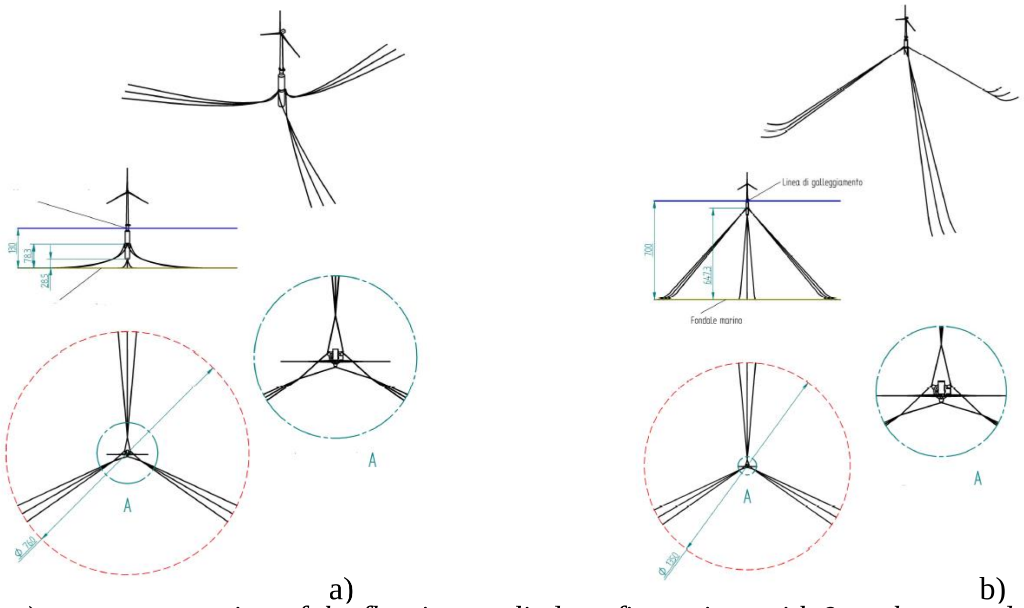
In the case of minimum depth of 130 meters the catenary mooring lines is formed throughout their length by chains. Their weight will work by elastic response and shock absorber for the inevitable movements of the structure. In this case the draught margin compared to the seabed is still of 28.5 meters, enough to allow the maximum possible vertical movements, caused by the tides and waves.

In case of maximum depth of 700 meters, due to the excessive weight, it cannot use the solution to the whole chain. In this case the line will be "taut-leg", made by lines in textile cord (polyester), with specific weight of 1.2 kg/litre. In this case the lines is distributed in a straight line at 45 degrees, and the flexible response will be ensured by the elasticity of the textile cable used, while the final section near the anchor will be chain made. So, the textile cable cannot be damaged from wear caused by the inevitable drag movements on the seabed and provide an additional reserve of elasticity through its weight to the system.

Considering a total system weight of over 17,000 tons, horizontal wind forces sustained by mooring lines are about few hundred tons. In the case of marine currents, the horizontal forces can reach values of approximately 3000 tons (see table 8). In particular, in the case of a “Taut-leg” configuration, to prevent the structure sinking, due to the vertical component of the tension exerted by the mooring lines, it is necessary to give the greater buoyancy reserve, increasing the diameter corresponding with the waterline up to the height of the service platform. It can be notice that:

- The anchor line attack about half height of floating structure (in correspondence with the centre of buoyancy), in order to neutralize the tilting moment that otherwise it would manifest with the marine current. That is assuming a constant current speeds along the entire height of the building, the contributions of the distribution of forces on the two halves of the floating device, generate a zero torque on the structure;
- The lines will be arranged (see Fig. 8), in order to allow a certain flexibility reaction to the marine forces, but also to restrict the movement of the structure in all horizontal directions. The three mooring systems shall be arranged in 120 degrees from each other, and each will be composed of 2 mooring cables with its anchor;

- The triangles of mooring lines in the vicinity of the structure is essential to allow the yaw system to steer the turbine against the wind direction (limiting the rotation of the floating platform - and the tower - around the vertical axis).



a) b)

Fig. 8. a) catenary mooring of the floating studied configuration, with 9 anchors on depth of 130 m (measures in meters) in the presence of sustained current; b) "taut-leg" solution, with 9 textile cable lines on a 700 meters depth seabed in the presence of sustained current

Table 9. Mooring line design

		Max	Min
Seabed depth [m]		700	130
Buoyancy depth [m]		101.5	
Floating centre [m]		52.3	
Anchor depth [m]		647.7	77.7
Type		Taut-leg	Catenary
Line length/depth ratio		1.5:1	5:1
Mooring line length [m]		1000	400
Maximum lateral thrust [kN]	By wind	1892	
	By sea current	29900	
Anchor number		6	
Anchor characteristic	weight [t]	40	
	ultimate holding power (UHP)[t or kN]	1700 or 16700	
Mooring line	Type	Fiber	Chain
	Material	Polyester	Steel
	Diameter [m]	2.58	1.62
	Weight per meter [kg/m]	42.3	234
	Breaking load [kN]	19620	159710
	Test load [kN]	13720	11170
	Single line total weight [t]		
	In water	10	81
	In air	42.3	94
Line length on seabed [%]		-	30
Pre-loading [kN]		300	-
Total lines weight support by the floating device [t]		121	341

6. Conclusions

In order to take advantage of most promising offshore wind resources, solving together the problem of social and visual impact of the turbines, this investigation has proposed off-shore floating technology as a valid alternative. In particular, the installation of offshore wind farms has been studied: the position from the coast could be at distances higher than 20 nautical miles (37 km) and bathymetric up to 700 meters.

Using scale economy, a 6 MW three-blade commercial turbine has been suggested to be mounted on floating structures. While in the Northern Europe seas there are high economic losses caused by frequent and prolonged storms throughout the year (loss of production due to the inability to access for maintenance), economic risks for severe weather conditions are much lower in the Mediterranean area.

Referring to floating wind technologies, this study, focused on design of a single Spar, suggests important indication on the use of this technology in specific environmental conditions.

From calculations, this technology is not very suitable for installation in areas with high sea currents, due to the important bending forces on the float and the high stresses on the mooring lines.

On the other hand, this technology is valid if currents are medium-low, depth is medium or large depth and also with strong winds with rough sea. Its huge moment and the large inertia of the entire system guarantee remarkable stability, even in extreme conditions. The great advantage of the Spar is that the system will naturally tend to its equilibrium position. Even in the extreme case of breaking of all connections and moorings to the seabed, the system will slowly drift, always remaining stable, until it meets a portion of the seabed, with a depth equal to the draft of the structure (about 100 meters), and smoothes run around on the muddy seabed (prevailing at those depths); recovery operations will restore normal operating conditions.

Compared to other solutions examined, the single Spar is, definitely, the most resilient technology to failures, and the most reliable in adverse weather and sea conditions. Its geometrical shape and the physics that governs its stability give easy recovery in the event of breakage of the mooring lines, preventing the collision with the mainland, thanks to its deep draft.

Nomenclature

V	wind speed , m/s
A	frontal area of the rotor, m^2
C_D	friction coefficient for the cylindrical body
S_R	rotor thrust, N
S_T	tower thrust, N
S_I	thrust on intermediate section, N
S_f	floating thrust, N
S_c	wind thrust on the cylindrical element, N
T_h	horizontal component of cables tension, N
P	total system weight (including mooring lines), kg
B_R	rotor arm, m
B_T	tower arm, m
B_I	arm of the intermediate section, m
B_w	weight force arm, m

Greek symbol

$\sigma_{eq.v.M.}$	von Mises equivalent thrust
σ_c	circumferential trhust
σ_a	axial thrust
σ_r	radial thrust

References

[1] Breton, S. and Moe, G., Status, plans and technologies for offshore wind turbines in Europe and North America. Renewable Energy(2009); 34(3): 646-654.

[2] Botta, G., Casale, C., Lembo, E., Serri, L., Viani, S., Resource and technology assessment for evaluating Italy's offshore wind energy potential, 2009 International Conference on Clean Electrical Power, ICCEP 2009, pp. 507-513.

[3] Lefebvre, S. Collu, M., Preliminary design of a floating support structure for a 5 MW offshore wind turbine. Ocean Engineering(2012);40:15-26.

[4] Roddier, D., Cermelli, C., Aubault, A., Weinstein, A., Wind Float: A floating foundation for offshore wind turbines. Journal of Renewable and Sustainable Energy. (2010); 2(3): 135-143.

[5] Jonkman, J.M., Matha, D.,. Dynamics of offshore floating wind turbines-analysis of three concepts. Wind Energy. (2011);14(4): 557-569.

[6] Li, D., Liu, S. and Zhang, X., Dynamical response numerical analysis of the offshore wind turbine tower under combined action of wind and wave. Jixie Gongcheng Xuebao/Journal of Mechanical Engineering. (2009);45(12). 46-52.

[7] Bisht, R. S., Datta, T. K., Jain, A. K.. Analysis of offshore guyed tower platforms to wind and wave forces. Journal of Energy Resources Technology, Transactions of the ASME. (1998); 120(4): 256-262.

[8] Wind Turbine SWT-6.0-154 – Available at:<htt://www.energy.siemens.com>

[9] Ertas, A., Lee, J., Stochastic response of tension leg platform to wave and current forces. Journal of Energy Resources Technology, Transactions of the ASME. (1989); 111(4): 221-230.

[10] Manwell, J.F., McGowan, J.G., Rogers, A.L.,. Wind Energy Explained: Theory, Design and Application. Wiley; 2010

[11] Munson, B.R., Young, D.F., and Okiishi, T.H., Fundamentals of fluid mechanics. Wiley; 1994 .

[12] Frandsen, S. and Thomsen, K.,. Change in fatigue and extreme loading when moving wind farms offshore. Wind Engineering. (1997); 21(3): 197-214.

[13] Liu, S., Li, D.,Huang, X., Fatigue characteristic analysis of the offshore wind turbine tower under combined wind and wave. Taiyangneng Xuebao/Acta Energiae Solaris Sinica. (2009);30(10): 1250-1256.

[14] Osborne, G., Latorre, R., Investigation of SPM mooring tension and barge orientation with wind, waves and strong current. Journal of Energy Resources Technology, Transactions of the ASME, (1991); 113(2): 75-79