OFFSHORE RENEWABLE ENERGY, THE EXPERIENCE OF A DESIGN OFFICE

MARINE 2011

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Key words: Offshore renewable energy, Engineering, Wind, Wave, Currents.

Summary: A general review of offshore renewable energy is given, showing examples and providing some important conclusions we have arrived at as a design office.

1 INTRODUCTION

The sea is not only the most efficient transportation system in the world, a source of hopefully renewable foods, etc., but also a relevant source of suitainable energy.

The sun radiation produces a temperature field, evaporation and pressure differences, and thus wind speeds are originated. Although the wind energy is a very small percentage of the sun energy that reaches the earth as it travels, we can collect it in a much more efficient way than its primary producer. Thus, if the sun radiation energy reaching the earth has average values of 200 W/m^2 and values of almost twice in suitable locations, we can get wind energy with average values of 500 W/m^2. Both gathering systems will have different efficiencies and important differences in capital cost. Therefore, although the wind is a subproduct of the sun heating, its energy availability is higher than for solar energy. At the sea, winds do have even better values than in land, in average speeds, number of hours and quality.

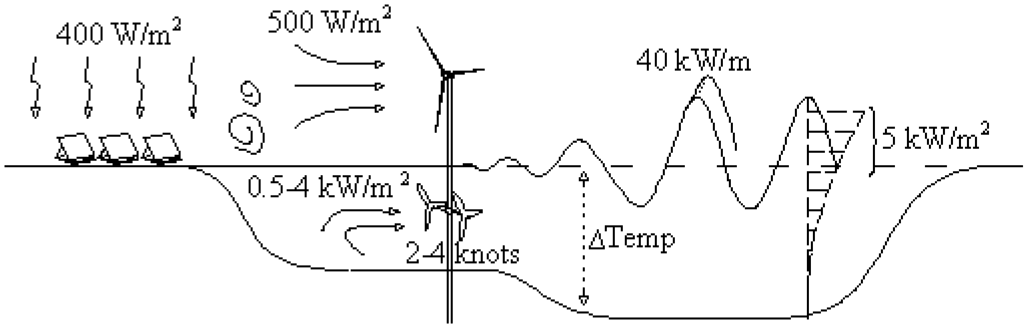

Figure 1: Energy densities in the ocean at different specific locations (yearly averages)

The wind itself is also responsible for the most impressive phenomena at sea: the waves. Persistent winds blowing over hundred and thousand miles produce waves travelling across the oceans. When such energy reaches the coast, in many suitable locations we can find density of energy around 40 kW/m. The worst part of this energy is that it is not amiable. A huge number of energy capturing devices are today at different stages: design, fabrication and testing.

The wind is also responsible for a component of the total current speed. The current speed is affected by others phenomena, being the tides an important one, though there are others related to the differences in levels (typical of some straits), temperature equalizing, etc. When we can trap the tide inside the coast, we recover its energy during the tide up and down using turbines. Other turbines may trap the current speed in the ocean, and there are several devices designed to work at different water depths.

Other type of energy stored in the oceans is the heat transferred by the sun and temperature interchange. To obtain its thermal energy, we need a temperature gradient, which exists as long as there are relevant temperature differences in depth. Several designs have been tested, but the main problem is related with the huge amount of water to be handled.

2 OFFSHORE WIND ENERGY

From all the different offshore energies, the only one being industrially developed today is the offshore wind, with perhaps the only exemption of some tide energy locations. The offshore wind generation capacity, although much smaller today than inland, has a large potential growth (see Figure 2).

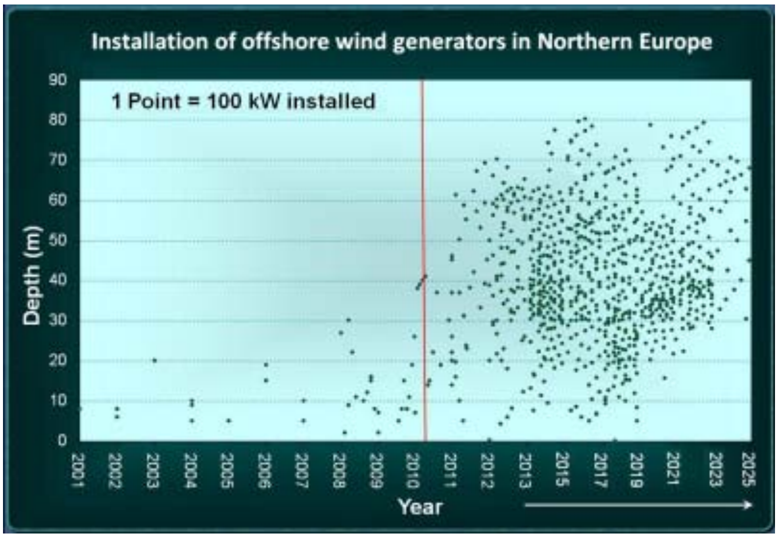

Figure 2: Seaplace growth prediction (made in 2010) for the offshore wind energy at the North of Europe

2.1 Fixed structures

Different fixed arrangements have been built as substructures for offshore wind generators. Some solutions for very shallow depths use concrete (gravity structures), but most substructures are made of steel. Although most of the so far installed wind turbines are of the monopod type due to the shallow waters and small unit power, the future developments will not be so easily satisfied with monopile structures, and new solutions are coming, either new designs or coming from the hydrocarbons industry (see Figure 3). There is no agreement about the best option for each case, although it is clear that sooner or later the jacket will be the preferred solution.

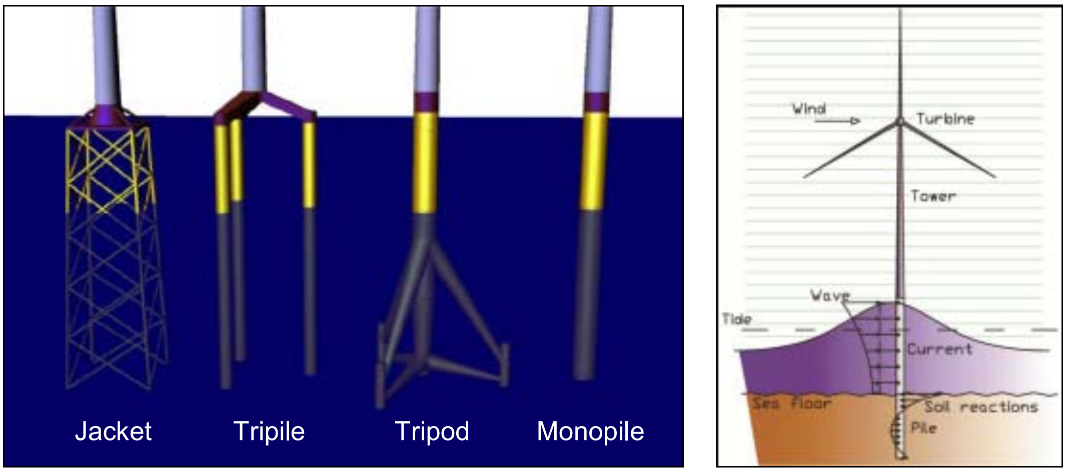

Figure 3: Overall view of the study we performed about offshore wind fixed substructures. Types of structures and types of loads.

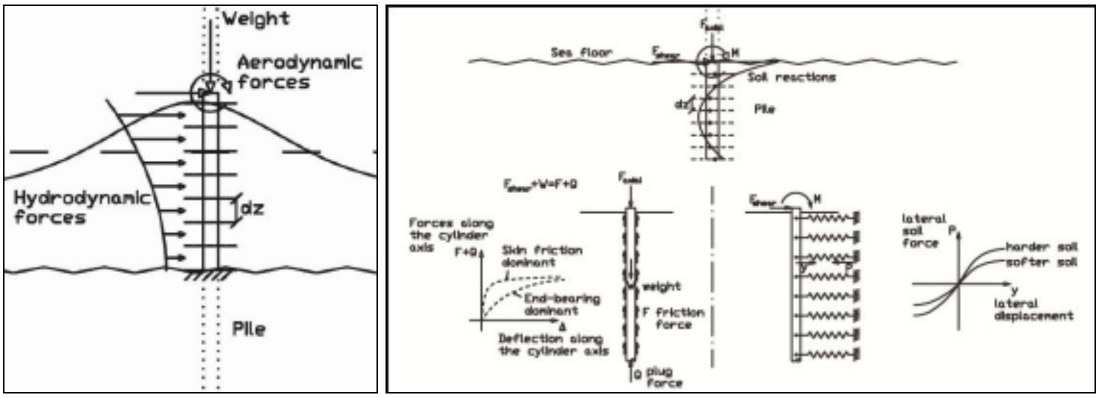

Figure 4: Simplified scheme of the structural analysis performed for offshore wind fixed substructures.

A routine that models the structural behavior of the 4 most typical steel arrangements was developed (Figure 4)[1]. The code optimizes the scantlings and obtains the most economical solution for each type and depth (Figure 5). The compared costs consider the price of steel and labor related to the construction of the units. Though the analysis includes simplifications and assumptions, all analyzed structures have similar design loads and conditions, which is why we may compare them and get some general conclusions. For instance, for 6 MW generators:

- Monopiles are the lightest solutions for water depths up to 25 m, and jackets are the lightest structures above this depth.
- Monopiles may be the most economical solutions just for waters less than 20 m deep, since above 20 m depth the thicknesses and/or diameters will be too big to handle.
- Jackets will be the best solution above 20 m, always considering they are built in series, as otherwise they could be much more expensive.

- Tripods are the solutions with bigger improving capacity with respect to the values given in Figure 5. The high variety of cones and parts used in the design could be further improved. However, we do not expect them to be cheaper than jackets, as the latter distribute stresses better.
- Tripiles are by far the least efficient solutions from the structural point of view, though installation prices could positively affect their final price. Nevertheless, we still expect them to almost always be the most expensive ones, because installation techniques are also being improved for jackets and tripods.

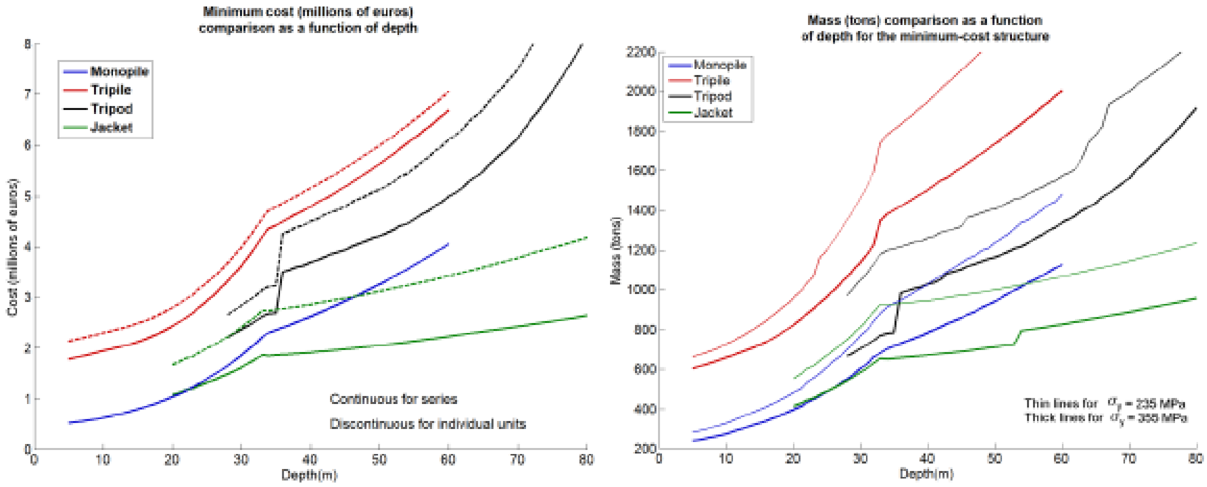

Figure 5: Overall results of the study we performed about Offshore-wind fixed substructures. Results are given as a function of depth. Left) Construction costs of the substructures and foundations, including material cost. Right) Mass of the most economical solutions, considering yielding stresses of 235 MPa and 355 MPa.

Since the jacket seems to be the most promising solution, we studied it more in detail[1]. Regarding the integration of the column and the jacket, there are several solutions around (Figure 6). A finite element analysis of the whole jacket was performed, as we illustrate in Figure 7, proving the good behavior of the transition based on a conical frustum.

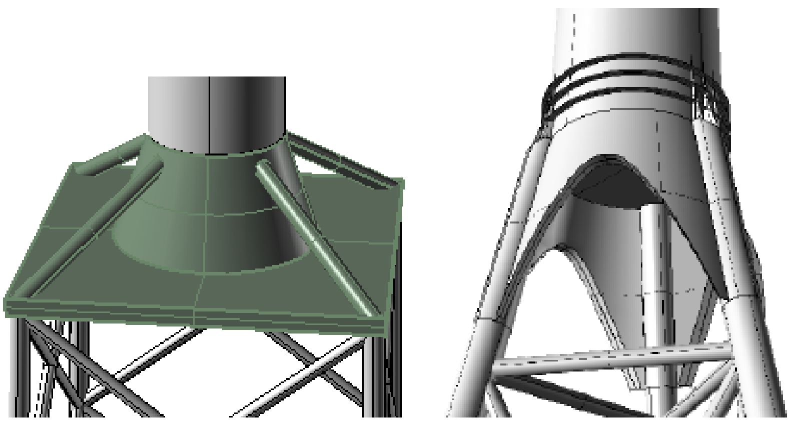

Figure 6: Two solutions for the transition of the jacket and the column. Left) Common solution found in the earliest generators. Right) Seaplace-recommended solution.

Attention must be paid to the resonance of the different frequencies involved in the unit (generator revolutions, blade frequency, wave frequencies, structure natural frequency), which could be a problem as the system goes deeper and the generator gets bigger.

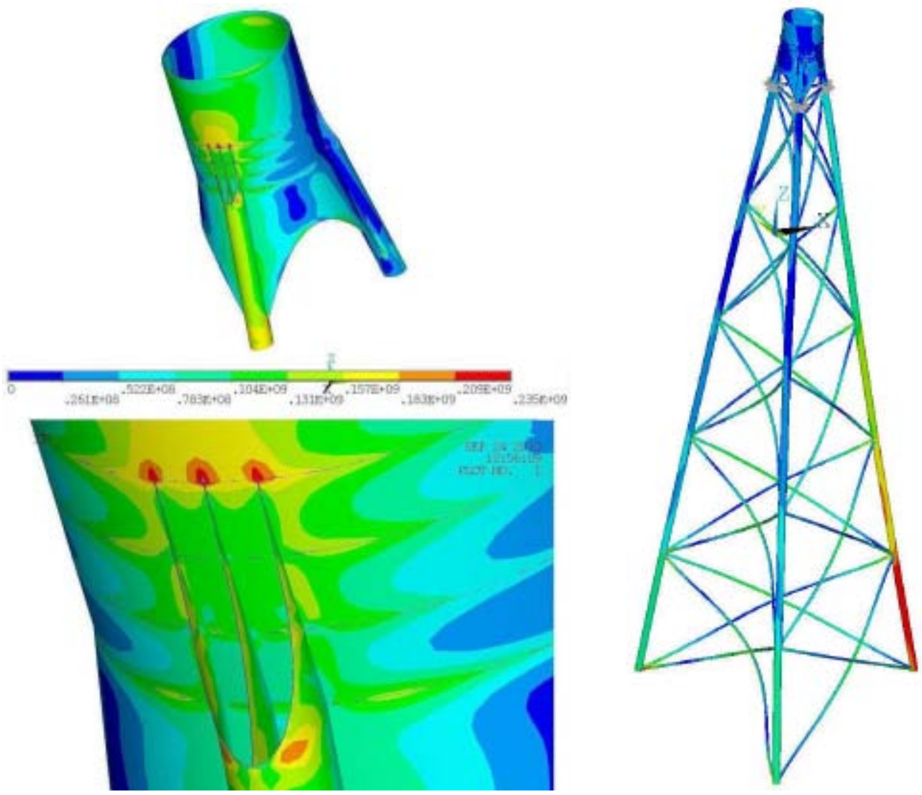

Figure 7: Finite Element Analysis and Optimization of the jacket and the conical frustum transition.

2.2 Floating solutions

Increasing water depths as the main factor and the unit power as a secondary will imply more expensive structures, and at a certain point, the floater will be cheaper.

The floating wind production will have to solve many wind generator design problems, but once these are under control, floaters will be installed even in water depths that now we believe are fixed solutions operating range.

Offshore floating wind is receiving great attention from Spanish wind energy companies over the last years. As a consequence, several JV huge research projects have been or are being developed focusing on all technical issues, ranging from design of support floating platforms to optimal blade's pitch control for floating wind generators. What follows is a short description of the three main types of floating platforms, design procedures and of wave tank tests used to validate designs.

As it is well known, there are three main philosophical ways of obtaining hydrostatic stability when designing a floating platform: ballast, tension and waterplane inertia. Based on these principles, there are platforms typologies that achieve its stability through them; namely SPAR platform through ballast, TLP through tension from tendon system and barge through waterplane inertia. The fact of only using waterplane-inertia stability on barges leads to uneconomical/unpractical designs for offshore wind turbines, and thus a combination of waterplane inertia with ballast is necessary. The hybrid concept is known as SEMI (semisubmersible).

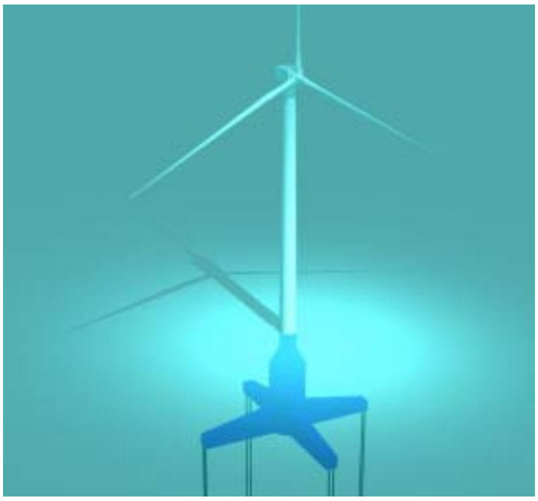

Figure 8: TLP concept

For floating generators, the maximum heeling angle/tendon angle (for the SPAR/SEMI and TLP respectively) for when the turbine is operating at full power must be limited.

Once the general arrangement of the platform is chosen and main dimensions are estimated from previous stability analyses, the next step is to make a structural analysis of the platform, applying relevant rules from Classification Societies and through FEM modeling. This way we obtain good estimations of weight distribution, which are accurate enough to be used as input to the seakeeping program. Throughout the basic design process care must be taken that the platform itself does not resonate with the main blade frequency of the turbine and that their natural seakeeping periods do not coincide with the most severe storms for the installation site. For the SEMI concept heave plates (bilge keel) can be used to damp heave motions and to modify heave natural periods.

Seaplace has developed a specific computation tool for floating wind platforms that handles efficiently the combination of seakeeping, mooring, wind and hydrodynamics loads of specials appendages such as the heave plate for heave damping. The Seakeeping program calculates the motion of the platform in 6 degrees of freedom on time domain when subjected to wind and aerodynamic thrust, current, waves and mooring forces. Spectral power density for wind fluctuations and for long crested seas could be input to the program.

Wave radiation/diffraction response of main bodies can be calculated on frequency domain by means of a diffraction program. An alternative procedure of estimating wave forces using a modified “Morison’s procedure” provides reasonable agreement with more accurate calculation and with tanks tests results.

An additional requirement for seakeeping behavior is the maximum hub acceleration. In case these limits are exceeded, modifications on the platform must be proposed and new simulations shall be carried out to check design suitability. Many computer simulations shall be performed before a model is constructed and tested at a wave tank. Some of the most important data that shall be measured is:

- Towing test of the platform at different healing angles to estimate drag coefficients.
- Forced oscillation tests in all degrees of freedom to obtain radiation response (added masses and linear damping).
- Excitation test (model fixed) to measure wave excitation forces.
- RAOS response in nominal and maximum operating condition of the wind turbine.
- Irregular wave tests for expected maximum sea state in nominal and maximum conditions.
- Survival test to demonstrate suitability of mooring design.

2.3 Installation of fixed units

Installation and future maintenance is an important part of the overall costs, requiring expensive equipment. The number of lifts will depend on the building strategy, and some of the lifts may require an accuracy that can only be accomplished by fixed operating cranes, such as the jack-ups. The bigger the jack-up crane, the smaller the number of lifts and the shorter the installation time.

But the jack-up solution is not the only one. The submersible crane is convenient for the shallower water depths (<40 m) and with large unit powers, as the concept requires great dimensions, solving in parallel the area required in those cases (see Figure 9 and Figure 10).

The piling operations will be an important part of the installation costs, although they are not so weather sensitive as the lifts, especially when these require accurate assemblies.

The installation may be done in phases, installing earlier the jackets or the piling, and later on the columns and equipment, or all through. The final decision will depend on the cranes availability and requirements.

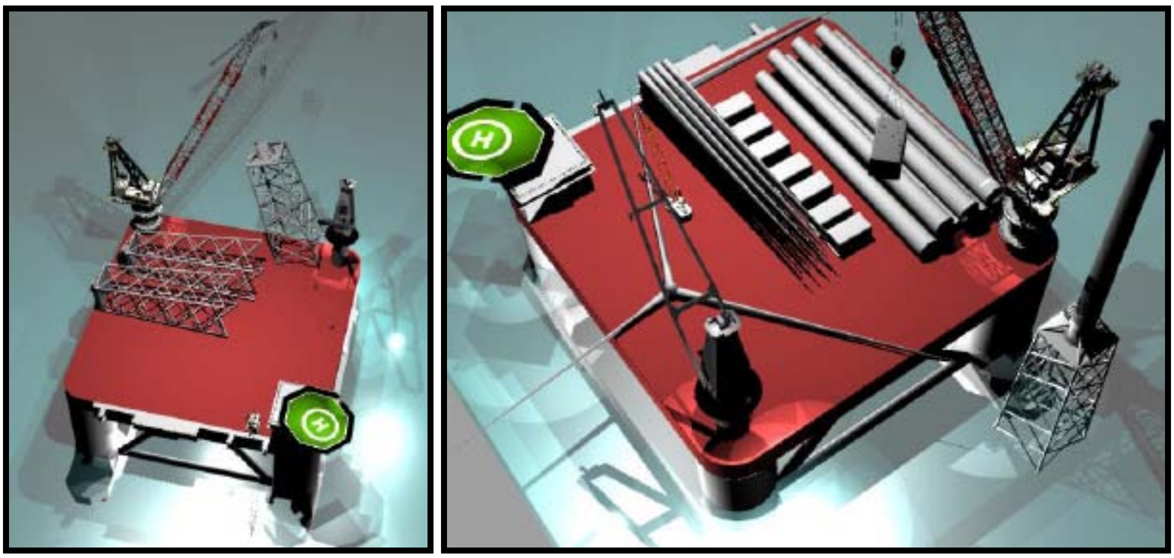

Figure 9: Installation unit for Offshore Wind turbines

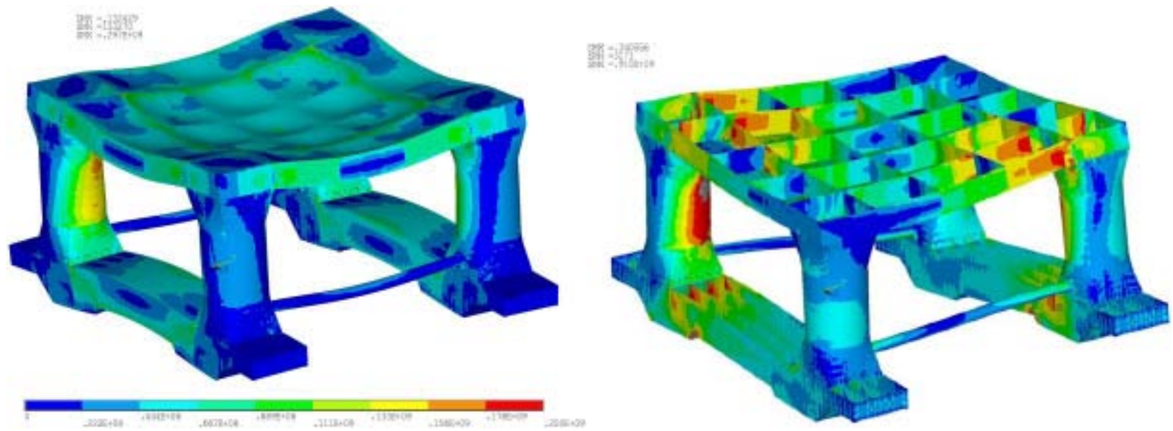

Figure 10: Structural behavior of a submersible installation unit for Offshore wind turbines. About 600,000 elements were used. Left) Stress distribution for a sailing condition. Right) Stress distribution for the worst condition, resting on two alternating legs, and without showing the deck top.

2.4 Installation of floating units

If rather than a fixed installation it is a floating one, the wind generation equipment can be assembled at the yard, avoiding expensive offshore cranes. At this respect, the TLP has some major differences as its stability in operation is granted by the tension at the tendons, so the TLP floater may or may not be towed fully assembled, depending on its design.

Thus, the comparison of floating platforms with the fixed ones is not only affected by the structure costs, but also by the huge saving in the installation costs of the floaters, specially the semisubmersible and SPAR units (see Figure 13).

The mooring will become a critical issue in the floating solutions. The anchor piles will be the most convenient anchoring option and, keeping in mind the usual water depths, chain lines will be in principle very suitable. The dynamics of lines shall be analyzed not only to take care of the wave cyclic loads but also the blade frequency, as there may be fatigue problems.

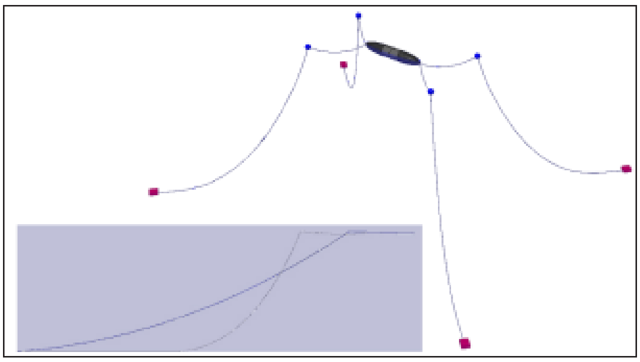

Figure 11: Mooring example

Dynamic effects on mooring lines have been studied for years, showing their importance. Experimental tests have been performed, measuring drag and inertial coefficients of mooring lines and evaluating mooring response with different configurations. This is directly applicable in the mooring design of a floating energy converter or any other offshore application. The influence of the following variables is frequently studied:

- Line type: chain, wire, synthetic ropes.
- Line characteristics: weight, length, elasticity
- Depth
- Initial tension
- Oscillations amplitude and period.

From all tests above, a complete matrix of results can be obtained. The availability of this type of data is very useful in an initial design stage to assess the dynamic effects relevance, as well as to choose a suitable configuration.

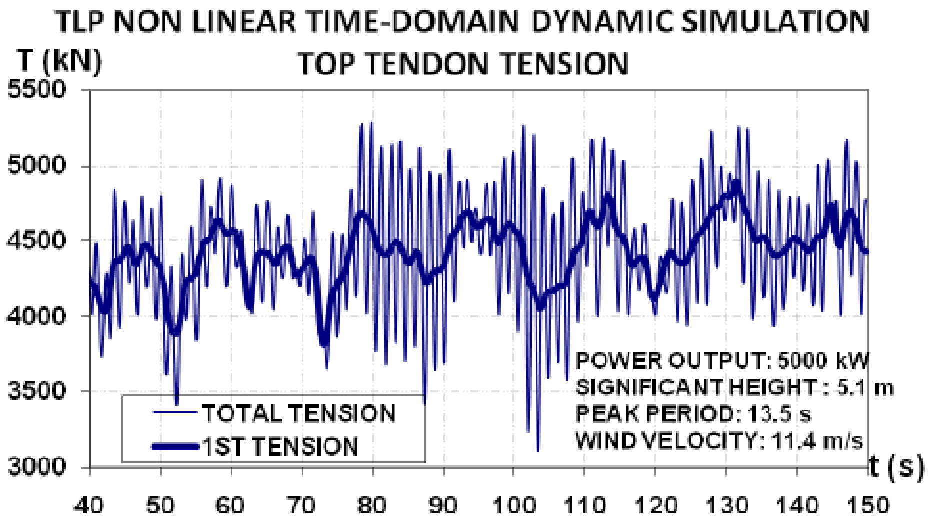

Figure 12: Springing in TLP

Additionally, experimental results provide an important basis to validate numerical approaches to determine the dynamic behavior of a mooring line. Numerically, mooring dynamics can be studied following two ways: Lumped Mass Method (LMM) and Finite Element Method (FEM)[3]. Regarding calculations, two methods can be used: frequency domain and time domain analyses. Time domain has the advantage that all non-linear effects (line stretching, geometry variations, fluid loading and bottom effects) can be modeled. In the framework of a study that Seaplace carried out, a numerical model to assess the mooring line dynamic behaviour was developed based on FEM with time domain calculations. It showed good agreement with experimental results.

In practical design, a quasiestatic approach is usually followed in the initial stage. However, this method considers wave dynamic effects through a static offset applied to the floating structure. It has been shown that the accuracy of the tensions calculated using this method varies widely depending on the vessel type, water depth and line characteristics. Dynamic analysis is more accurate, and therefore normally used in the final stage. It allows taking into account the specific mooring conditions, as well as particular resonance effects such as springing, VIV, etc. As set forth in API Guidelines[4], for a permanent mooring design, which is the case of a floating energy converter, a dynamic analysis is highly recommended, specially with high frequency oscillations and small natural periods.

2.5 Analysis of costs

The learning curve will reduce the overall costs of the structure construction and mostly of the installation process. At this respect the scale factor will be an important item, as the lack of restrictions at sea will allow a unit power increase with major cost savings. Figure 13 gives a rough comparison of the costs of fixed and floating solutions.

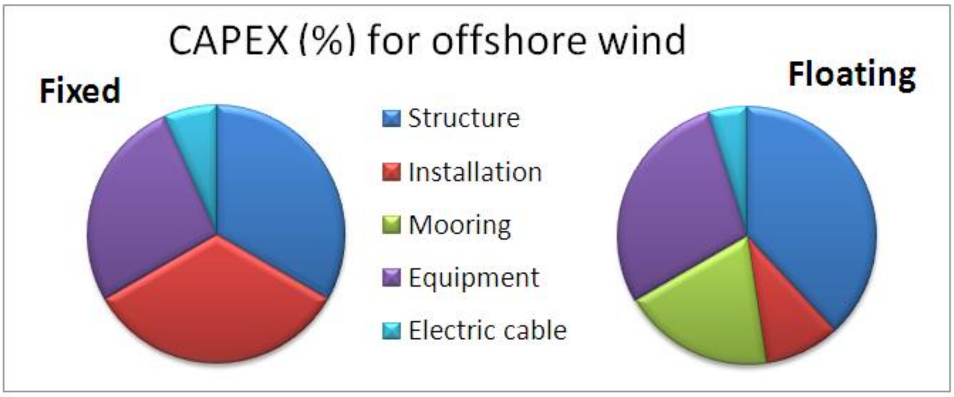

Figure 13: Cost distribution of offshore wind energy turbines

3 WAVE ENERGY

We have seen that the average wave energy is quite large, even after realizing that it is given per unit width, and it also provides many operating hours per year. But the bad side is quite relevant too, as the cyclic character of the wave velocity and accelerations, the extreme conditions and the slamming effects may rapidly deteriorate our structures, moorings and power generation mechanisms.

Besides, whilst with wind energy the scale was an important factor for future cost saving, this does not happen with wave energy. Increasing the wave energy generator size will not imply an energy increase. Therefore there is no scale factor advantage, as we discuss next.

When facing the design of a point absorber for a specific location we have to determine the optimum size of the floater in the sense of being the most effective on average wave power extraction. Conditions for optimum power extraction are well known and for a regular wave can be summarized in the following: WEC (wave energy converter) velocity must be in phase with the wave excitation force and its module has to be such that maximum theoretical power extracted from the sea be equal to half the radiated power due to WEC movement oscillating freely.

Far from resonance conditions control must be applied for WEC point absorber to increase the amount of power that can be extracted. There are two main control strategies; reactive control, which tries to balance continuously potential and kinetic energy, i.e., it takes the oscillating system to resonance, and discrete control (latch and release control) with the same global goal but exerting control effort at discrete time spots. Both control strategies imply power consumption, but reactive control demands by far more power.

Reactive control might be more suitable if we were able to design our WEC with a natural oscillating period close to that of maximum power contribution for specific wave climatology. Unfortunately, seas with a considerable average wave power level, above 25 kW/m, provide their energy at relatively large periods. Floaters with large natural periods are necessarily massive and, as a result, the ratio of average power to WEC volume will be very low making them uneconomical.

For wave point absorbers a more reasonable design approach would be to achieve the optimum power-volume ratio in spite of the fact the floaters will not always be naturally in resonance, and to apply discrete control to bring the system to a somehow forced resonance with waves.

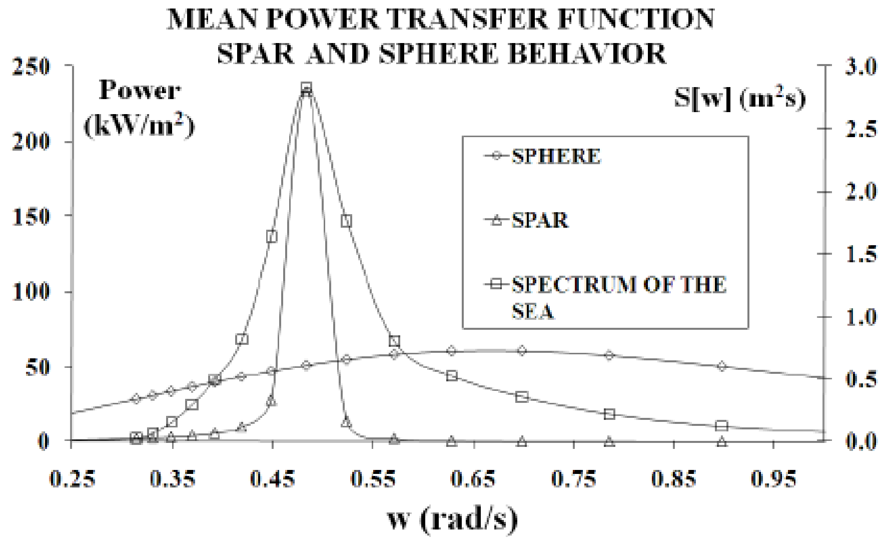

Figure 14: Mean power transfer funtion – heave movement spherical vs cylindrical floater

Figure 14 illustrates the two approaches already presented. The mean-power transfer functions of two different floaters is shown, both having equal diameter. The SPAR natural heave period is very close to that of the design sea state, whereas the sphere has a much lower natural heave period. PTO linear coefficient has been chosen to provide the highest average power for the design sea state with no control action, neither continuous nor discrete. Despite the fact that close to the design period the SPAR is five times more efficient, the ratio of average power per volume is much more favorable to the spherical case.

4 CURRENT ENERGY

Apart from the wind generating current, which is maximum at surface and reduces drastically with depth, there are other inducing mechanisms, being the cyclic tides the most important. Nevertheless, others like the evaporation and oceanic currents may be maximum in some specific locations.

The current energy is quite high and it is much more constant and predictable than the wind. It is not easy to convert the current components close to the surface into electric energy, as the mechanism will also be affected by the undesired effects from waves.

The deeper currents are not so strong except in some specific locations like straits, where we could recover some of its energy. Away from the wave effects, the rather constant speed can be converted into energy in specially designed turbines. Several designs are in the market, and some are at a prototype stage.

The installation of a nozzle will have several advantages: it will concentrate the energy, provide space for the electrical equipment, and guarantee the buoyancy (see Figure 15).

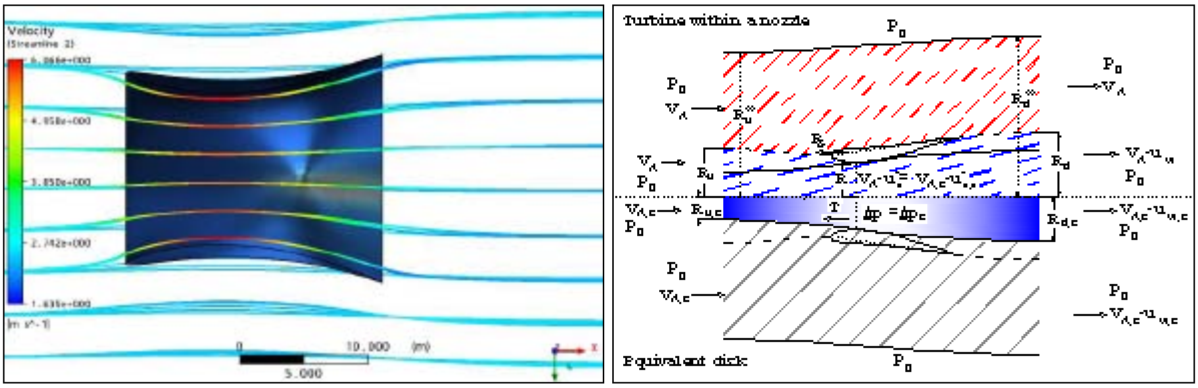

Figure 15: Left) CFD computation of the flow through a nozzle. Right) Effect of the nozzle

5 CONCLUSIONS

The growing fixed offshore wind industry will require many different structures, with a huge range for optimization. When reaching larger water depths, the floating generation will benefit from the industry and economy developed for the fixed solutions.

The wave generators facing large cyclic and stream loads need large engineering efforts and costs for a small amount of recovered energy. The currents, either from tide damns or in open seas, are very promising in specific locations, provided we avoid the wave loads.

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