FOUNDATIONS FOR OFFSHORE WIND FARMS

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EXTENDED ABSTRACT

Almost 3,000 wind megawatts had been installed offshore at the beginning of the year 2011 and, although the first offshore wind farm experiment took place in 1990, most of the facilities built up to then have been pilot projects. This statement confirms that offshore wind power can be considered as an incipient market and then, the scarce experience existing in this field. This short experience is even more evident due to the variability of the offshore wind facility characteristics: seabed depth, geotechnical properties of the ground, loads for the design of the structures, etc. There is still a lot to study and to improve regarding the knowledge of several issues connected to offshore wind farms, for example, the foundations. Besides, this is still most important because it is expected an important growth of offshore wind megawatts in the next future and, as a result, offshore wind farms will begin to form part of marine and coastal landscape, being considered then as part of that environment.

To achieve improvements in the foundation field, it will be necessary to be based in the existing experience with application in the offshore wind industry, like the experience from wind power industry – onshore and offshore, although the last one is very scarce –, maritime engineering and oil and gas offshore industry.

The first offshore wind facilities were built in locations close to the coast with foundations below 25 metres and with favourable geotechnical properties, mainly sand. Most were founded on steel monopile foundations and gravity based structures. As time passed, these installations were extending to greater depths which, added to an increasing size of wind turbine generators, led to other, more complex foundation solutions appearing, such as tripods and jackets.

A technical-economic barrier of around 40-50 metres is currently assumed regarding the foundations. Anyway, several research projects are ongoing with the purpose of finding how to overcome this barrier, and by means of new solutions for the different water depth ranges combining the technical feasibility and the cost-effectiveness. Such projects may be considered as divided, according to whether they are focused on the development of new types of more effective direct foundations than those existing or on the development of floating supports. Nevertheless, it is foreseeable to have to wait to mass produce floating foundations because it will be necessary to make changes in the wind turbine generators to achieve their correct operation. This paper includes a revision of the characteristics of the different foundation types used up to this moment or that can be used in the next future in the offshore wind industry.

Keywords: renewable energies, monopile, gravity based structure, tripod, jacket, hybrid foundation, floating support.

1. INTRODUCTION

The first offshore wind facility experiment took place more than 20 years ago. However, this type of installations has continued being built from then, being most of them pilot projects. Offshore wind power can still be considered then as an incipient market. And as a result of this, the experience is limited in most of the aspects related to this field, and also then in foundation techniques. This scarce experience is even more evident due to the variability of different characteristics like seabed depth, geotechnical properties of the ground, loads for the design of the structures, etc. Besides, this is still most important because it is expected an important growth of offshore wind megawatts in the next future. In fact, the almost 3,000 offshore wind megawatts at the beginning of 2011 confirm the boost beginning in this field with several countries leading this development, like the United Kingdom, Denmark, Holland, Sweden and Germany (Esteban *et al*, 2010).

As consequence, it can be stated that there is still a lot to research and to improve concerning foundations for offshore wind farms. To achieve these improvements, it will be necessary to learn from the existing experience in different fields like wind power industry – onshore and offshore, although the last one is very scarce –, maritime engineering and oil and gas offshore industry. Foundations are a key aspect having influence on the technical feasibility of the project (for example, problems with the grouting and with the primary steel of monopiles have happened), the economical feasibility of the project (foundation costs are around 25% of the total cost of the project – see figure 1) and the environmental feasibility of the project (one of the issues to take into account is the relationship between this type of facilities and coastal processes).

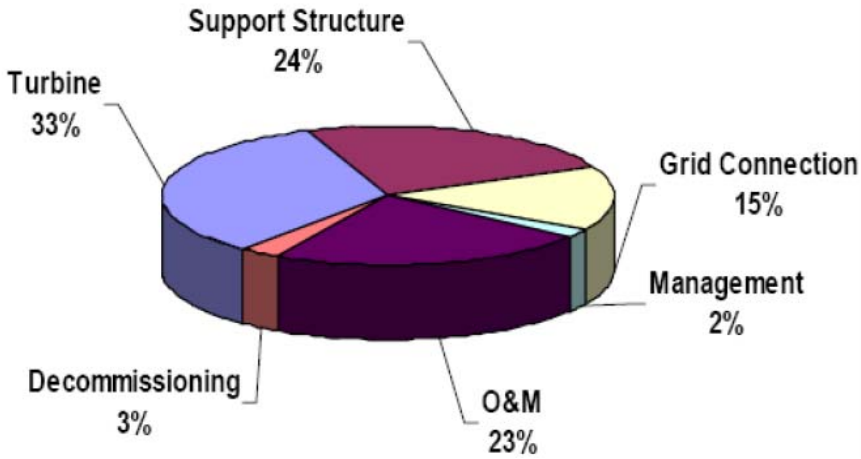

Figure 1: Costs distribution for offshore wind facilities (www.offshorewindenergy.org).

Most of offshore wind installations built up to now have been founded in water depths below 25 metres, either the use of monopiles or gravity based structures. With the increase of depths in the locations of offshore wind farms, other foundation technologies are beginning to be competitive, as it happens with tripods and jackets. And looking for technical and economical feasible solutions for different depth ranges, there are numerous research projects, including them such direct as floating foundations (Rey *et al*, 2010)

The content of the paper is: 1) Introduction; 2) a brief revision of the state of the art; 3) foundations for offshore wind facilities, firstly those used up to this moment and, secondly, those forecasted to be used in the future; and 4) conclusions.

2. STATE OF THE ART

The first wind turbine generator in the sea, of 220 kW unit power, was installed in Sweden in 1990. This was located 350 meters from the coast, and supported on a tripod structure anchored to the seabed about 6 meters depth.

Experimental low rating projects were carried out between 1991 and 1998. Different models of wind turbine generators (450 kW to 600 kW units power) and also different types of foundations (monopiles and gravity based structures) were tested in those installations, characterized by distances of up to 4 kilometers from the coast and depths of up to 6 meters. “Vindeby” was one of the offshore wind facilities constructed during this phase; this has been in operation since 1991. This phase was useful mainly because although certain doubts were initially raised, most of those facilities showed good profitability and reliability indices.

Later, multimegawatt wind turbine generators began to be used, being the first project of these characteristics the “Utgrunden” facility, built in Sweden in 2000. Several of these facilities marked the commencement of the first commercial wind farms: “Blyth”, “Middelgrunden” and “Yttre Stengrund”. Later, the “Horns Rev” and “Nysted” facilities, both on Danish coasts, were the confirmation of this type of facility’s adaptation to the marine environment and are the first ones with offshore transformer substations. The foundations constructed in this phase were mainly monopiles and GBS ones, but also and exceptionally the suction caisson in the “Frederikshaven 1” (Esteban *et al,* 2010).

As from then, facilities of this type have continued being built, using not only monopiles and gravity based structures foundations, but also another typologies like tripods and jackets. The distribution of offshore wind power in operation at the end of 2008 is exposed in the figure 2.

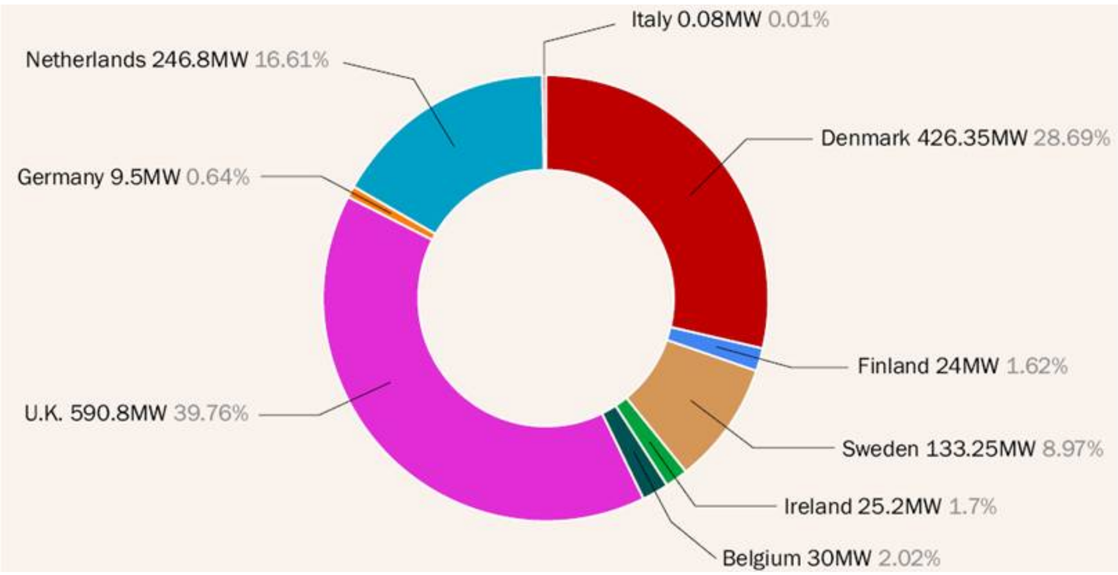

Figure 2: Distribution of offshore wind megawatts in operation in the different countries at the beginning of the year 2009 (www.ewea.org)

It is essential to push the use of offshore wind energy to achieve the commitments acquired in the Kyoto Protocol. In the future, it is expected a huge increase of the offshore wind power installed, not only in the already experimented countries. Regarding this, there are several theories - all of them with optimist perspectives - about the evolution of the offshore wind power installed.

3. TYPES OF FOUNDATIONS

This epigraph contents, firstly, a discussion about the foundations currently used and, secondly, a thought about the foundations forecasted to be used in the future.

3.1. Current types of foundations

First offshore wind facilities were built in locations close to the coast with foundations below 25 meters and with favorable geotechnical properties, mainly sand. Most of them were founded on steel monopile foundations and gravity based structures foundations. As time passed, these facilities were extending to greater depths which, added to an increasing size of wind turbine generators, led to other, more complex foundation solutions appearing, such as tripod and jackets (Figure 4). All of these types of foundations are exposed in the following paragraphs.

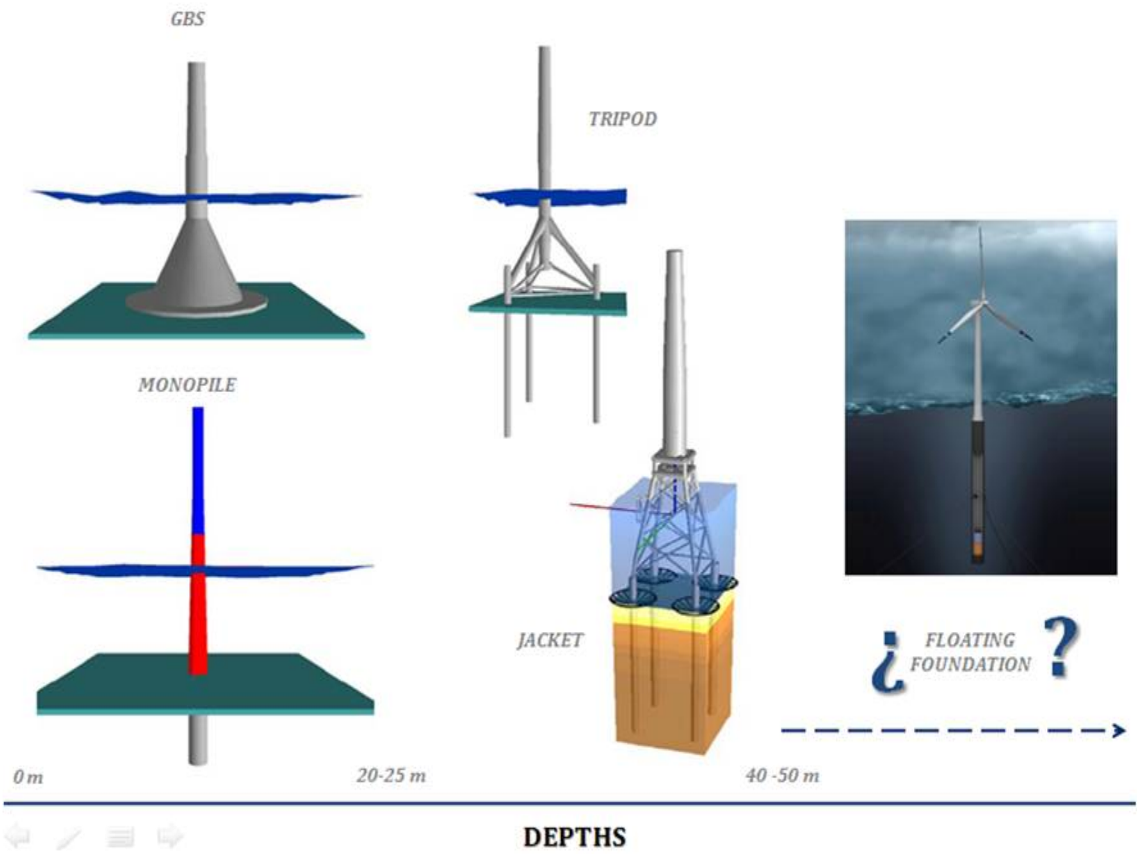

Figure 3: Foundations types regarding the seabed depth (Esteban *et al*, 2009).

Steel monopiles are deep and individual foundations that, by means of their driving or/and drilling in the ground, achieve the load transmission. They are competitive foundations for small and medium size wind turbine generators, although can be competitive also for some big wind turbine generators. Their mass production and their installation are easy, being the most difficult question to find suitable vessels for their transportation and installation.

While there are some opinions exposing that monopiles are suitable for drafts between 0 and 25 meters, other ones extend this range up to 30 meters depth (Det Norske Veritas, 2007; Krolis *et al*, 2007). Nevertheless, the development of new hammer to drive or/and drill monopiles with bigger diameters would let to win some meters of draft. Monopiles generally used in offshore wind farms are characterized by variable thickness along their length, around 50 millimeters but 100 millimeters in the areas more loaded, diameters around 5 meters and weight higher than 600 tons. These dimensions depend on a lot of determining factors; therefore, it exist a wide range of dimensions. Specifically, the length of the monopile has to be function of the soil properties and the loads to be supported; for example, for 25 meters deep, sands in the location and the usual diameter of monopiles, the length of the monopile can be more than 40 meters.

Monopiles are feasible for grounds with a layer of soft soil over the competent soil or rock layer. In fact, it is necessary to consider the possible scour effect in the design of the whole structure, being this effect lower than in GBS (Rudolph *et al*, 2007).

A critical aspect of this foundation is the joint between the own monopile and the transition piece. This joint allows the leveling of the wind turbine generator according to the tolerance permitted and facilitates the access for the operation and maintenance activities. The transition piece overlaps the monopile a length around 1.5-2 times the diameter of the own monopile, and it is connected by means of grouting. This grouting is producing a lot of problems in offshore wind farms in operation; therefore, this question is being reconsidering as a main aspect of the design of this type of structures.

Gravity Based Structures (also called GBS) are able to maintain the stability facing any conditions, only by means of the own weight of the structure. These foundations are competitive when environmental loads are relatively limited and when the own weight of the structure are significant. They are indicated when it does not exist construction methods for another type of foundations. Also when it is high the mobilization cost of the installation methods. This is because they are pre-cast concrete structures in a port close to the final location of the offshore wind farm. They can be manufactured by some constructor companies; in fact, there are research projects looking for the optimization of this kind of structures for the offshore wind industry.

There are different opinions regarding the suitable depths for this type of foundations. Some of them defend the use of the GBS between 0 and 10 metres deep, and other ones between 0 and 25 metres deep (Ashuri *et al,* 2007; Det Norske Veritas, 2007; Krolis *et al*, 2007).

The shape of the structures is used to concentrate their weight in the base, looking for a reduced diameter in the medium sea level, achieving so to reduce the hydrodynamic actions due to the wave and the currents. Although the most usual shape is the conical one, these structures can adopt other shapes. The typical diameter in the base of conical GBS is around 30-40 metres, although this magnitude depends on several determining factors.

The ground has to have enough resistance capacity, and in most of the cases it will be necessary to dredge the superficial layer of the seabed, supporting then the foundation on a previously prepared surface. Likewise, it will be compulsory to consider the possible scour effect in the design of the structure, planning some protection component.

Tripods and **jackets** are steel tubular foundations inspired in the oil platform. These foundations have been short tested up to this moment, but their future is too promising. The diameters of the tubes forming part of them are, generally, between 1.5 and 2 metres. In particular, jackets used for offshore wind farms are tubular lattice with four legs that, due to the small diameters of the tubes, are little exposed to the wave and the currents; then, they are appropriate for severe maritime weather. And, on the other hand, tripods have a central column below the wind turbine tower, following the monopile philosophy somehow, but connected by means of a tubular structure to three inferior legs.

There are some references holding that these structures are suitable in water depth between 25 and 50 metres, while other ones prescribe their use for more than 20 metres water deep (Ashuri *et* al, 2007; Det Norske Veritas, 2007; Krolis *et al*, 2007). The barrier about 40 – 50 metres depth is imposed by the financial profitability of the project; in fact, similar structures have given good results in oil and gas offshore platforms in deeper waters due to the different cost structure in the oil and gas and in the offshore wind industry.

Depending on the soil properties, the structures will use as foundation either piles or GBS; then, this type of foundation is very versatile in spite of the ground in the location. Their dimensions depending on a lot of determining factors: soil properties and loads, for example (Seidel, 2007).

The installation method most used for the jackets consists on the driving or/and drilling of the piles with the help of a template resting on the seabed. Lately, the jacket is transported to the location and placed with the monopiles, the structure is leveled and the connection between piles and jacket is carried out by means of grouting. Tripod installation is similar to jacket´s one, although in the "Alpha Ventus" offshore wind farm (Germany) the installation began with the placement of the tubular structure, and later the piles are driven or/and drilled through pile sleeves. And finally, the joint between legs and piles were filled in with grouting. In this case, the leveling of the structure was carried out once the installation was finished, taking the coordinates of the final position of the structure, and placing a bridle joint in the upper part of the tubular structure (Rey *et al,* 2010).

3.2. Foundations for the future

A technical-economic barrier of around 40-50 metres is currently assumed (Hingtgen, 2003), in relation to foundations, for the construction of this type of facility whilst several research projects are ongoing with the purpose of finding how to overcome this barrier. Such projects may be considered as divided, according to whether they are focused on the development of new types of direct foundations more effective than those existing or on the development of floating supports (Ashuri, 2007; Knauer *et al*, 2007; Tong, 1998) (Figure 4).

Direct foundations in a research phase are usually the result of several combinations of the types of direct foundations discussed above and may be called hybrid foundations. Hybrid foundations embrace multiple options since foundations may be completely different and, therefore, so may their impact on littoral dynamics (Byrne, 2002; Nielsen *et al*, 2007; Det Norske Veritas, 2004; Ronglien *et al*, 1994).

Floating solutions emerged like alternatives to other kind of foundations for offshore wind farms in deep locations (more depth than 40-50 metres). Anyway, they are not still technical-economical feasible alternatives. The main structural ideas used up to now for the design, construction and installation of these kind of foundation have been inherited from the oil and gas offshore industry, but there are some different aspects like the costs that can be faced in the offshore wind installations, several important determining technical factors that have to be solved, mainly in relation with the dynamic behavior of the whole wind turbine generator – float. Regarding this, it is foreseeable that the use of floating foundation will involve variations in the wind turbine generators, for example in their control system.

Massachusetts Institute of Technology (MIT) classifies floating structures according the system used to achieve the stability in three general categories: "Ballast Stabilized" – stabilized due to the weight of a substructure that creates an stabilizing effect –, "Mooring Line Stabilized" – stabilized due to the weight of a substructure that creates an stabilizing effect – stabilized due to stressed cables – and "Bouyancy Stabilized" – stabilized leaning on the water surface –. Although floating structures can use only one of these systems to be in stable equilibrium, it is usual to combine some or all of them (Butterfield, 2005).

Scientific research about floating foundations is very active. In fact, there are several research projects running. For example, the most advanced one is the "Hywind" project, developed by the Norwegian company "Statoilhydro". This is the world´s first full-scale floating wind turbine, installed in the Norwegian coast, 200 metres depth; its main characteristics are SPAR floating foundation – ballast stabilized –, turbine size 2.3 MW – Siemens model –, turbine weight 138 tons, turbine height 65 metres, rotor diameter 82.4 metres, draft hull 100 metres, displacement 5300 m3, diameter at water line 6 metres, diameter submerged body 8.3 metres, mooring with 3 lines. The installation of offshore wind farms in some location – deep ones – only would be possible if floating foundation will reach the enough maturity to be technical and economical feasible.

4. CONCLUSIONS

Because offshore wind is an incipient market, there is still a huge improvement margin in several issues, being one of them the foundations techniques. In fact, there are numerous challenges in the construction of foundations of offshore wind farms, and it will be necessary to give responses to them, analyzing particularly each location.

Numerous solutions are possible for foundations of offshore wind facilities. Anyway, nowadays, only some of the direct foundations exposed in this paper are feasible for offshore wind farms from a commercial point of view; for example: monopiles and GBS. Besides, there are other types of direct foundations like tripods, jackets, tripiles and so on, being the jacket foundation the most emphasized one due to be considered as one of the most solid alternative for the construction of offshore wind installations in the next years. In fact, several designer, manufacturer and constructor companies are working in the jacket concept looking for the reduction of the costs.

Floating foundations are above all medium-long term alternatives; and together with several types of direct foundations, floating foundations will be solutions to overcome the 40-50 metres technical-financial barrier assumed up to this moment. However, it is foreseeable to have still to wait some time to mass produce floating foundations because their cost is still very high, clearly higher than the direct foundation cost; besides, it will be necessary to make changes in the own wind turbine generators to achieve their correct operation.

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