Review of Options for Offshore Foundation Substructures

Prepared by the Center for Wind Energy at James Madison University

August 2012
An offshore wind turbine is massive in size – from the root of their foundation to the top of the nacelle, wind turbines can reach a height of 250 meters (820 feet).\(^1\) Upcoming offshore wind turbines are rated at 5MW and larger turbines of up to 10MW are being developed. As wind turbines get larger, the importance of developing cost-effective foundations that can safely support these turbines increases.

In general, wind turbines can be classified into three classes, depending on the water depth as shown in Figure 1, which are

- **Shallow Waters** – 0 to 30 meters
- **Transitional Waters** – 30 to 60 meters
- **Deep Waters** – 60 to 900 meters

![Figure 1 - Different offshore wind turbine foundations including the monopile, jacket/tripod, and the three primary types of floating structures.\(^2\)](image)

**Shallow Depth Foundations**

**Gravity Base**

Gravity foundations were the first type of foundation used by the offshore wind energy industry and can be made from steel or concrete. The foundations are built onshore, then transported and lowered into place using cranes. Sea bed preparation is required – silt must be removed and the sea bed must be smooth before the foundations can be lowered. Once in place, the foundation is filled with sand or gravel to achieve the required weight to achieve stability.

Gravity base foundation structure is limited to depths of less than 10 meters because the foundations are too heavy and expensive to install in greater depths.

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\(^2\) **Floating Wind Turbines. Roddier, D, Weinstein, J.** s.l.; Principle Power, April 2010
Monopile foundations are the most commonly deployed foundation structure used in the offshore wind energy industry to date. Monopiles are typically hollow, steel cylinders with a diameter between 3.5 and 4.5 meters and a surface thickness of around 5cm. The length of a monopole varies, depending on the site, but is normally around 30 to 50 meters long.

Some seabed preparation might be required, such as the laying of gravel to prevent erosion. The piles are typically driven into the seabed, using specialized vessels called jack-up barges. After the pile has been driven in, a transition piece is attached on top of the pile in a special concrete casting process. The transition piece is usually pre-installed with various features such as boat landing arrangement, cable ducts for the submarine cables, and turbine tower flanges for the bolting of the turbine tower.

The monopile foundation has been critical in the early years in the development of the offshore wind industry in Europe, mostly because the technology is an economical solution for wind turbines at shallow depths. Moreover, the sandy and gravelly composition of the North Sea seabed makes it possible to drive the piles to their required depth with minimal drilling. It is unclear whether the monopile would be a suitable foundation structure for wind turbines in the Atlantic Ocean because of the risk of extreme events like hurricanes.

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Suction Caisson

Suction caissons are simple steel fabrications that look like upside down buckets which can be designed to be lighter than the steel required for an equivalent monopile foundation. The installation method is simple and quick – a single unit can be deployed and installed in a few hours as a single operation. The caisson is allowed to settle into the seabed and a pump is attached to the head. The pump is used to apply suction to help the caisson to pull itself deeper into the seabed. Auxiliary equipment and consumables such as hydraulic hammers and grouting spreads are not required. Finally, at the end of the turbine’s life, a suction caisson can be removed completely from the seabed by reattaching the pumps and applying pressure inside the caisson, leaving little trace that it was ever there.

Suction caissons have several advantages over the monopile including higher durability, no need for specialized vessels, the ease of installation, and the structure’s greater resistance to vertical and lateral loads due to their larger diameters. Suction caisson foundations are being considered for a 200MW offshore wind farm in Hong Kong, in waters around 30 meters deep.

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Transitional Depths

In deeper waters between 30 to 60 meters, shallow foundation structures can be replaced by fixed bottom systems that use a wider base with multiple anchor points, similar to what is done in the oil and gas industry. Transitional substructure technologies are typically most viable at depths up to 60 meters. The first floating offshore wind turbines in transitional water depths were deployed at Beatrice, off the coast of Scotland. The demonstration project consists of two 5 MW turbines at 42 meters depths in the North Sea.

Tripod

A tripod foundation is a transitional depth foundation for offshore wind turbines that are based off similar foundations used in the oil and gas industry. The turbine tower rests upon a steel pile, similar to a monopile foundation. A steel frame is attached to the pile which distributes the loads from the tower onto three steel piles, which are driven into the seabed to a certain depth, depending on the seabed geology and water depth. A typical tripod structure is shown in Figure 5.

The design of the tripod foundation gives it sufficient strength to be places in deeper waters, while maintaining the advantage of minimal sea bed preparation. This extra strength should also give turbines using this foundation more resilience to hurricanes and tropical storms. However, the bulky frame means that tripods are unsuitable for shallow waters, since service vessels would have difficulties in approaching the turbine.

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The tripod foundation was deployed for the first time at Alpha Ventus in Germany in 2010. This project will provide valuable information about the viability of offshore wind farms in transitional water depths.

![Figure 5 - A typical tripod support structure for offshore wind turbines in transitional water depths.](image)

**Jacket**

A jacket foundation is a very large multi-chord base formed of multiple sections of structural tubing or pipe that are welded together. The jacket is prefabricated onshore and placed upon a large transport barge to be transported to the installation site. The jacket foundation structure is an adaptation from the oil and gas industry and have been installed a sites hundreds of meters deep.

The jacket is a semi-submerged structure, with a small portion of the jacket extending above the surface of the water. The exposed portion of the jacket is the portion upon which the turbine tower can be mounted, as seen in Figure XXXXX. For this reason, wind turbines with a jacket foundation are called jacket-tubular structures, since the tower is a tubular structure.

Jacket structures have gone under intense modeling and testing and can be installed in waters as far as 60 meters deep. Studies have shown that jackets weight half of what a monopile would. This decrease in weight can also play a large role in the reduction of cost in transportation and installation. One other advantage to the jacket foundation is that minimal seabed preparation is required.

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Truss Tower

Truss, or lattice towers, are an alternative foundation substructure to tubular towers and can be seen in Figure 7. Truss towers were not developed for onshore wind turbines because of their aesthetic appearance and complex fabrication process. However, the truss tower has several key advantages over tubular towers, namely having less weight and a more flexible design. The open sections of the truss tower allow waves and wind to flow through the structure, reducing the loads. In addition, wind farms utilizing truss towers can be placed far enough offshore to mitigate the visual impacts.

Truss tower substructures have been deployed as two demonstration 5MW wind turbines in the Beatrice project, off the coast of Scotland. The feasibility of this kind of structure was evaluated based on the economic impact and the structural behaviors. In tubular-jacket substructures, transient pieces could have stress concentration issues. This disadvantage is avoided in truss towers and could mean than a truss tower may be more optimal than a tubular-jacket structure.

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Floating Deepwater Technologies
In the next few years, large offshore wind farms in very deep waters in Europe are a likely possibility in the deeper parts of the North Sea. Unfortunately, the costs of shallow and transitional depth support structures get prohibitively high at these depths. However, there are alternative schools of design for support structures in deep seas, including floating support structures.

Floating structures must have enough buoyancy to support the weight of the turbine and to restrain pitch, roll, and heave motions within acceptable limits. The most important loads to consider are wind turbine thrust, wave loads, wind turbine torque and drift forces. There are some key differences in the load characteristics of floating wind turbines to that of floating oil rigs. While floating oil rigs and payload and wave driven, floating wind turbine loads are primarily wind-driven overturning moments. Floating support structures have one immediate advantage – probably the most attractive is that it will allow for the offshore wind industry to expand to new countries and regions, such as the Mediterranean, Norway, the United States and East Asia. There is a wide variety of technology solutions proposed as a result of the number of choices of concept available and corporate interest. Finally, many floating concepts are easier to construct and install than fixed structures – the decommissioning process is easier as well.

However, floating support structures have several key challenges to overcome, one of which is turbine stability. Floating structures must be designed in a way that they can support wind turbines in the megawatt class, while minimizing turbine and wave-induced motion. The added complexity in the design process, including understanding the coupling between the support structure and the wind turbine is another hurdle the industry must overcome. There are significant concerns to the design and

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8 [Online] [Cited: August 17, 2010.] http://www.ifb.uni-stuttgart.de/ifbmedia/bilder/07_Jobs/03_SD-Windenergie/truss2.jpg.
costs of the electrical infrastructure. Finally, there is a lack of experience in deep water offshore wind farms and care must be taken during construction, installation and O&M procedures.

While no full-scale floating systems have yet been deployed, a number of companies have developed full-scale prototypes. A number of other companies are still in the concept development stage. Floating support structures can be classified into three main classes:

- **Buoyancy stabilized** – uses the water plane area to achieve stability, similar to the way a barge does. Simple moorings are used to keep the structure in place.
- **Ballast stabilized** – uses a very large weight deep under water, providing a counterbalance to the loads. Simple moorings are used to keep the structure in place.
- **Tension-leg platform** – uses tensioned mooring arrangements to keep the structure stable.

Each of the classes is technically and practically viable and is actively being pursued, each having their advantages and disadvantages. Several concepts, such as the SWAY model being tested in Norway, are combination of the three classes. Several examples of proposed deep water concepts are given in Figure 8.

Some preliminary studies have been done already to assess floating systems, but none of the public studies to date have attempted to optimize the platform cost and geometry.

The wind turbine platform and mooring system should provide the most potential for system cost reduction because the application is new and the most significant cost saving design tradeoffs have not yet been explored. However, a solid basis from which to determine the optimum design has not yet been established.

The commercial investment in floating wind turbines is a technological challenge, but a necessary one if the full wind potential is to be exploited, especially in regions like the Mediterranean where there are precious little shallow waters, or the Atlantic, which has a significantly larger wind resource if deep wind is enabled.
Figure 8 - Floating deepwater platform concepts (left to right): semi-sumbmersible tri-floater, barge, spar-buoy with two tiers of guy-wires, three-armed mono-hull tension leg platform (TLP), concrete TLP with gravity anchor, deep water spar.

9Ballast-Stabilized

Commonly known as spar buoys, ballast stabilized foundations are one of the concept floating offshore wind turbine foundation structures currently being researched and developed. A spar buoy is a tall, thin buoy that floats upright in the water. It is characterized by a small water plane area and a large mass. Adjustment of these two parameters tunes the spar buoy to reduce the response to wave forcing. Spar buoys are traditionally known for their use in making oceanographic measurements.

There have been significant technical challenges in the attempt to use spar buoys to support large wind turbines. The structure must be able to support major horizontal loads centered at heights well above sea level. The center of gravity of the vessel must be lowered to below sea level, which can take up to 2,400 tons of ballast to stabilize the structure for a utility-sized turbine. While this has proven to be a major engineering challenge, the major issue with spar buoys has been balancing the conflicting requirements of the main design drivers, namely

- Maximizing pitch stiffness to minimize vessel heel
- Maximizing the natural heave period to reduce wave-induced motion
- Minimizing cost

The drivers impose conflicting demands on the water plane area, vessel mass and vessel dimensions to be simultaneously as large as possible to minimize heel and motion, and as small as possible to minimize cost. It is this conflict that greatly reduced the viable design space for spar buoys.

Despite these challenges, a ballast stabilized concept has been developed by the company StatoilHydro. The concept is currently being testing in the Hywind pilot project over a two-year period. The turbine is shown in Figure XXXX and is rated at 2.3MW and is designed to operate in water depths between 120-700 meters. This project will provide valuable information as to how the wind and waves affect the structure, which will help in the improvement of the design, in particular reducing the cost.

**Tension Leg Platforms**

Tension leg platforms (TLPs) are also called mooring-line stabilized foundations and are similar to spar buoys. The mooring-line stabilized turbines are fixed in place with tension leg platforms and suction gale anchors. These turbines are lighter than ballast stabilized wind turbines which allows for more motion of the tower. If the motions of the tower are not controlled they can lead to catastrophic impacts. Currently the mooring line stabilized foundation requires extremely expensive and heavy foundations in order to prevent motion.

The major challenges in developing a successful design are

- Installing the structure safely, reliably and cost effectively while maintaining stability throughout the entire process, which includes towing, preparation, tensioning of the cable and during submersion of the structure.
- Developing anchoring for ground conditions at the site. Gravity anchors, piled anchors and suction anchors have all been considered but none are easy or cheap to design or handle.

Despite the challenges, TLPs are considered to have the most potential for success over the other two classes from both a technical and economic point of view. The TLP concept experiences relatively little tilting motions. Results published and financed by the Research Fund for the Italian Electrical System in 2007 indicate that TLP systems could be less expensive compared to the other floating concepts.

A preliminary design was developed and evaluated from a technical and economic feasibility standpoint with reference to a large offshore wind farm with 24 turbines rated at 6MW each. The turbines were arranged in four rows of six turbines each, placed around 20km offshore in waters 200 meters deep. A general evaluation of the possible unit cost of the 144MW wind farm was calculated, and an offshore production cost of around 150€/MWh ($208/MWh) was calculated. Typical onshore wind farms have production costs of around 120€/MWh ($166/MWh). However, this general calculation is just an estimate, since annual operation and maintenance costs and annual energy production of offshore wind farms are still uncertain.

**Buoyancy Stabilized**

Buoyancy stabilized foundations or hydrostatic turbines are one of the lesser known foundations still being researched. It has also been called the floating jacket concept. The foundation uses a stabilized barge on the surface of the ocean in order to support the wind turbines. The barge is stabilized with catenary mooring lines attached to anchors on the sea bed.
This type of foundation has not found wide practical use yet due to its susceptibility to large waves and large motions due to waves. The major challenges in developing a successful design are minimizing wave loads, motion response and structural loads of the floater. The design of catenary moorings suitable for shallow waters is another engineering challenge for buoyancy stabilized systems. Foundations have been designed, derived from the oil and natural gas industry, but the gyroscopic motion of the turbine made this difficult.