Floating Wind Power in Deep Water – Competitive with Shallow-water Wind Farms?

a report by

Eystein Borgen

Sway AS

Pioneering projects with a few bottom-mounted wind turbines in shallow water were first installed over a decade ago. In the last few years several large-scale commercial offshore wind farms have been installed in the North Sea, with more to come. The European Wind Energy Association (EWEA) expects that 40GW will be installed offshore by 2020, a challenging task given the large number of turbines, the short time-frame and the harsh offshore environment to be dealt with.

The enormous potential energy resource offshore, covering more than 70% of the Earth's surface, can only be tapped into by those countries blessed with access to large shallow-water areas with good wind resources, simply because it is too expensive to install wind turbines in water more than 30–40m deep. 'Unfortunate' countries such as Spain, most of the US, Japan, Korea, Norway and many more therefore cannot expect to play a major role in the offshore renewable rally that has now emerged in northern Europe. However, is this an accurate observation?

It is true that the cost of wind turbines per MW installed increases with greater depth for fixed bottom-mounted turbines. This is because the loads (overturning moments) on the foundations increase with greater depths. The foundations therefore need to be both longer and stronger, resulting in increasing capital expenditure (CAPEX). Most observers will therefore be tempted to draw the conclusion that the cost of producing the energy will always be higher if the water depth increases. However, this is not necessarily the case.

There are two potential reasons for this. The first is easy enough to grasp: if the wind blows more strongly and more steadily further out to sea in deeper water, the additional power production will positively influence the economy and potentially offset higher investment costs. The second potential reason will be discussed below and is simply the answer to the following question: can the total costs of a windfarm actually be kept unchanged, or even reduced, when moving out to deeper water by changing the technology from fixed to floating foundations? To answer this question it is necessary to understand both the cost drivers involved and the means of increasing power production from the wind farms.

The net present value of an offshore windfarm and the cost of energy depend on several factors, such as the cost of the turbines, towers and foundations, the cost of installation, the cost of grid connection, life-cycle maintenance costs, annual power production and the price of electricity, including public subsidies and finally the risk level, which strongly influence the required rate of return on the CAPEX. All of these factors except the price of electricity and in some cases the public subsidy levels differ between offshore and onshore windfarms.

For offshore wind farms, where the turbine size is not limited by transportation on roads, the effect of the turbine size is an important factor to understand, in addition to the water depth at the location in question, for the following reasons:

- larger turbines offshore result in lower grid connection costs due to having fewer units to connect with subsea cables;
- larger turbines offshore result in fewer foundations and turbines to install and therefore normally lower installation costs than for more and smaller turbines; and
- larger turbines mean fewer units to visit during maintenance.

The problem of ever-larger turbines is the so-called square–cube law, meaning that if the rotor diameter is doubled (and therefore the swept area and power production is increased four-fold), the weight and cost of most of the turbine and tower/foundation components increase eight-fold due to the length increases in all three dimensions (we live in a 3D world). This is why the development of new structural concepts for both the turbines and the tower/foundations is required in order to considerably reduce the cost of energy by increasing the turbine size and taking advantage of the three major cost-saving factors listed above.

Most of the planned large offshore windfarms in Europe will be located in fairly deep water of 20–30m or more. In general, monopile foundations have been very successful in shallow water for smaller turbines of 2–3MW due to the simple construction and corresponding low cost of €2–3/kg steel fabricated. Jacket and tripod structures are more cumbersome to weld together and the cost of such structures is typically €5–6/kg. However, in water depths of 20–30m and with larger turbines, conventional monopile foundations become prohibitive due to the insufficient strength and stiffness they can offer. Monopiles are simply too soft, and the natural frequency of the tower may coincide with the natural frequency of the 1-per revolution (1P) rotor frequency, resulting in large and unacceptable vibrations. Therefore, new concepts such as jacket and tripod solutions are now being used for the largest offshore turbines. The latest 5MW installations have shown that for water depths of 30m or more, the jacket solution seems to offer a lower weight and cost compared with the tripod.

When shifting from a monopile foundation to a jacket, the tower/foundation stiffness increases considerably, and another rotor frequency potentially triggers tower vibrations, the so called 3-per revolution (3P) rotor frequency of a single blade passing the tower. The steel tower on top of a jacket is therefore often narrower to give the necessary flexibility to avoid 3P vibrations, but with much thicker wall thickness to maintain sufficient strength, resulting in an increased tower weight. In such a situation, slightly deeper water with a corresponding longer and more flexible jacket may in some cases actually not considerably increase the total weight and cost of the tower and foundation.

Figure 1: Tower/Foundation/Anchor Costs, Including Installation

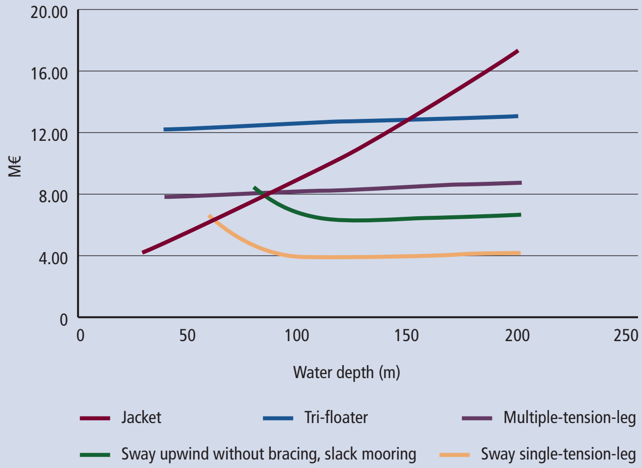
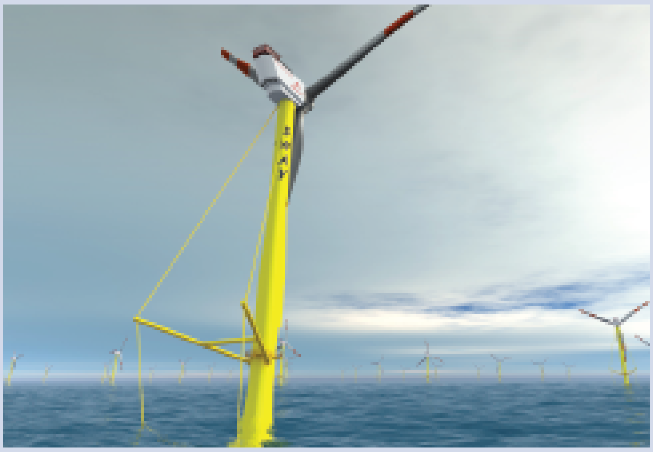


Figure 2: Wire Bracings on the Upwind Side of the Tower



It is evident that the picture of how the cost of energy changes with both the water depth and turbine size is not always very obvious. Factors such as the development of new concepts that may reduce the tower and foundation costs or increase the turbine size without a weight or cost penalty may also completely change common perceptions of the lowest possible cost of energy produced from offshore wind. Floating foundations are also one factor with the potential to change this picture.

In the oil and gas industry, bottom-fixed platform substructures were designed for ever-increasing depths in the 1970s and 1980s. Conservatism in the industry resulted in jackets being installed in water depths of more than 400m in the Gulf of Mexico in the late 1980s. This approach quickly changed when floating production vessels were accepted by industry. Today, no oil and gas company would even consider building a fixed platform in 400m water depth. It is likely we will see the same trend in offshore wind.

One of the advantages of floating wind turbines in the initial market introduction phase is that the existing learning curves and experiences from shallow-water wind turbines in most cases are directly applicable to floating turbines. At the same time, it is clear that the challenge of understanding and analysing a floating wind turbine is something quite different from understanding and analysing a bottom-fixed wind turbine. The development of special advanced computer simulation codes is fundamental to our understanding of the physical behaviour

Table 1: Comparison of Approximate Weights and Costs of Tower/Foundation/Anchor for Jacket at 30m Water Depth and Floating Systems at 120m Water Depth

	Jacket at 30m Depth[1]			Sway Single-tension-leg Floating Monopile at 120m Depth			Sway Upwind without Bracings, Slack Moorings at 120m Depth			Multiple-tension-leg at 120m Depth[3]			Tri-floater at 120m Depth[4]		
	Steel Weight (te)	€/kg	Cost (M€)	Steel Weight (te)	€/kg	Cost (M€)	Steel Weight (te)	€/kg	Cost (M€)	Steel Weight (te)	€/kg	Cost (M€)	Steel Weight (te)	€/kg	Cost (M€)
Turbine size	5MW			5MW			5MW			5MW			5MW		
Tower	210	2.5	0.53	1,050	2.5	2.63	1,800	2.5	4.5	300	2.5	0.75	300	2.5	0.75
Foundation	500	5.8	2.9	N/A[2]			N/A[2]			650	5.8	3.77	2,000	5	10
Anchor wires/ wire bracings	N/A			50	5	0.25	40	5	0.2	150	5	0.75	N/A		
Anchor chains/ clump weights	N/A			N/A			180	2	0.36	N/A			260	2	0.52
Anchors/piles	315	2	0.63	90	2	0.18	150	2	0.3	600	2	1.2	200	2	0.4
Misc. anchor system	N/A			50		0.5			0.4			0.8			0.4
Foundation and tower installation costs			0.40			0.40			0.60			0.70			0.30
Total	1,025		4.46	1,240		3.96	2,170		6.36	1,700		7.97	2,760		12.37
Relative to jacket at 30m			1			0.89			1.43			1.79			2.78

1. www.alpha-ventus.de/index.php?id=80
2. Foundation integrated and included in tower weight.
3. www.bluehusa.com/pressrelease3.aspx
4. www.principlepowerinc.com/images/PrinciplePowerWindFloatBrochure.pdf

of these concepts and the safe dimensioning of the structures. This is not an easy task that can be carried out in a few months; rather, it has proved to require years of development and engineering effort.

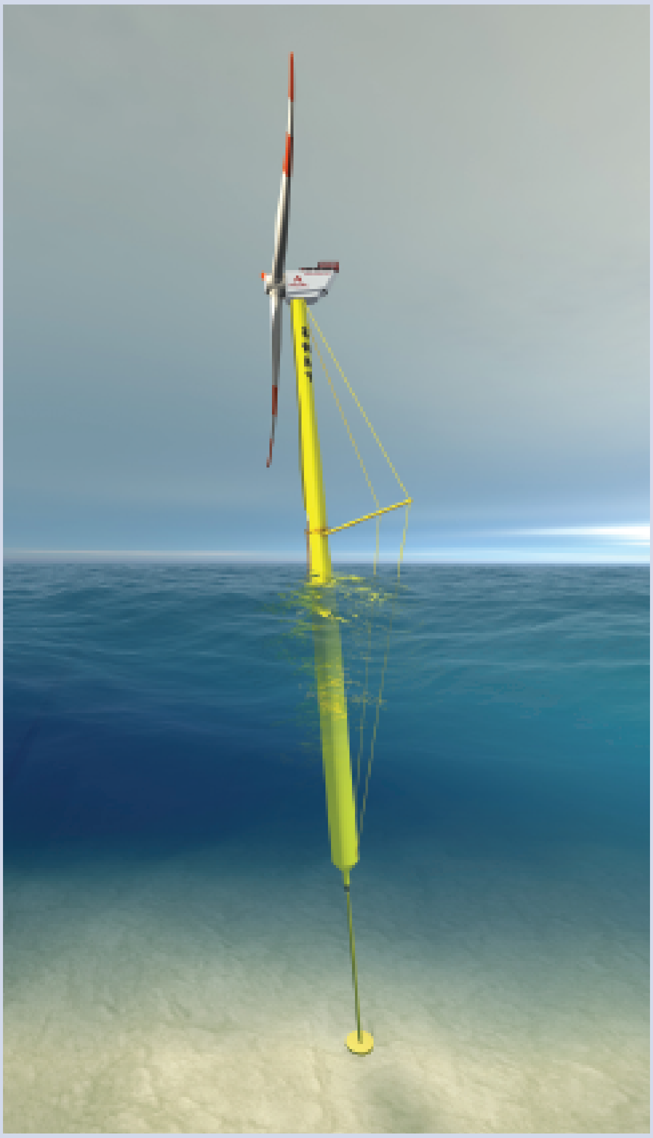
A major factor to include when simulating the behaviour of a floating wind turbine is the coupled motions of the system as a result of the relative wind interacting with the wind turbine rotor and, simultaneously, the waves interacting with the floating foundation. Commercial simulation programs that can handle such coupled motion of a floating wind turbine have not been readily available. This necessitated the development of partly in-house computer codes during the development of the first floating concepts over the last decade.

There are many good ideas 'floating' around regarding floating wind turbine concepts, and it is not an easy task for future developers and energy producers to evaluate which of the concepts will suit their projects the best. Full-scale prototypes will have to be constructed, most likely with participation from energy companies, prior to large-scale commercial deployment. By participating in the operation of the prototypes, energy companies may benefit from early market operation experience and controlling the risk prior to constructing large commercial windfarms in deep water.

Last year the first full-scale floating wind turbine was installed by Statoil off the west coast of Norway. This concept, partly licensed to Statoil by Sway, is similar to the Sway system in that it uses a monopile spar buoy tower where the wind turbine tower is extended approximately 100m below the surface. Heavy ballast is installed at the bottom of the tower, bringing the centre of gravity below the centre of floatation; this gives the tower sufficient stability to carry a 2.3MW wind turbine on top. This very important full-scale prototype project will demonstrate that this concept is safe and viable.

Several other floating wind turbine concepts such as the multiple-tension-leg platform of Blue-H and the tri-floaters of Principal Power and WindSea have been proposed. These initiatives are being funded

Figure 3: Side View of the Sway System



in-house or by investors in order to develop and commercialise the technologies, the carrot being that if the cost of energy produced from floating windfarms turns out to be interesting to energy companies, the potential for offshore renewable power production will increase dramatically worldwide.

> By participating in the operation of the prototypes, energy companies may benefit from early market operation experience.

A cost estimation (see *Table 1*) was carried out by the author based on publicly available information on steel weights for the different tower/foundation/anchor concepts and cost per kg for the type of construction in question. The costs of the anchor systems were assessed based on a rough estimation of the assumed anchor line lengths and forces in the anchor system. The installation costs were also based on estimations assuming the cost benefits of multiple installations in a 200MW windfarm. The figures should therefore only be used as a generic approximation of the relative costs of the different solutions.

In *Figure 1* the cost trends relative to different water depths are shown. In approximately 40–50m water depth, tri-floaters and multiple-tension-leg platforms can be used, but the tower and foundations seem to be more expensive than the jacket solution up to around 90m for the multiple-tension-leg platform. For the tri-floaters, the jacket seems to be more economical for even greater depths. Relative to the Sway system, the jacket seems to be the most economical alternative from 30m to about 70m depth. However, when the water depth reaches approximately 60–70m, the Sway technology will cost the same as the jacket. An interesting point is that moving into waters deeper than 70m, the cost of the Sway system actually decreases sharply, and at 100m the cost flattens out at a level below that of the jacket at only 30m water depth. The reason for this is that the Sway system (see *Figures 2* and *3*) utilises the water depth to gain its stability. To achieve the optimum stability-to-weight ratio, the tower needs a minimum water depth of approximately 100m for a 5MW turbine.

It can therefore be seen that if the water depth exceeds approximately 30–40m, it would be more economical to avoid depths between 40 and 100m and instead place the windfarms in 100–200m water depth. This may at first seem to be a paradox, but the reason behind it is that when the floaters start to compete with the jackets, the Sway-type floating monopiles, being arguably the most economical of the floating concepts, are the most energy cost-efficient at water depths greater than 100m.

As a result, it could be possible to reduce the cost of energy compared with a 30–40m depth windfarm by instead placing the windfarm further out to sea in stronger winds with a corresponding increased annual energy yield from the turbines; at the same time, the turbines will not be visible from shore, reducing issues of public conflict. This is, of course, good news for all of the countries mentioned at the beginning of this article, and countries such as Spain, the US, Japan, Korea, Norway, etc., are actually very well positioned to play a strong role in harvesting offshore wind.

Just as the monopile is the most cost-effective solution for small turbines on fixed foundations, the patented Sway elongated floating monopile seems to be the most economical solution for floating foundations for small turbines. When Sway commenced its development of the floating monopile in 2001, it was based on the very low fabrication costs of such designs compared with the more complex semi-submersible truss structures, as well as the good motion characteristics. However, it was quickly realised that for larger turbines the floating monopile solution, just as was the case for the monopile solution for fixed foundations, did not offer sufficient stiffness and strength to be cost-effective for turbines in the 4–5MW range and above. In particular, fatigue of the towers has proved to be challenging for the floating towers and foundations due to the additional motion and inertia forces compared with a fixed tower. At the same time, it was understood that it was critical to be able to install turbines in the 5–10MW range to bring down the cost of energy in the future.

> Most of the planned large offshore windfarms in Europe will be located in fairly deep water of 20–30m or more.

Sway's solution to this was to locate the yaw bearing, which is normally positioned at the top of the tower, at the bottom of the tower instead, such that the entire tower would 'weather-vane' using a down-wind orientated turbine and always keep the same side of the tower towards the wind. This made it possible to equip the tower with wire bracings (see *Figures 2* and *3*) on the upwind side of the tower, just like the wire stays of a sailboat mast, increasing the stiffness dramatically and at the same time eliminating the problem of fatigue in the tower. The Sway solution is therefore able to use the cost-effective floating monopile concept for turbines of 5–10MW and above.

The technology for cost-competitive floating wind turbines has already been developed. The next three to four years should be used to construct and operate full-scale prototypes and small pre-commercial floating windfarms. The reward of a successful deployment programme will be that in the future practically all countries with access to either shallow or deep water with good wind resources will be able to economically tap into the unlimited clean energy of offshore wind. n