OFFSHORE WIND TURBINE FOUNDATIONS

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The offshore wind turbine foundation space is going through what may be its most interesting transition to date. Monopiles, the mainstay of the offshore wind industry so far, are stretching the boundaries of what was thought technically possible.

This is leading to a rethink of how the monopile can be further optimised and expand their boundaries, with an eye on installations involving deeper waters and bigger turbines.

At the same time, however, the supremacy of monopiles is being questioned in new offshore wind markets, such as Asia or the US, where technical or commercial considerations might dictate the use of alternative designs.

Jacket foundations are already being touted as an alternative to monopiles in deeper waters, and this trend looks set to grow in markets where monopile construction is not yet consolidated.

Further forward, though, the future of offshore wind looks to be increasingly dominated by floating turbines.

It is too early to say which, if any, of the four currently mooted floating foundation concepts will emerge to dominate the offshore wind market in water depths beyond around 50 meters and with turbines of more than 12-15 MW by 2023/2025, when the first commercial-scale floating arrays are expected. It is thought, however, that barge concept will enable installation at 28m or 30 meters where challenging seabed conditions make bottom-fixed options economically not viable.

With developments taking place on so many fronts, this white paper aims to collect the latest thinking from industry experts and provide a snapshot of the foundation market today, plus its perspectives for change in the future.
**Introduction**

Offshore wind faces an obvious challenge compared to onshore installations: each turbine needs to be raised above the water by means of a foundation. This adds to the materials and installation costs involved.

By some estimates, foundations can account for up to a third of the total installed cost of an offshore wind turbine.

In mature wind farms, where foundation production and installation have been optimized, this cost is likely to be significantly lower, perhaps down to 15% or 20% of the total.

But foundations “still make up a large part of the capex” for a wind farm, according to Rhodri James, Manager of Policy & Innovation at the Carbon Trust, which leads a joint industry project called the Offshore Wind Accelerator.

“Costs have dropped, but there is not full transparency over where,” he says.

Acting against this general trend in cost reduction are two other trends in offshore wind. One is that as prime nearshore wind farm sites get taken up there is a growing need for developers to move into deeper waters further offshore.

The other, primarily driven by the cost reductions that can be achieved from installing fewer, larger machines, is a trend towards bigger and bigger wind turbines.

While the current upper limit in terms of turbine capacity is set by MHI Vestas’s 9.5 MW V164 machine, which has been selected for the Triton Knoll project, there is now talk of turbines of up to 15 MW. In fact, all leading OEMs have started the development of their new 1”X” platforms – not knowing yet what “X” stands for but very likely more than 0 – essentially at the request of asset developers and asset owners who see turbine size increase as another way to reach grid parity in a regular fashion.

A move to bigger turbines should, in theory, allow for a per-megawatt reduction in foundation costs, since fewer foundations would be required for a given level of energy production.

However, the move to bigger turbines and deeper waters also tests the limits of existing foundation design, which so far has been dominated by monopiles.

Thus, a challenge for the industry is how to transition as quickly as possible to new foundation concepts without adding significantly to overall costs.
FIXED FOUNDATIONS

To date, all the commercial offshore wind farms in the world, bar one, have used fixed foundations. There are five main concepts for fixing wind turbines to the seabed:

- **Monopiles**
- **Jackets**
- **Gravity bases**
- **Tripods**
- **Tri-piles**

Given the relatively low and decreasing penetration of tripods and tri-piles, only monopiles, jackets and gravity bases will be discussed in this analysis.

### Monopiles

Monopiles represent around four-fifths of all offshore wind foundations installed today. Their popularity is largely based on the simplicity of their design, which makes them relatively cheap and efficient to manufacture at scale.

They have also benefited from the fact that Europe’s offshore wind markets, which up until recently accounted for all the installed capacity in the world, are particularly suited to monopile installation.

Typical sites chosen for development so far have been in relatively shallow waters, often on soft but firm substrates that could help with foundation installation and stability. The concept has not been free from problems, though.

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This problem was subsequently solved through changes in connection design and is no longer an issue, according to experts. But other challenges remain.
Monopiles may suffer from internal corrosion and scouring, which can weaken the structure and threaten the stability of the turbine. Despite these challenges, though, the monopile has proved to be a remarkably versatile foundation design.

Monopiles have been deployed with ever-larger turbines in ever-deeper waters, currently up to 41 meters in the case of XXL designs.

Manufacturer EEW is said to be planning 9-meter-diameter monopiles that will take 8 MW-plus turbines at water depths beyond 60 meters. How much further monopile design will be able to go is still open to question.

The Carbon Trust’s Offshore Wind Accelerator and DONG Energy are leading a joint industry project, PISA (for Pile Soil Analysis), which aims to extend the viability of monopiles by reviewing all the variable associated with their design.

“It’s a new design methodology completely,” says Michael Stephenson, Offshore Wind Associate at the Carbon Trust.

To date, monopile design has relied on experience from the oil and gas industry, where long, thin piles can be used because the loads they support are not as dynamic as in the wind industry.

Nowadays in wind, though, “piles are so much shorter and wider that they fall outside the process design scope,” Stephenson says.

Phase I of the PISA project, looking at verifying this methodology, was completed last year. The next phase will end in Spring 2018 and Stephenson believes developers will be quick to incorporate any findings into their design methodology.

Elsewhere, more sophisticated modeling techniques could potentially bring about further monopile cost reductions by allowing foundations and turbines to be modelled as an integrated whole.

Such more accurate modelling might allow developers to discard some of their more conservative monopile design assumptions.
This in turn could perhaps allow for greater optimization that could shave something in the order of 10% to 15% off costs, says RV Ahilan, Group Director for Renewables Advisory & Energy Technology at LOC Group.

Overall, says Lars Kristensen, Senior Vice President for Wind & Renewables at the foundation manufacturer Bladt Industries, improvements to design and manufacturing might allow costs to be reduced by between 25% and 30%.

Continued cost reduction combined with increased design flexibility could help monopiles stay in the game as the offshore wind industry moves towards the installation of the 12 MW to 15 MW turbines anticipated by recent ultra-low auction pricing results in Europe.

While it is still unclear what foundation designs will be most appropriate for these massive machines, “the expectation is that the window of opportunity for monopiles is widening,” says Stephenson.

**Jackets**

Jackets were the third most widely installed foundation design in 2016. But the concept’s market share has been extending. In 2016, 12% of European offshore wind foundations were jackets, up from 3% in 2015, WindEurope data shows.

The uptick in jacket installations was due to them being chosen for the 67-turbine Wikinger project owned by Iberdrola Renovables Deutschland in Germany.

But Lorena Tremps, Structural AI Engineer for Offshore O&M at ScottishPower Renewables, another Iberdrola subsidiary, says the developer has favored jackets for most of its projects.

The decision of whether to choose jackets over monopiles “depends a lot on the project,” she says.

However, jackets are generally considered to be better than monopiles for installations where the substrate is poor and / or ‘deeper water’, because the design is less susceptible to lateral forces that might cause a monopile to tilt in soft soil.

For the same reason, jackets have been preferred for installations at depths beyond the 40 meters or so that monopiles can achieve today. “Jackets are the accepted alternative to monopiles in deeper waters,” confirms Stephenson.

Furthermore, a jacket’s greater stability will likely make it a good option for the larger, heavier turbines due on the market, which would require additional damping if placed on a monopile. The main downside to jackets is cost.

Because it has numerous welded joints, a jacket can cost up to 40% more than comparably-sized monopile.

This means that a jacket only has a limited advantage over monopiles, even for bigger turbines in deeper waters. Beyond around 60 meters in depth, for example, jackets may become prohibitively expensive (due to comparable higher fabrication and installation cost that monopile, claims Ting Sie Chui, Technical Director at COWI.)
Gravity bases

While monopiles and jackets look set to remain the foundation options of choice for most offshore wind projects, other structures are still favored in specific situations.

Gravity-based foundations, for example, are well suited to rocky sea beds where there is no danger of scouring. The design also benefits from ease of installation: it can be built on land, towed to site and then filled with water as ballast to sink onto the sea bed.

Despite this, gravity bases have fallen from grace over time. The design accounted for 25% of all foundations installed as of 2010, falling to 10.4% by 2014 and 7.5% by 2016.

Part of this may be due to offshore wind’s move into deeper waters, as early gravity base designs worked best in water depths of up to 12 meters.

The design also requires a significant amount of dry dock space per unit, which could have high set up cost for fabrication facilities and complicate large-scale production. In future, though, deep-water variants of the concept could help gravity bases make a comeback for water depths beyond around 50 meters. For example, EDF demonstrated this with five float-out gravity base designs foundations at Blyth this year, which proved the technology ahead of large scale deployment at their 498 MW Fécamp project.

Furthermore, gravity bases have also proved popular in China, where shallow waters are the norm and there is no native monopile manufacturing. The Chinese have also adopted small tripod structures for some projects in very shallow waters.

However, says Ting Sie Chui at COWI UK: “Now more wind farms in China will be using monopile in the next few years. Relatively fewer selective sites will be using jackets.”
FLOATING FOUNDATIONS

Despite efforts to adapt current foundation designs to deeper and deeper waters, most experts agree that at some point it will no longer be viable to rely on foundations that are fixed to the sea bed.

For example, says RV Ahilan: “I would be very surprised if people proposed a fixed structure for 100 meters.”

Because the sea bed drops away sharply from land in many parts of the world, this means potential offshore markets including Japan, the Mediterranean and the West Coast of the US are all likely to be beyond the reach of fixed-foundation offshore wind developments.

For these markets, floating foundations are critical. Floating foundations are only just starting to become a reality, with the first pilot plant, Hywind, currently under construction in Scotland.

“We’ve had floating 1.0, which is the initial single-unit demonstrators with wind turbines ranging from 2 to 6-8 MW,” says Bruno Geschier, Chief Sales Officer & Marketing Officer at Ideol, and Chairman of WindEurope’s Floating Task Force.

“That phase will roughly come to an end by 2020 or 2021. After that we will switch to floating wind 2.0, which is commercial arrays. Commercial-scale floating arrays will undoubtedly follow the same trends that the rest of the offshore industry will experience by 2023 onwards: arrays getting bigger, ranging between 600 to 1000MW; design lives that will exceed the current 20 to 25 years and reach 30 years plus; compatibility with the new 12-15MW wind turbines as well as a less tangible yet increasingly important parameter: the highest possible local content. All these parameters can no longer be denied or ignored as they are what all the key European (and non-European) industry stakeholders are aiming at. These parameters will shape what the floating wind industry will look like by 2023/2025 onwards as they will heavily impact floater dimensions, constructability and launchability, logistics and storage, O&M, wind turbine installation, offshore operations, etc.”

One challenge that floating foundations will have to overcome is with funding.

While lenders are comfortable with all major fixed foundation types, says Clement Weber, Director at the renewable energy financial advisers Green Giraffe, “the floating foundation concept makes enough difference to change the lenders view on the technological risk. Raising non-recourse finance for these projects will be available under strict conditions: in-depth review by the LTA, strong contractual protection, adequate insurance cover and decent contingency budget”.

At this stage of market development, four types of floating foundation design are being put forward:

- **Spar**
- **Semi-submersible**
- **Barge**
- **Tension-leg platform (TLP)**
Floating foundation designs. Source: Carbon Trust.

Of these, only the first three are at a pre-commercial stage that allows for any meaningful evaluation of capabilities.

**Spars**

Offshore wind experts agree that it is too early to tell which floating design, if any, will dominate the market. For now, the bulk of operating experience is with spar designs, which were piloted by Statoil before being scaled up for use at Hywind.

The 91-meter Hywind foundations (78m below sea level in the operational phase) were built in sections that were assembled horizontally at the quayside. After assembly, the foundations were placed onto a transportation vessel and taken to the installation site. The foundations were floated off the vessel at the installation site.

The advantages of the design are that it is based on tried-and-tested oil and gas engineering principles and looks to be a stable platform for even very large wind turbines, with a maximum operational depth of around 750 meters. It also appears to have scope for rapid cost reduction.

Based on the experience with the concept to date, “there are a lot of things we will have to optimize” for the next plant using spars, says Bjørn Ivar Bergemo, Area Manager for Tower, Substructure and Anchoring Systems, at Hywind Scotland.

Likely the biggest challenge facing further commercialization of spars is that they need a minimum water depth of at least around 95 to 100 meters.
This means that in some waters of between around 60 and 100 meters in depth there will be a requirement for an alternative floating design. For this reason, Geschier, at Ideol, predicts spars will ultimately only be able to capture around 10% to 15% of the floating offshore market.

**Semi-submersibles**

After spars, WindEurope considers the semi-submersible concept to be next in line in terms of technology readiness. The industry body predicts the technology will reach technology readiness level (TRL) 9, ready for actual application in its final form and under mission conditions, by around 2020.

Leading the development of the technology is Principle Power Inc. with the WindFloat design, which had a 2 MW demonstration off Portugal from 2011-2016 and is now planning a pre-commercial array (also in Portugal) using 3x 8.3 MW turbines, expected to be installed in 2018 or 2019. Principle Power Inc. have also been selected for one of four pilot projects in France (installed ~2020/21).
**Barges**

The French foundation maker Ideol has developed and patented a square ring barge-style concept with a central pool to dampen motion even in relatively shallow waters, this from 30 meters depth making it particularly suitable for shallow sites where bottom-fixed solutions are not economically competitive given though seabed conditions.

The company claims it is the only design that can be made from either concrete or steel, with 100% local construction, compatible with shallow draughts, existing port facilities and commonly available installation vessels.

“I see very few technologies, like ours, that will be suitable in any depth,” says Geschier.

Ahilan, at LOC Group, says: “The number-one choice in my view would be either a TLP or a spar because in both cases you almost completely neutralize the vertical motion of the turbine. In terms of documented capability, the spar is in a better position.”

Some retort to using a TLP or a spar this is that putting a 12 or 15MW machine on top will have implications on both the size and the cost of construction and installation of such technologies.

Either way, it will not be long until Ideol’s design is put to the test. The concept is slated for installation in France’s Floatgen floating wind demonstrator, which is scheduled for commissioning before 2018.

Two other projects, a 3 MW demonstrator in Japan which is currently under construction and scheduled for commissioning by August 2018 and a 24 MW project in the French Mediterranean, are slated to take Ideol barge foundations. Ideol’s technology is also at the centre of several commercial-scale arrays bot in and outside of Europe and is the only one with a commercial-scale pipeline in excess of 3GW.
Conclusions

According to figures in WindEurope’s Floating Offshore Wind Vision Statement, published in June 2017, around 80% of European offshore wind resource is at depths of more than 60 meters. Japan has a similar figure and for the US the level is 60%.

In total, this adds up to almost 7,000 GW of potential, with Taiwan adding a further 90 GW. For comparison, Europe, which accounts for practically all the offshore wind installed worldwide, had 12.6 GW of grid-connected offshore capacity in 2016. Bear in mind that these figures are based on total potential, which is not limited by several constraints that would limit deployment. However, it is true that floating wind will open new markets and opportunities for offshore wind.

This seems to indicate that, long-term, floating foundations may become the dominant substructure in offshore wind. Most experts believe the floating portion of the offshore market will grow slowly, however.

The Carbon Trust estimates around 150-200 MW by 2020/21, if slated pilot projects go ahead, and 500-1000 MW by 2025 as the first commercial projects come online. Partly this is to do with cost.

While fixed-foundation offshore wind plants are now achieving cost levels of as little as GBP£57/MWh, the costs for spar-based pilot projects are believed to be in the region of £180 to £190/MWh, says the Carbon Trust’s James. However, considerable cost reduction is expected when moving to larger scale deployments.

“Floating as a technology is clearly in its early days,” says James at the Carbon Trust, “but it’s been progressing more rapidly than people were expecting it to.”

The technology could come in at under £100/MWh within a relatively short span of time, he predicts. This would open vast new markets in places such as Asia and North America, taking the offshore wind industry to a new level altogether.
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