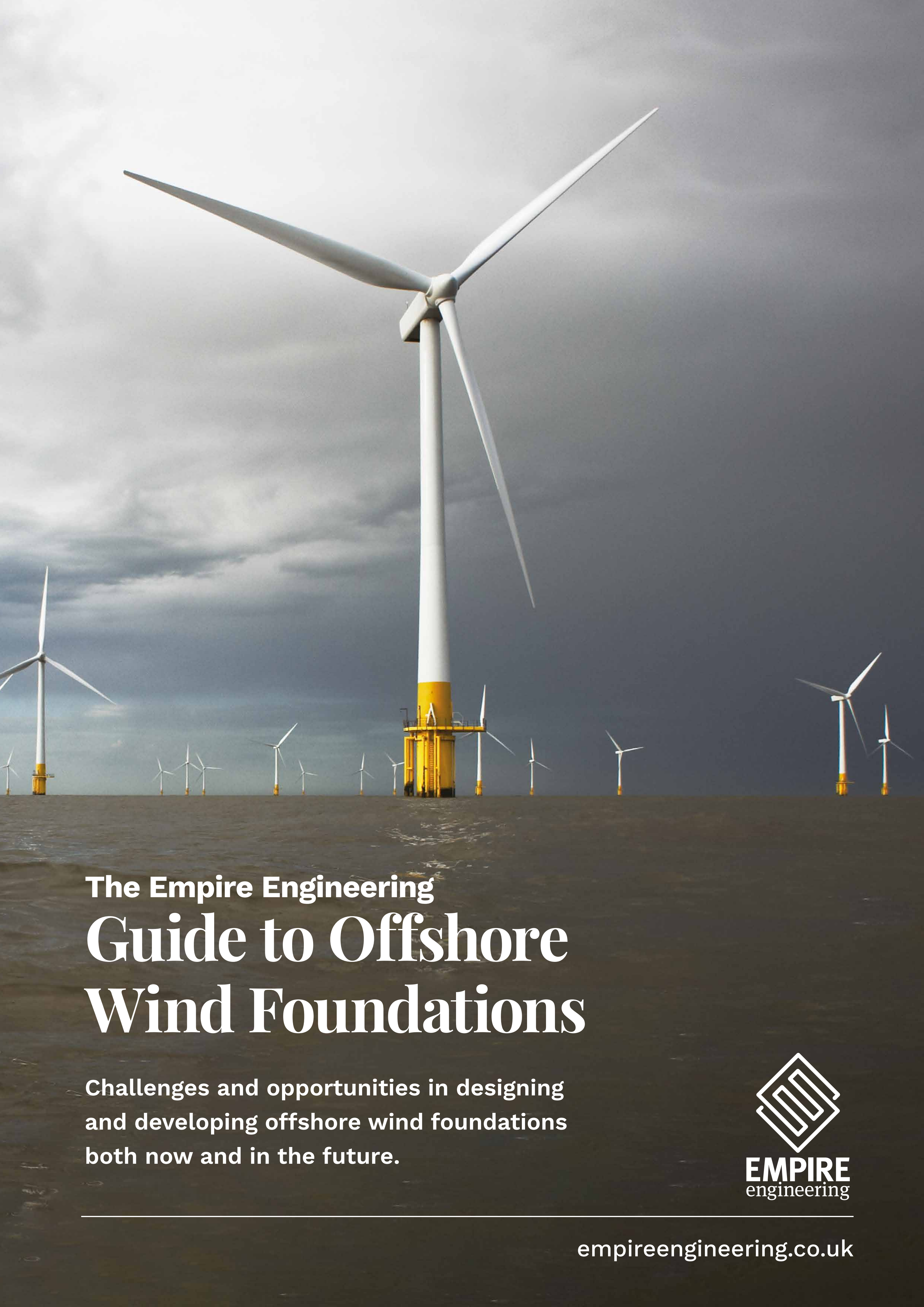

The Empire Engineering

Guide to Offshore Wind Foundations

Challenges and opportunities in designing and developing offshore wind foundations both now and in the future.

EMPIRE
engineering

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Foreword

The world's first offshore wind farm was built in 1991, just 30 years ago. Since then, those who've been in the industry have both fought and worked hard to overcome many obstacles to bring offshore wind to the point it is today – a viable alternative to fossil fuels that has an incontrovertible role in helping the world meet net-zero targets.

It's an industry I've always been proud to be a part of – it's innovative, challenging and filled with dedicated, intelligent, motivated people. What we do makes a real difference. But if we're going to expand the industry at the rate that is needed to have a meaningful impact on the current climate crisis, we need skilled people. And we need lots of them, around the world.

We need the expertise from Oil and Gas (O&G) industries, we need new graduates, we need people from different disciplines and with diverse perspectives, and they need offshore wind-specific knowledge.

Through our series of 'Tech Sessions', our training courses, and our first-of-its-kind conference that focuses on wind turbine foundation technical challenges, we've been able to both learn and share our knowledge as experienced experts. The conversations and the insights that I've had have been brilliant! We've only been able to do it because of the generosity of others in our industry who share our dedication to renewable energy and offshore wind, and who are willing to share what they know.

This guide was put together to share some of what we've learnt about offshore wind foundations over the years. If you're new to offshore wind and are starting on your first project, I hope this guide is useful in helping you understand the industry and some key technical challenges we're facing related to foundation design. If you're considering moving into the industry, hopefully this guide gives you an idea of the opportunities there are to flex your problem-solving skills and make that difference.

Karl Davis,
Managing Director of Empire Engineering

Karl Davis

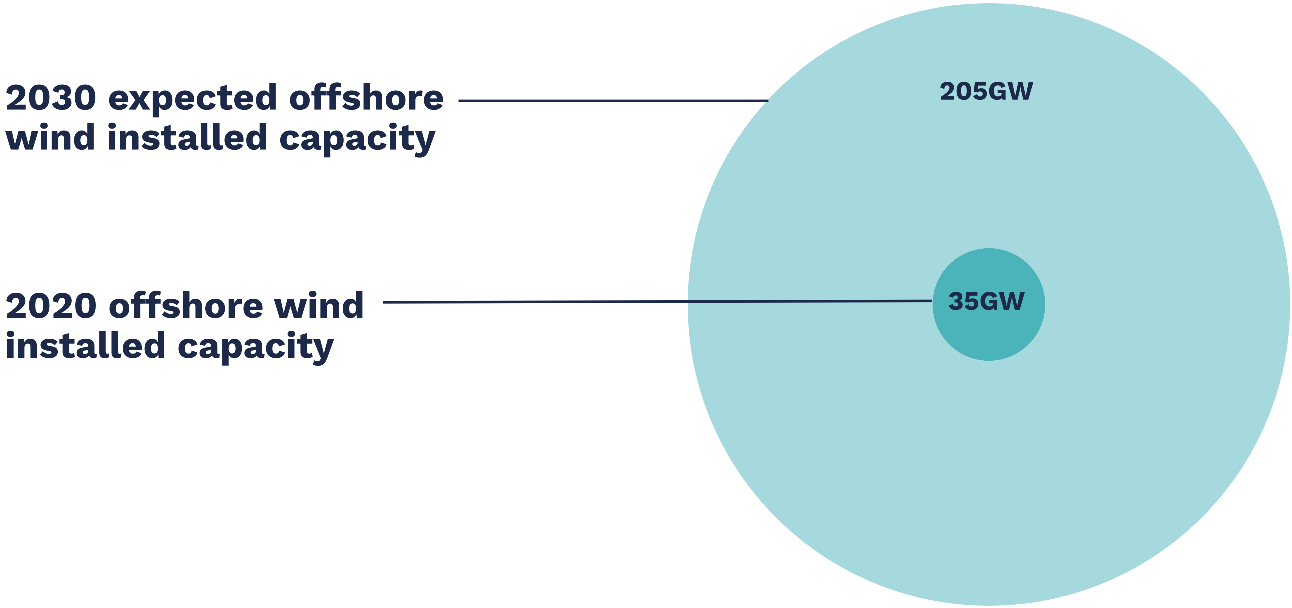
Introduction

By 2030, it's expected that there will be 205GW of power generated by Offshore Wind Farms (OWFs) globally. As of the end of 2020, there was 35GW installed, most of it in Europe; it took 30 years to do. Over the next decade, the offshore wind industry is expected to achieve over 5 times that. This growth will be global, although most of it will be in the Northern Hemisphere. In 2020, a total of 6GW was installed; this is incredible, but provides perspective on the task we face in this industry.

For wind turbine foundation designers, some of the biggest challenges over the next decade will be the shift from shallower sites to deeper water, and a move into new markets where supply chains are not yet established. Offshore wind has become competitive with fossil fuel alternatives, but how do we keep it this way in deeper sites and different markets?

This guide examines some of the technical, operational and logistical challenges we're already dealing with as designers now, and what we may face in the future. It also takes some of the key lessons we've learnt in our time in the industry and explores opportunities that can support us in reaching our goals.

The ambitions for offshore wind have never been as high, and neither have the stakes. If we're to cut carbon emissions in any real way, we need offshore wind to succeed. The task before us is immense and exciting.



The big questions

Although this guide focuses on offshore wind foundations, it's impossible to consider the future of their design without considering the industry as a whole. There are rapid global changes to the market and new technologies on the horizon. We don't have the answers to many of the questions these changes pose, but we can and must reflect on how the answers could impact the choice and design of offshore wind foundations in the coming years.

Will offshore wind subsidies continue?

How will offshore wind grow globally?

Can bolted MP-TP connections work for future XXL monopiles?

How will supply chains cope with increased demand?

How do we meet skill shortages over the next decade?

How big will turbines get?

Will we still need jacket foundations in the future?

Which countries will develop fabrication capabilities for offshore wind?

How will the demand for specialised transport and installation vessels be met?

Would it be better to focus on getting cheaper turbines than bigger ones?

What will climate change mean for future offshore wind farm developments?

Could floating wind foundations bring down O&M costs?

How quickly can floating wind become competitive with other foundation types?

Offshore wind foundations now

Of the 35GW of offshore wind power installed around the world at the end of 2020, over two thirds is in wind farms off the UK, Germany and China. The overwhelming majority of these wind farms use monopile foundations. Typically, if you're developing an offshore wind farm now, you're choosing between a monopile, jacket, or gravity base structures.

The dominance of monopiles

The end of the monopile has been predicted more than once since it became the foundation-type-of-choice in the offshore wind farm sector. As the sites for offshore wind farms grew deeper, it was predicted that monopiles would be replaced by jackets. Now it's thought that floating foundations will replace them. Yet monopiles remain the most common and cost-effective choice for offshore wind foundations right now. In 2020 around 80% of offshore wind turbine foundations were monopiles[1].

Innovation and the evolution of monopile designs have kept them cost-competitive in ever-deeper waters. Today, wind turbines are being installed on monopile foundations at sites with water depths we would have consigned to jackets less than a decade ago. Until recently, a seabed sufficiently soft for pile-driving yet firm enough to provide stability was another requirement for monopiles, but even that is being challenged with the first drilled and grouted monopiles being installed off the coast of France.

Monopiles will be here for a while yet, and we consider how they may develop in "*Evolving foundation designs*" on p.20.

"We'll always choose monopiles unless they're not feasible, because jacket costs are much higher than people think. Most of the projects that have had a crack at the serial production of jackets have had big cost overruns. From a project risk point of view, people go for monopiles wherever they can because they're a known technology that we can produce lots of."

Karl Davis,
MD of Empire Engineering

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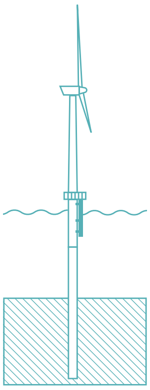
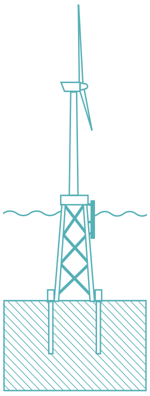
[1] 2020 offshore wind in Europe key trends and statistics



Monopiles

Monopiles currently dominate offshore wind sites around the world. Being circular, they are far easier to design and analyse than other foundation types. A proven technology with mature supply chains, they can be mass produced and the vessels to transport and install them already exist.

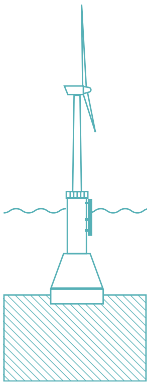
Depths: From around 10m to 55m



Jackets

Jackets are more complex and labour intensive to fabricate and install than monopiles. However, they are more tolerant of varied geotechnical conditions, and can be used in much deeper water. They are also stiffer structures and require less steel than monopiles for deeper water locations.

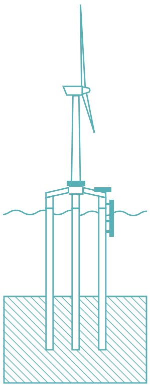
Depths: From around 40m to 100m



Gravity base structures

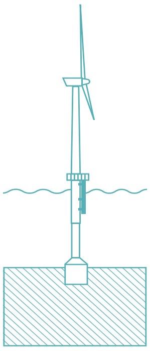
Gravity Base Structures (GBS) are the oldest and simplest foundation type, relying on the weight of the ballasted concrete base to provide stability. The volume of materials needed for depths beyond 35m makes them very expensive for deep-water sites. The fabrication and installation requirements are totally different to other fixed-bottom foundations.

Depths: From around 15m to 40m



Tripods and tripiles

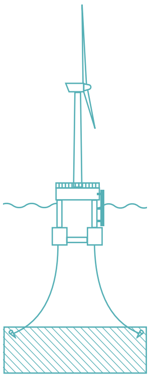
The use of these is rare, as they have not proven to be cost-effective options for offshore wind.



Suction bucket

Suction buckets need very specific seabed conditions. They don't require any pile-driving or drilling and offer the advantages of silent installation and being fully removable at decommissioning, compared with jackets and monopiles which are typically cut off just below the mudline.

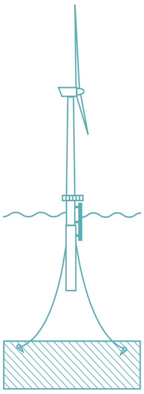
Depths: From around 10m to 55m



Semi-submersible floater

Semi-submersibles consist of multiple columns, to provide hydrostatic stability and multiple pontoons to provide additional buoyancy. The foundation is kept in position by catenary or taut spread mooring lines and drag anchors. While the motion of a semi-submersible is a salient design challenge, it's suitable for a wide range of water depths.

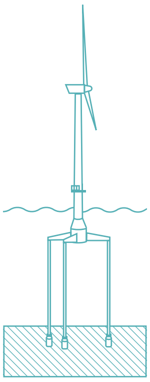
Depths: From around 40m



Spar floater

The spar concept is a large deep draft floating cylinder with a low waterplane area, ballasted to keep the centre of gravity below the centre of buoyancy. The foundation is kept in position by catenary or taut spread mooring lines with drag or suction anchors. A spar has good stability, and its design is simpler than the semi-submersible, but fabrication, transportation and installation are more challenging because of its tall structure.

Depths: Usually from 100m



Tension-leg platform

A Tension-Leg Platform (TLP) is a vertically moored platform. Like a semi-submersible, the TLP consists of columns and pontoons. The TLP's unique feature is the mooring system, which consists of vertical tendons which restrain the heave motion, but the TLP is laterally compliant and will surge, sway and yaw. A TLP also has good stability and can be used in a range of water depths, but its construction and anchoring system costs are higher than other floater designs.

Depths: From around 40m

We asked 100 industry professionals which floating offshore wind foundation they think will dominate:
70% opted for semi-submersible.

How do you decide on your foundation concept?

When developing an offshore wind farm, selecting the foundation type is one of the most complex questions a developer has to consider at a very early stage. The fast-evolving offshore wind industry has provided plenty of options, including conventional foundation types and innovative ideas, but how do you make the decision?

The real question is, given your specific site and your choice of turbine, **what foundation type will yield the lowest life cycle cost at the lowest risk to your project?** There are literally hundreds of factors to consider, from local manufacturing capabilities to the availability of installation vessels.

In the concept design and selection phase, it's critical for developers to have a systematic way of listing all the potential risks and costs to consider so that foundation options can be assessed in a quantitative way. The weight of each factor can then be adjusted according to the demands of the project.

Key considerations for designers:

01. The water depth of the site
02. The composition of the seabed
03. The Metocean conditions
04. The proposed turbines

Secondary considerations:

05. Local fabrication capabilities
06. Transport and Installation strategies (T&I)
07. Operations and Maintenance (O&M) strategies
08. Decommissioning concerns

It's important to consider fabrication, transportation and installation but at this stage there won't necessarily be a lot of details. If you do have the detail, consider it because it offers opportunities for optimisation that you don't often get this early on (more on the benefits of life cycle design on p.31). If you don't have the details you still need to consider how the big picture will be influenced by procurement strategies, political constraints or the fabrication capacity of a country or market.

01

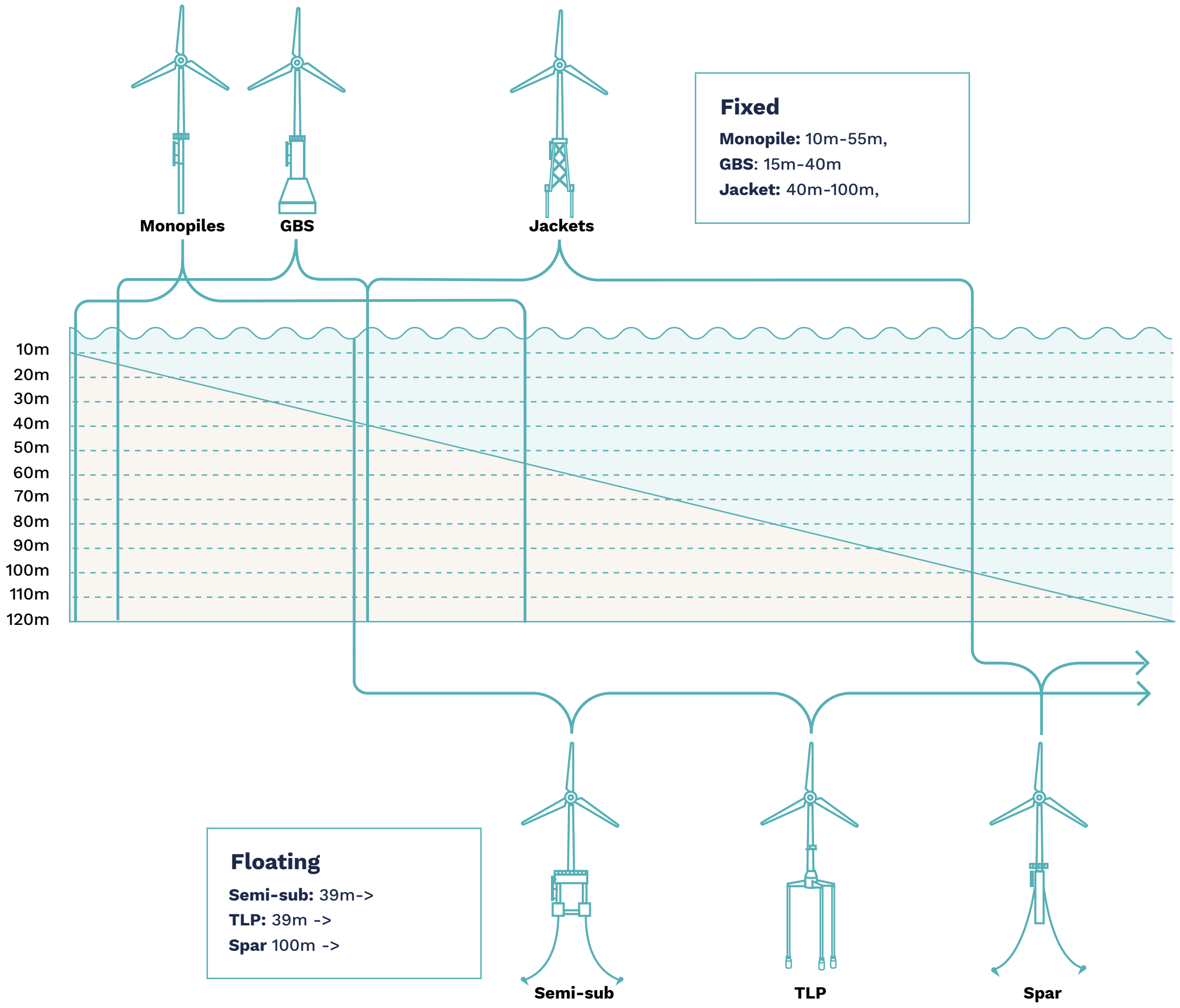
The water depth of the site

Water depth is an obvious and critical factor. Accessible shallow-water sites have already been exhausted in some parts of the world, and around 80% of global offshore wind resources are in water over 60m.

Water deeper than 25m will usually eliminate gravity base structures from your foundation options; deeper than that and they become very expensive. Ten years ago, sites deeper than 30m would have excluded monopiles too, but not today. Now, being able to install monopiles in water up to 45–50m is not a question, and it's widely believed that the monopile could be used in waters up to 60–70m in the future, given the right conditions (see p.20 for more on "*How deep can monopiles go?*").

The jacket is currently the most versatile foundation type for medium water depth (50–80m). Technically it could be used at depths up to 200m,
as it already has been in the O&G industries, but cost-wise this wouldn't be feasible for wind farms at these depths.

Although floating wind turbines could technically be installed in water as shallow as 30m, its difficult to envisage them being competitive with fixed foundations in less than 80m of water depth. Deeper than 80m and jackets or floating foundations are your only feasible options, and floating foundations really come in to their own beyond 100m, where jackets will become very large and expensive.



02

The composition of the seabed

The geotechnical conditions at a wind farm site are critical to foundation design decisions. Weak soils can lead to excessive pile penetration and hard layers can limit pile drivability. For monopiles in deeper water, you want a stiff soil to help with increasing the natural frequency, but not too stiff to make drivability an issue, which might force you to use alternative installation techniques such as drive-drill-drive or even drilled and grouted monopiles, as are planned for some French sites.

Gravity based structures and suction buckets are extremely dependent on ground conditions too. Large boulders or a very mobile seabed won’t work for suction buckets, and gravity base structures require a relatively flat seabed and often seabed preparation, which can add to costs.

03

The Metocean conditions

Obviously the Metocean conditions of the wind farm site are critical for the design of the foundations themselves, specifically for analysing the loads they will be subjected to. However, they are significant to your foundation selection process in other ways too. Conditions at sea dictate the windows you will have to work offshore and the type of work you can do. For example, some sites are deemed unworkable for installation during the winter months. This will have repercussions on your schedule.

04

The proposed turbines

The bigger the turbines, the bigger the rotors, the more loading the foundations must be able to withstand. In theory, any of the foundation types could accommodate the greater loading – they would just have to be bigger. So, for a monopile to sustain the extra load it would have to have a larger diameter, wall thickness and embedment depth so that it could go deeper into the ground. The increased size and mass would in turn have implications for fabrication, transport and installation. Jackets are fundamentally better at dealing with increasing loads from larger turbines, and they offer much greater stiffness at increasing water depths, but manufacturing large numbers of very big jackets presents its own challenges.

05

Local fabrication capabilities

Where is the foundation going to be built? Will the foundation be built in one single piece in one yard or in modular sections? Are there local facilities that can make the type of foundations you are considering, or will you need a specialist fabricator? If local capabilities don't exist, could you develop them? Usually, with the scale of offshore wind structures, they need to be fabricated close to or at a port, as transporting them on land isn't feasible. Often there are political constraints that limit your fabrication options too, for example you may be bound to use a certain amount of local skills and materials. Gravity base structures are often considered as they may afford an opportunity for local fabrication, although typically the time required to develop these local facilities isn't compatible with project timelines.

06

Transport and installation (T&I) strategies

Depending on the location of the fabrication yard, transport can be more or less complex. Are local ports feasible to store and loadout the foundation? Could they accommodate floating foundations or pre-ballasted gravity base structures that can be wet-towed? Will the foundations require Heavy Lifting Vessels (HLVs) or jack-up vessels to install? Will these be available? What are the weight and height limits of the cranes? If your jackets or monopiles are fabricated in the Middle East or Asia, how will the transportation affect the fatigue life of the structures?

07

Operations and maintenance (O&M) strategies

Operation and Maintenance (O&M) requirements are a nice-to-have at the early planning stages of a project, but these requirements are not usually going to make a huge difference between one concept or another. There are perhaps two caveats to add here. Firstly, the decision between conventional MP/TP and TP-less monopiles may be driven by O&M costs (more on that on p.25). Secondly, the step change between fixed and floating structures can also have significant O&M implications that are worth considering.

08

Decommissioning concerns

Can the foundation be fully decommissioned? Does it need to be? Would leaving it in place have a serious environmental impact? Different decommissioning processes will have different costs associated with them. For example, suction buckets offer easier deinstallation and no materials are left in place.

Future foundations: thinking ahead

There are a number of market trends and new technologies that will have an impact on the offshore wind industry and foundation design over the next decade. This section considers what they are and how we need to adapt and evolve our designs to meet what has always been our biggest challenge – reducing the Levelised Cost of Energy (LCOE) for offshore wind.

Expansion into new regions

Offshore wind is no longer niche and restricted to Europe. In 2019, China installed more capacity than any other country, and Taiwan, Japan, South Korea and Vietnam are all investing in developing OWF and their own supply chains, as are the USA and to a lesser extent Canada. Other countries like Brazil, Mexico, India, Sri Lanka, Australia and others are preparing the necessary systems, legislation and partnerships to take advantage of offshore wind in the near future. These new markets will drive technological advances because it will be a much bigger industry.

In countries such as the UK, Germany and China, where offshore wind is well established, many of the shallower sites have already been developed, and with 80% of the world's offshore wind resource potential lying in waters deeper than 60m[2], there will be a drive to develop economical foundation designs for deeper waters (more on that on p.20).

> "The speed of offshore wind development in Asia is tremendous. Taiwan, Japan, South Korea and Vietnam have all picked up the game aiming for net-zero in the near future. However, local content requirements are always a huge barrier for developers to cross over since most of the work still relies on European consultancies and contractors."

Wei-Ting Hsu,
Structural Engineer at Empire Engineering

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[2] NREL, EIC Global Offshore Wind Report 2019: Norwep, Equinor, internal analysis

Turbine sizes

Wind turbines are increasing in size for increased capacity and power efficiency. The next big turbine to be installed will be the 14MW Siemens Gamesa, which has a 222m rotor diameter with 108m-long blades and will be ready for serial production in 2024. Following close behind it are even bigger turbines from Vestas, with a 20MW turbine seen as inevitable. The greater size means greater weight and height, which has knock-on effects for the cost and complexity of foundation fabrication, transport and installation.

The question is at what point will monopiles no longer be an option for these massive turbines? Will floating wind be more suitable and competitive as turbines get even bigger? Or will turbine size be limited by feasible foundation design? Also, would it be better for the cost of energy if the industry was to focus on producing cheaper turbines rather than bigger ones? In the end it will be about what is most cost-efficient, which might not be ever-bigger turbines.

> “It’s an interesting perspective that floaters could be much more competitive when you go truly big, and we might be coming towards some sort of limit to fixed-bottom foundations with 15- to 20-megawatt turbines. Although I expect it will be possible to manufacture and install monopiles for a bigger turbine, it would be so cumbersome and expensive that the limit would be a financial one. Bigger turbines might be where floating starts to compete, because cost-wise, floating really still struggles to compete right now. You only want to use these if you can’t make a monopile work. The question is: just how far can we push the monopile in certain locations”

Karl Davis,
Managing Director of Empire Engineering

The commercialisation of floating foundations

Floating offshore wind is predicted to reach commercialisation by 2030, by which stage it's anticipated there will be 6GW installed globally[3]. The current LCOE for floating wind can be 2 to 3 times that of fixed wind because the CapEx costs are high. Although floating wind can't currently compete with fixed foundations in depths below 90m–100m, and the facilities for the serial production of floating foundations is yet to be developed, there is currently a lot of investment and excitement around floating offshore wind.

> "Based on many industry forecasts, the cost of floating wind could drop by around 70% by 2030. Given that right now the cost of floating can be up to three times higher than fixed-bottom, this will make floating wind financially competitive in the future."

Aaron Zigeng Du,
Head of Empire Engineering's
London Office

Portugal, UK, France and Japan are leading the way in floating wind development, while Norway, Denmark, the USA and South Korea are in close pursuit.

New players in the industry

As the shift to renewable energy gathers pace, the industry is likely to attract more developers and suppliers with floating skills from the O&G industries around the world. These companies could further accelerate the development of floating foundation types.

It's also likely that smaller outfits in marine services will take advantage of the very different opportunities that will come with the growth of floating wind. Coming from various backgrounds and bringing with them a variety of experiences, they should be able to inject some competition and hopefully innovation into the offshore wind industry as a whole.

> "We haven't really had a radical change in technology throughout our journey in offshore wind. The turbines we have today, although obviously very much bigger, are pretty much based on the concept of a sub-one-megawatt onshore wind turbine. If you think about the potential for innovation over the longer term – because we're not going to solve our climate change problems in the next 5 to 10 years, this is a long journey that we're on – then it could be quite fascinating if we got new OEMs and other players coming into the industry on the back of floating wind. That might shake things up a bit."

Sally Shenton,
Director of Generating
Better Limited

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[3] p.96 GWEC's Global Offshore Wind Report 2020

A shift to life extension

A number of existing wind farms are approaching the end of their original design lives. As the CapEx of these assets should now have been paid off, there will be a natural tendency to try and extend the life and eek out every last joule of energy. This will present some interesting new challenges to the industry: finding ways to safely operate aging infrastructure in arduous environments, or looking at re-powering existing sites.

AI and IoT

The offshore wind industry has embraced cutting-edge technologies such as Artificial Intelligence (AI), Internet of Things (IoT), machine learning and blockchain to improve the efficiency of power generation, increase turbine reliability and reduce operation and maintenance costs. The advances made in these areas will continue to make offshore wind more competitive.

Hydrogen and other new energy technologies

The evolution of technologies such as hydrogen could make offshore wind more cost effective and increase the capacity for storing energy generated by offshore wind. Rather than the expensive large-diameter electricity export cables that run onshore from wind farms, we could potentially use tubes to transport hydrogen onshore instead. Given that it may be easier to fit hydrogen electrolysis systems on a floating wind system than on a fixed one, this could possibly alter the demand and adoption of floating wind.

The current LCOE for floating wind can be 2 to 3 times that of fixed wind because the CapEx costs are high. Although floating wind can't currently compete with fixed foundations in depths below 90m–100m, and the facilities for the serial production of floating foundations is yet to be developed, there is currently a lot of investment and excitement around floating offshore wind.

> "Offshore wind farms produce a vast amount of data. Everyone in the industry knows that this data can be valuable, but unlocking their value has proven a slow and bumpy process. So far, the WTG energy yield and Rotor-Nacelle structural performance have attracted more attention. But we must remember that monitoring data can offer valuable insights into the behaviour of the support structure and the soil too. Probably the biggest hurdles to overcome at this stage are data storing and management issues, data availability across the industry and, last but not least, identifying the most important goals to pursue, especially related to risk mitigation and O&M cost reduction. "

Eleni Minga,
Lead Fathom Developer and
Structural Engineer at
Empire Engineering

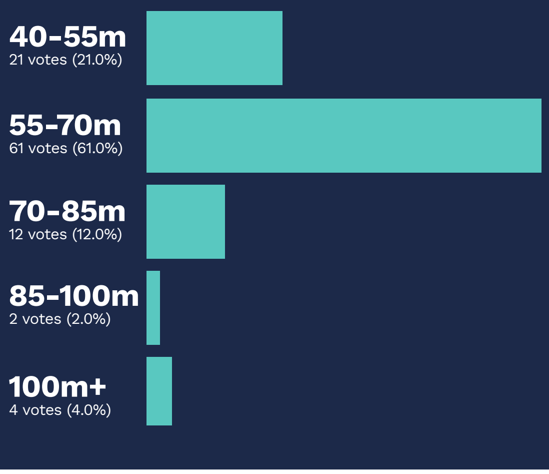
Evolving foundations designs

How deep can monopiles go?

Going back 10 years, the general view was that the monopile was a foundation choice for relatively shallow waters of 20m–30m. Today we can put monopiles in at 45m without question, which we couldn't do just 5 years ago, and projects with 10MW+ turbines in 55m+ of water are not out of the question.

So, how deep will the monopile go? It's not a simple question to answer. Our designs and design methodologies have improved a lot in terms of what we can do now. But there are other things we have to consider. Can we meet the requirements of ever-bigger turbines in deep waters? What are we capable of fabricating? Can we transport them? Can we install them?

In a recent poll we did, 60% of industry professionals agreed that the monopile could and would reach 55m to 70m depths. 4% said it could reach 100m.



Design and fabrication

To make a monopile for deeper waters, with larger and heavier turbines, we need longer monopiles with larger diameters and thicker walls. Length is not typically a limitation, but maximum diameter can be. Currently fabricators can roll a monopile with a 10m diameter, and facilities that can roll 14m monopiles are being developed.

Then there's the diameter to thickness (D/t) ratio of the monopile to consider. This is a measure of the fragility of the structure. As we push diameters higher, our minimum thicknesses also increase, leading to very heavy structures, with wall thicknesses of 120mm+. The ability to fabricate these simply doesn't exist in many markets, and where it does, it's expensive. Take the USA as an example: currently monopiles fabricated in the US have a maximum of 80mm wall thickness. Whilst this is expected to change, it will be quite some time before fabrication capabilities catch-up with where designers are likely to want to go.

Using thicker plates will also take us into new territory in terms of fracture mechanics.

> "The use of 100 or 120mm-thick plates for the larger monopile diameters is both driven and limited by the existing D/t ratios used in the codes. But I think that this is an area where we can try and push that a little bit, because the D/t on a 12m monopile has a significantly lower limit on thickness. We can certainly do more research around how a 10 or 12m monopile reacts to thickness of 70 and 80mm. We could even push that D/t limit out to 150, 160mm or potentially further."

Dr Alan Marson,
Principal Engineer at Empire Engineering

Turbine and tower designs

Keeping the structure's natural frequency sufficiently high in increasing water depths is a challenge. Wind Turbine Generator (WTG) manufacturers specify an allowable frequency range for the combined foundation-tower-turbine structure. This effectively puts a hard limit on how far we can push the monopile in terms of water depth for a given turbine. As turbine towers get taller to keep those ever-growing blades well clear of the water, keeping a monopile within this range becomes more difficult.

One way to address this is by designing stiffer turbine towers, which typically requires increased diameter. Reducing fatigue loads via tuned mass dampers can help too. The key here is for WTG suppliers and foundations designers to collaborate and design an integrated structure from pile tip to the WTG nacelle. Advances are being made in this area, but more can be done, and if WTG manufacturers were to relax these requirements it would have a big impact.

> "We've been living with slender monopiles for so long and using simple SN curves to predict what will happen in our structures. But going to thicker walls, we're fast moving into probabilistic fracture mechanics, because we don't know what happens at 120mm+ wall thickness, and the engineer's task to foresee what will happen becomes much more profound. For example, when you weld two sections of 120mm together, what is the consequence of that? The responsibility of that can't be put on the fabricator alone."

Morten Tobias Lind,
Engineering Manager at Copenhagen Offshore Partners

For further reading visit our full article on *How deep can the monopile go in offshore wind?*

The simple mass of the nacelle is also really important, as that has a big impact on the structure's natural frequency – light nacelles make your life easier. Then there are the WTG control algorithms. Clever controls can widen the frequency band the foundations can be designed for, and also reduce the loads on the foundation. This all comes at a cost to energy production, so there is a trade-off between maintaining an economical foundation design and extracting maximum energy from the wind.

Transport

How to transport longer, heavier monopiles is another challenge we'll have to deal with in deeper sites. Besides having vessels and cranes that are big enough to handle larger monopiles, there's the integrity of the monopile during transportation to consider. The longer and heavier the monopile, the more complicated it becomes in terms of the overhangs on the vessel, the spans and the local stresses induced by the sea fastenings.

Could floating monopiles out to site be an option in the future? We know it's been done in the past, but the risks of leaking end seals and tales of lost monopiles have put most developers off this option.

Installation

Lifting and driving become difficult when you get really big. Most of the existing fleet of jack-up installation vessels were limited to about 1000Te monopiles, although their cranes have been upgraded to push these limits and jack-up legs extended to go into deeper water. Recently installers have gone to floating installation, but this comes with its own challenges, particularly in terms of weather limitations.

In terms of driving the monopile, IHC and Menck keep building bigger hammers, but right now, there isn't a hammer to drive these proposed XXL monopiles. Developing and building hammers takes time, and there might be technical size limitations. Also, the risks of buckling increase as the D/t ratios go up. We're already seeing alternatives to driving, such as drilling and filling with concrete or grout, and there are other technologies with potential, such as vibrodriving in sites with suitable soil conditions.

Our engineering intuition is that on a site with favourable soils and Metocean conditions, and working with a cooperative WTG supplier, putting a 10MW turbine on a monopile in 55-65m of water is possible, provided you can find a way to transport, handle and install a monopile with a diameter of 10-12m.

> "I think we can probably get some of the smaller turbines – the 8MW ones – out to around 65m if you push them out to 12 or even 14m in diameter. Because then your D/t ratios mean that you end up with a really thick monopile anyway, so loads actually don't concern you so much. Also, if you're hitting some resonances from the turbines, you can deal with that a lot easier. But I think as we go to the bigger turbines, the 15MW, maybe even the 20MWs, I think you'll see the limit coming back in to about 50 to 55m because those turbines are going to be so much heavier and so much more difficult to deal with from a design perspective."

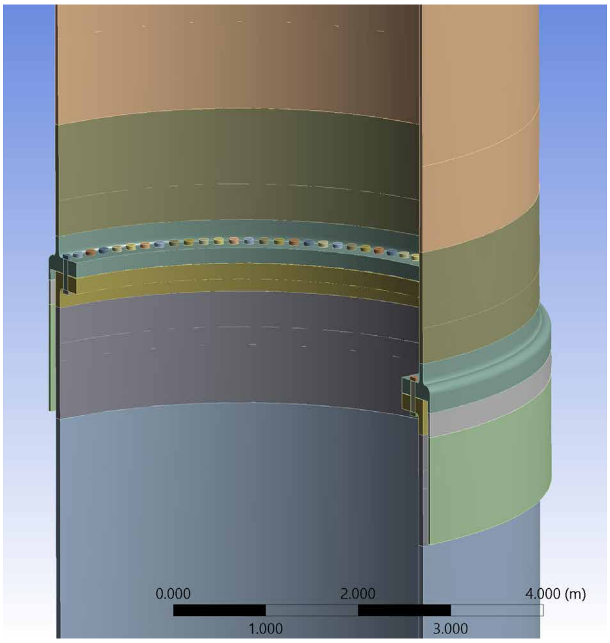
Karl Davis,
Managing Director at Empire Engineering

Can bolted connections work for the next generation of MP-TP interfaces?

A challenge for the future of monopile designs centres on the interface between the monopile and the wind turbine tower. Until recently, monopiles have always been designed with a Transition Piece (TP). In the early days the connection between the monopile and the transition piece – the MP-TP – was grouted. In more recent years, following some issues that were experienced with grouted connections, engineers have opted for a flanged connected with bolts, which do offer benefits of being easy to inspect and replace.

However, bolted flanged connections present their own challenges as monopile diameters and wall thicknesses increase. Some believe that the days of the bolted connection are numbered and we should be looking to other technologies – like crimping, slip joints or new welding technologies – to solve the issues that the bolted connection on XXL monopiles present.

Below: Finite Element model of a bolted MP-TP flange connection

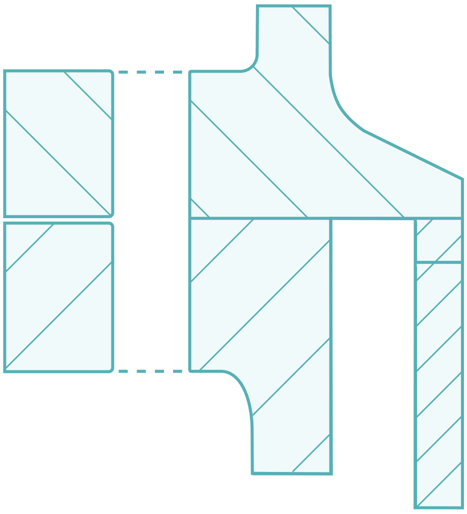


Bolted connections and the alternatives

Most designers consider the top-of-the-range M72 HV bolts to be inadequate to provide the required preload within the huge joints that will be needed by the next generation of wind turbines. Already designers are finding that some deviation from the standards with regards to the waviness or run-out tolerance of the flange is required to get the connections to work, and a lot of analysis to justify our decisions.

Although bolts up to M80 will be on the market within the next year or two (and are already being used in foundation designs), and bolt manufacturers can go up to M100 if required, the issue that arises is that these deviate from the standards and norms that everyone is designing and fabricating to. And although the strict tolerances set out in the standards were devised for slender monopiles with far smaller diameter and wall thicknesses some 15 to 20 years ago, a more recent investigation has found that rather than being too strict, the tolerances may in fact not be strict enough for modern monopile connections. This is because the thickness of the monopile walls makes it harder to close the gaps between the flanges.

Below: MP-TP flange cross section



For further reading visit our full article on *Does the monopile transition piece have a future in offshore wind?*

Bigger monopiles are only going to increase the amount of hammer force required. And even if you were to have a TP-less design, you would only remove one of these connections and then be driving on the connection between the monopile and the turbine tower.

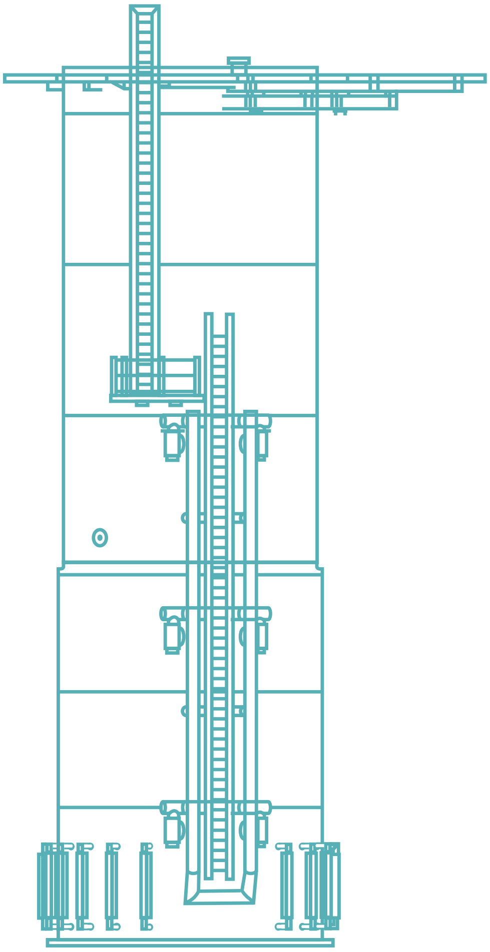
And are HV bolts really the best solution anyway? They were originally adopted because they were available. Whichever way we end up going on this, there will need an industry-wide discussion if the standards are to accommodate new practices, whether they're bigger bolts or alternative connection methods and technologies.

Are TP-less monopiles the way forward?

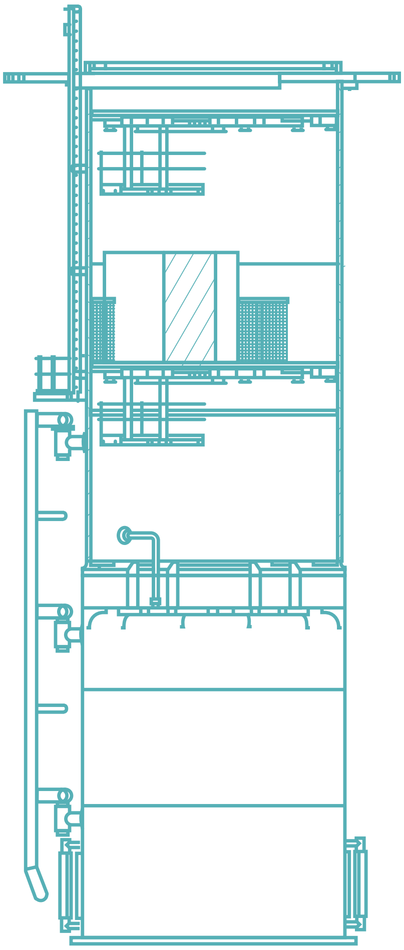
TP's were originally used to correct the out-of-verticality of a driven monopile, to meet the verticality requirement of the Wind Turbine manufacturer. With experience, monopile installers have got very good at driving monopiles in straight, so this need has fallen away.

One solution to the bolted connection issue would be to get rid of the TP. Monopiles without TPs were first used in 2004 on Scroby Sands OWF and have recently seen something of a renaissance. As the integrity of the connection between the MP-TP always carries some risk and the connections require time and resource in terms of installation and maintenance, there are some strong arguments favouring the TP-less design.

Below: External Components



Below: Internal Components



Traditionally the TP, including internal and external platforms, switchgear, cable hang-offs, anodes and boat landing, is installed once the monopile has been driven in place. With a TP-less monopile, these components would have to be attached directly to the monopile offshore.

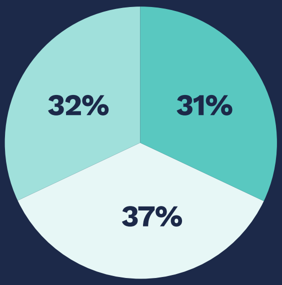
One of the potential risks around TP-less designs is therefore driving damage on attachments for the secondary steel. However, this issue also exists for traditional TP-MP designs and is nothing that careful detailing and good engineering can't address.

Another risk to potential cost savings lies in offshore installation. Designers would need to work with installers to ensure the final design is workable offshore. Designs would need to take into account how the components stack on the installation vessel, the lifting times, sequences required and how construction and fastenings would work offshore.

Similarly not working closely with fabrication and installation experts could result in sub-optimal designs that don't translate into real cost savings.

> "In the cost analysis for the concept study we did for TP-less designs, we saw that the major cost reduction would be during the OpEx phase, principally driven by the removal of the flange between the monopile and the transition piece. We saw typical savings of around 6 to 10% - that's 6 to 10% of the overall cost of the foundations, so that is quite a substantial saving. We also found that if you can reduce the operational costs, you start to make life extensions more economically viable."

Andrew Hodgson,
Senior Engineer at
Empire Engineering



In a survey we conducted with 113 industry professionals, 31% felt that M72 and larger bolts were the right next step for the industry. 37% said they were not; and 32% weren't sure.

In the same group, 51% preferred bolted connections to grouted connections, wedges, slip joints or a TP-less monopile. 24% selected a TP-less monopile as their preference.

For more visit our *Webinar on designing the monopile without a transition piece why, how and when?*

How will floating foundations become competitive?

> "I believe floating wind can significantly reduce its cost, achieve the economies of scale and reshape the offshore wind industry in the next decade. But it will need government support, low-cost financing, and continued design optimisation, along with improved fabrication processes and reduced O&M costs. Finally, I think that knowledge transfer from the supply chain developed in the oil and gas industry is really important. This will be crucial for the floating wind industrialisation."

Aaron Zigeng Du,
Head of Empire Engineering's London Office

As it stands there are approximately 40 floating wind concepts being tested, prototyped or developed worldwide. Most of them are based on the four types of floating structures that originated in the O&G industries: semi-submersible, barge, spar and Tension-leg platform (TLP). The semi-submersible has become the most popular option because it can be used in a wider range of water depths than the spar, and costs less to construct and anchor than the TLP.

To reduce the LCOE of floaters, the biggest challenge will be to maintain the floating turbine's performance while reducing the structural size and weight of steel. To reach the lightest possible floater design, one of the key challenges will be to improve the coupled floater-turbine analysis and integrated design process.

Wind turbine original equipment manufacturers (OEMs) have been reluctant to test their turbines on new floating structures because of a lack of experience and confidence in new floating technologies, alongside a backlog of fixed-foundation projects. To support future wind turbines of 15–20MW, floating structures need to be properly analysed for integrated aerodynamic loads on the turbine and hydrodynamic loads on the foundation and the mooring system. This requires close collaborations between floater designers and wind turbine OEMs to provide design optimisation. This collaboration is one of the key things that will enable design improvements.

With government support, floating offshore wind developers need to bring together stakeholders, including wind turbine OEMs, floater designers, and technical specialists and lenders to accelerate the design optimisation of floating offshore wind. Over the past decade the bottom-fixed industry has shown how significant optimisations can be achieved through such a collaborative approach.

Fabricating a large quantity of floating structures needs particular attention. In the similar way that jackets can be made in parts in various fabrication sites and transported to one final yard and assembled, floating structures could be built in modules with each module being built in specialised shops. That would allow a 'serial-like' fabrication process to be put in place. The final assembly of floaters needs to be done at port, so we will need major investments to increase the port acreage, the drydock sizes, and float-out draft.

Looking beyond the foundation fabrication, it's anticipated that floating foundations could cut costs in other areas of the wind farm life cycle, notably installation and maintenance. Installation would require tugboats as opposed to expensive installation vessels to pull the floating wind turbines to their sites, and the cost savings to be had by towing WTGs to port for maintenance rather than hiring specialist vessels to do maintenance at sea are promising. The O&M activities could be carried out in the port, making weather conditions less of an issue than they are for the maintenance of bottom-fixed wind farms.

Will we still need jackets?

That's a good question. If the cost of floating foundations comes down sufficiently over the next decade, and we can make monopiles work in deeper sites, then the need for jackets would be minimal, and likely only for very specific site conditions where soils are unsuitable for monopiles, and Metocean conditions are unsuitable for floating.

> "When I first heard the tow-to-shore concept for maintenance, I was very sceptical about whether that would be the right approach. But I've been working with others to look at the risks and challenges of doing main component maintenance on site, and I do believe that towing floating turbines to shore, as long as the facilities are close enough, will be the most cost effective. The alternative to a tow-to-shore main component exchange is using an enormous floating crane vessel, which may not be available for the three days a year that you need it to do the maintenance on your site. The waiting times that you might have for that vessel coupled with the cost of it, can completely destroy the business case."

Sally Shenton,
Director of Generating
Better Limited

Where is the frontier between fixed and floating foundations?

From a technical perspective, floating offshore turbines could be installed at water depths as low as 30m. But economically, floating offshore wind can't compete with bottom-fixed offshore wind on shallow water sites at the moment.

It's widely thought that for water depths greater than 60m, bottom-fixed offshore wind foundations become uneconomical, even though a recent study suggests this frontier might be closer to 90m. Others believe that the transition between fixed and floating foundations could be as low as 40 to 60m.

Based on today's technology and industry experience, we would say that this frontier will be somewhere between 60 and 80m a decade from now, although it will always depend on the location and conditions of the site.

Potential bottlenecks for the growth of offshore wind

As more countries opt for offshore wind to address their energy needs in a sustainable way there are a number of potential bottlenecks that are likely to slow down global growth in the industry.

Supply chains

The competition for existing resources and the development of supply chains will be one of the biggest bottlenecks to the growth of offshore wind globally. Besides the supply of wind turbines and foundations, there will be competition for the specialised vessels and equipment needed to transport, install and maintain the components of a wind farm.

The enormous installation vessels take years to design and build, and just as was the case in onshore wind a decade ago, it's conceivable that getting your hands on enough turbines for an offshore wind farm in a couple of years' time could be a very real challenge.

Smaller wind farms being developed in countries new to the offshore wind market also risk being marginalised as OEMs are likely to prioritise big orders in established markets over smaller ones in developing markets. This may put the brakes on these countries' plans to adopt offshore wind.

The value of offshore wind supply chains to any economy will also mean most regions will want to develop supply chains of their own. The political demand for local content from local supply chains will create significant lags in developing big offshore wind projects as fabrication facilities and capabilities will first have to be developed.

In countries and markets where no fabrication facilities exist, floating foundations may have an advantage, as countries who are not fixed on including local content could tow floating wind turbines from fabrication facilities in Asia or Europe, with the overall cost still being competitive.

> "With the global expansion of the offshore wind industry, there's a need to build competent regional logistical hubs with global partners and local experts, as the European one may struggle to service both APAC and the US."

William Cleverly,
Group Managing Director of Renewables, AqualisBraemar LOC Group

Skills shortages

Another potential bottleneck, which we're already seeing with staffing offshore wind projects, is the growing competition for a skilled workforce. Until a mature pipeline for offshore wind-specific skills is developed, this will slow development.

Port facilities and vessels

In newer markets, sufficiently large and deep ports with the right cranes will be needed for both transport and O&M. These could take some time to develop and will need investment.

Although floating wind may not require the large T&I vessels that bottom-fixed foundations do, and they could potentially be towed to shore for maintenance and exchanges. However, even with floating foundations you will need deep water ports with exceptionally large cranes to accommodate them.

Grid infrastructure and storage

Without serious planning, investment and development, existing grid infrastructures won't be able to take advantage of the full potential of offshore wind. If offshore wind is to replace on-demand energy sources, we need to be able to store it more efficiently. The question is, how fast can energy companies develop storage facilities? And will technologies like hydrogen electrolysis make this storage easier?

> "Not all our energy demands can be met with electricity, so the whole topic of the energy mix and storing power needs to be discussed and agreed. That is a challenge that we need to deal with to be able to use the full potential of offshore wind farms. It's also linked to our electrical infrastructure – we don't currently have a grid system that can use the full supply of electricity produced by offshore wind."
>
> 
>
> **Lars Lonstrup Nicolaisen,**
> Vattenfall Offshore Wind

Permitting

Seabed leasing and permitting for offshore developments is well established in some markets, although these processes often fail to provide developers with the certainty they need to invest. In many countries, there are no seabed leasing or permitting systems in place yet, and establishing them could take years of political wrangling.

> "To meet the ambitious targets for offshore wind, we have to address the lengthy process of getting projects off the ground. How could we reduce the time cycle of projects from the current 10+ years to less than 5 years? The momentum for energy transition, net-zero targets and initiatives like the UK's Offshore Wind Sector Deal will help, but permitting processes need to be simplified."
>
> **William Cleverly,**
> Group Managing Director
> of Renewables,
> AqualisBraemar LOC Group

Political will

For offshore wind to grow it needs government support and for politicians to prioritise long-term planning over short-term political gains. A lack of long-term commitment poses a challenge to what we can achieve and how much the cost of offshore wind energy can be reduced. For example, there's currently little political interest in improving the grid infrastructure or developing energy storage solutions to make the most of offshore wind energy. Long-term certainty could also help to encourage developers and investment in developing local supply chains and skills the industry needs.

Minimising risk and optimising foundation designs

As with any engineering and construction project, offshore wind farms are complex. In our experience, there are issues in a number of areas that may increase project risk and minimise the potential to optimise foundation designs. Here we touch on how to mitigate these risks and create the conditions for optimised designs.

Collect sufficient geotechnical data

To develop difficult offshore sites and reduce costs, optimising foundation designs is a necessity. Efficient geotechnical design is a cornerstone of achieving this. It's common that insufficient data on soil conditions is gathered in the early stages of a project. All too often Cone Penetration Test (CPT) or borehole test data doesn't come close to covering all the proposed turbine locations in the OWF layout. Unconservative or over-conservative assumptions made when deriving soil curves, or stiffness for normal, extreme and severe sea states, may lead to incorrect interpretations of the foundation's behaviour to loading from the turbine and waves.

Besides working against optimisation, assumptions about soil properties create risk and costs that are often underestimated by developers. Designing with insufficient soil data early on means designers have to make conservative design decisions to mitigate possible risks, or risk design changes further down the line.

> "Geotechnical investigations are done early in the project, at a time where you may want to limit costs. But geotechnical data collection is a cost that is often misunderstood, because it comes back to bite you later.
>
> If there's not enough soil data for the geotechnical evaluations, we have to make conservative estimates about the soil properties, and the designer has to design to mitigate against these possible risks. Usually this means compensating through bigger, heavier or longer designs, which usually means more steel, which increases costs to your project through the fabrication, transport and installation. It's a false economy."

Martin Underlin Østergaard,
Lead Geotechnical Engineer
at Empire Engineering

Design for the full OWF life cycle

Full life cycle design means treating a design not just as a theoretical process, a calculation note or a CAD drawing, but as something you're going to have to build, transport, operate and maintain for 25+ years, then decommission. Full life cycle design takes every step into account. It ensures you don't run into a major installation issue when the installation vessel can't upend your monopile, or you've got a number of turbines offline because your Crew Transfer Vessels (CTVs) can't access the boat landings in storm season.

So, what does this look like in practice across the three phases of engineering design: concept design, Front-End Engineering Design (FEED) and detailed design?

01. Concept design stage

At the conceptual stage, you need to choose the type of foundation you will use. Typically, you'll be choosing between monopile, jacket or gravity base structures. In the future, floating foundation options will need to be factored in too. What you need to consider and why is covered in the previous section (see p.11 "*How do you decide on a foundation concept?*").

02. Front-end engineering design (FEED) stage

At the FEED stage the foundation design team needs more information from the developer. Ideally, this should include at a minimum:

- A preliminary, high-level **fabrication** methodology. What are the main steps for fabricating your structure? What is the welding process for steel structures? What is the concrete pouring technique? What are the fabrication shop limits or lifting limitations?
- A **basic method statement for T&I** with requirements for the installation vessels (type of vessel, length, draft, deck capacity, craneage). This enables the design team to do the necessary calculations for the T&I engineering.
- A **preliminary O&M strategy**. Along with the strategy, the following details should be provided: how many boat landings are planned? What size and shape are the vessels? What are the personnel numbers? Also, what are your basic boat landing and platform requirements?

At this stage, decommissioning criteria would be a nice to have, but again, it's not critical.

Risk management versus "risk accounting"

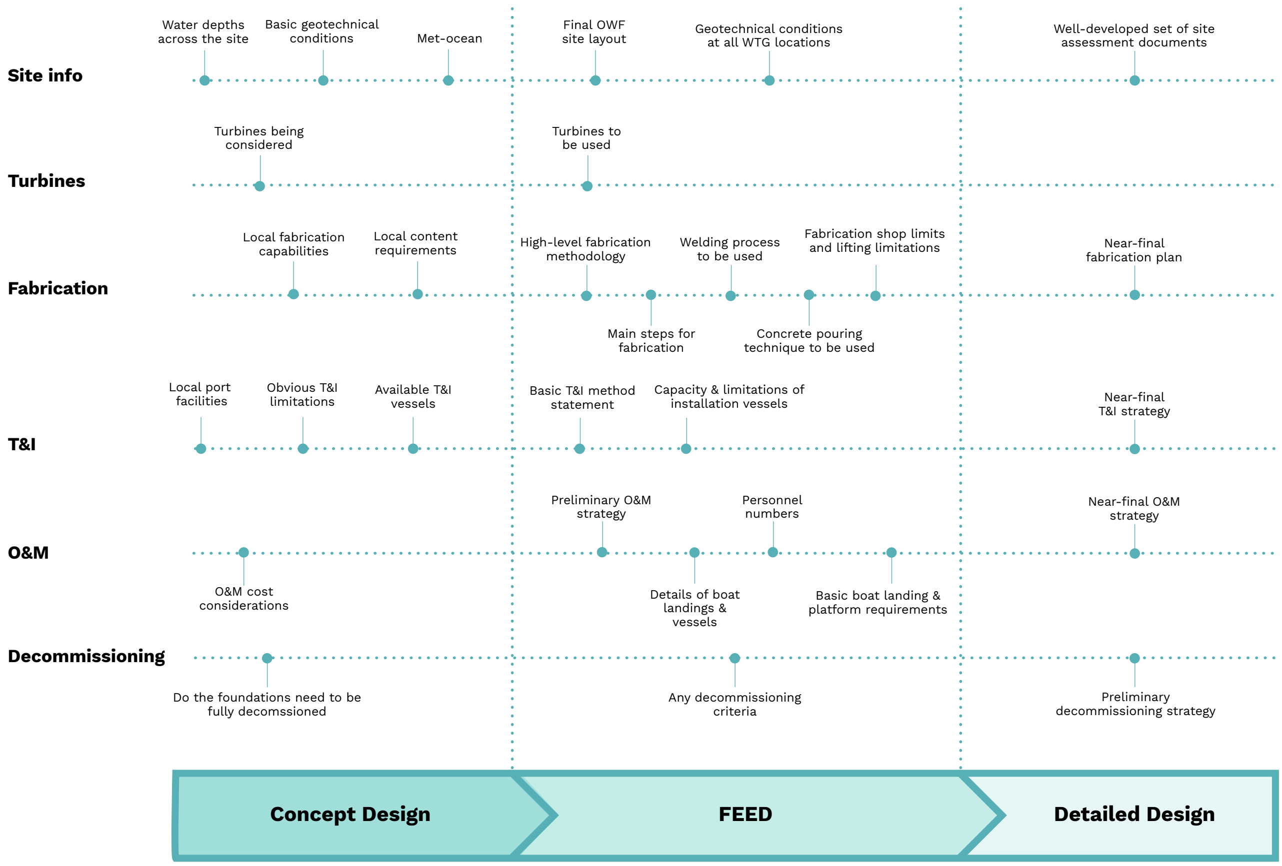
We use the term "risk accounting" to describe the approach to risk that currently dominates in the offshore wind farm development process. There are risk registers, checklists and phase-focused risk analyses, and risk mitigation strategies. However, what is often lacking is a much broader life cycle view of risk and an understanding of how early cost, design and development decisions can both mitigate risks and support opportunities for innovation. Take the examples of limiting geotechnical data collection on p.30 or delaying critical decisions on p.33.

03. Detailed design stage

In this phase, the design team get down to nuts, bolts and welds. If you want an optimised design and to avoid nasty surprises further down the road, then by this point there needs to be:

- A final (or near final) fabrication plan or methodology.
- A final (or near final) strategy or methodology for T&I.
- A final O&M strategy, since requirements for boat landing, ladder and platform access and craneage will be frozen once detailed design commences.
- A preliminary decommissioning strategy.
- A well-developed set of site assessment documents (Design Basis Part A).

It is possible to do detailed design without knowing the fabricator and the installer. But this requires contingency planning for the final fabrication and installation methods. The designer will have to make some assumptions and the developer will typically end up with a less optimised structure and more risk of having to make expensive last-minute design changes. These are big construction projects and when you build these big structures, even small details can quickly become major headaches.



Balance the risk of diligence versus timely decisions

To meet the uncompromising timelines in offshore wind projects, you should expect to make some decisions based on incomplete information. This can be uncomfortable, but the delays required to make the 'perfect decision' can pose a much greater risk to the project than a decision made without all the information you might like to have. Inexperienced developers often prioritise diligent decision-making over timely decision-making, particularly around key aspects like turbines, foundation type or EPCI Contractor. This is understandable – no one wants to make a mistake with a €100-million contract. However, the risk this poses to the project schedule is often not fully understood in terms of the overall process.

For example, during turbine selection, a lengthy negotiation process with various suppliers is typical. It usually takes longer than planned and delays in confirming the turbine make/model/size are often accepted as essential to getting the best contract. What's often forgotten is that without a confirmed turbine, a full geotechnical campaign can't go ahead, as the turbine selection impacts the wind farm layout and therefore the borehole/CPT locations. Since a geotechnical campaign can only happen in certain seasons, a few months' delay in turbine selection can delay your entire programme by 12 months.

These can be tough commercial and technical decisions to make, but the risks of delaying them shouldn't be underestimated. A well-defined plan of when key project decisions need to be taken is essential in OWF development.

Why does knowing installation methods matter?

An example of the value of life cycle design

Tensioning is largely accepted as being the method of choice for large-diameter bolting, such as that used in the flanged monopile-transition piece (MP-TP) connection. Unfortunately, if designers don't have certainty about the installation method, they have to design the MP-TP connection for torquing and tensioning.

With tensioning, you can move the bolts closer together so you can get 10 to 15% more bolts on your Pitch Circle Diameter (PCD) which helps you achieve your load. You can also move the bolts closer to the flange wall, reducing your bending stresses.

If you can design for tensioning from the beginning, you can save material on the flange because it doesn't have to be quite as big. It also means you can meet the tolerances required for the connection, which is becoming more and more challenging to achieve as turbines get heavier and monopiles get bigger (there's more on big bolted connections on p.23).

Invest in expertise for the integrated load analysis (ILA) process

The primary objective of an Integrated Load Analysis (ILA) is to obtain well-defined loads for the WTG substructure (the tower and the foundation), accounting for the dynamic interactions of wind and wave loads on the complete structure.

After completing the ILA process, you can close the detailed design process with materials procurement and T&I logistics with improved confidence. It also makes the project financing process a lot easier, and greatly improves the likelihood of a positive final investment decision.

Any shortcomings in the ILA process can lead to lengthy detailed design delays. It is essential that the project developer, WTG supplier, foundation designer and independent verification body define and agree robust mechanisms for performing an ILA at the outset to ensure the accuracy and reliability of the results. This is a complex and high-risk area where there really is no substitute for battle-hardened experience.

The interpretation of site-specific soil conditions

Geotechnical design aims to ensure that loads on the foundation structure can be safely transferred to the surrounding soil volume. This includes considerations of soil capacity, deflection and rotation of the foundation, dynamic interaction between the foundation structure and the surrounding soil as well as foundation installation. Each of these evaluations requires a unique methodology and a corresponding understanding of the soil behaviour.

As mentioned, having insufficient soil data is one issue that is quite common, but another is the assumptions that are made about that data, which can have a significant impact on ILA outcomes.

Wind/wave correlation

Designers use varying approaches to determine how the wind loads on the turbine and the wave loads on the foundation structure impact the design. For example, they may consider wind and wave magnitudes but neglect directionality, or consider the percentage of occurrences of wind actions on the WTG and wave actions on the foundation in isolation. A robust assessment methodology must take into account the concurrent wind loads on the WTG at the hub height and wave loads on the foundation structure.

To establish the critical set of correlation equations that interlink wind speed at the hub-height with significant wave height (Hs) and zero-crossing peak period (Tp) in a spectral domain can be a time-consuming process, and can therefore be very tempting to avoid. However, in terms of gaining accurate insight into fatigue and minimising risk, this process can't be neglected.

Then there are breaking waves to consider. For these are unpredictable and forces are large, and the wave theories begin to break down, or at least become significantly more empirical and uncertain. The unknowns and complexities ramp up nearly as quickly as the wave itself.

In addition to breaking waves, we have wave run-up forces that can damage platforms if not designed for. These are doubly complex because predicting the worse cases is not trivial, and the loading calculation is still very much an emerging field.

Primary steel orders: before or after certification?

Certification of a foundation design reassures developers, insurers, banks and investors that the design is safe, reliable and robust. Unfortunately, in practice, certification can take anything from a couple of months to a few years depending on the project. Within the context of offshore wind projects timelines, a long delay can be devasting. In fact, it isn't uncommon to see certification at the top of project risk registers for this reason.

To mitigate the risk of ordering the wrong primary steel, some developers want the foundation design certified prior to ordering. Any delays to certification then delay the steel order, which can lead to order slots being missed and delays to fabrication. On sites with seasonal installation restrictions this can lead to a catastrophic 12-month delay.

Other developers will order primary steel as soon as the detailed design is complete, taking the risk that certification could demand a design change and therefore a change to the primary steel order, which could lead to both steel delivery delays and additional costs.

So, what should you do? On a site without unusual site conditions, using a design with little novelty, and if you have an experienced detailed designer and certifier, the risks of problems arising during certification are limited. However, if there is anything unusual in the site conditions – unusual soils, breaking waves, typhoons, TP-less monopiles (more on those on p.25), exotic turbines – or either the designer or the certifier has limited experience, problems often arise. In these situations, make sure you engage with the certifier and start discussing the difficult points early, so that you can resolve any tricky technical problems before the project deadline.

Support innovation in foundation designs

As we've mentioned, full life cycle design is fundamental to optimising offshore wind foundation designs, but creating conditions that support innovation requires more than that. We believe there are plenty of opportunities for us as an industry to do it.

Improved feedback loops across the life cycle of a project

On many wind farm development projects, the foundation design job ends when the design engineers send over the final detailed drawings. Foundation design teams often get limited feedback on their design decisions through the fabrication, transport, installation and commissioning phases of the wind farm's development, or indeed once the wind farm is in operation. Any feedback that is provided is often in the form of a written report.

More robust and visual feedback – like videos of key transport or installation processes, for example – would help foundation designers understand what works, as well as what unforeseen challenges their design decisions may have caused at other stages of the project.

This type of feedback, from the fabrication through to the maintenance phase, would enable designers to identify opportunities for improvement which could in turn benefit the developer if they work with them on the next project. That is one of the advantages that developers with in-house design teams have.

"I remember in my first week of working as part of a developer's team, I saw some videos of a cable pull in operation. It kind of blew my mind, because until that point I'd never really thought what a messy situation it is, with all the tools, all the equipment and all the people.
When you're a designer, you have your crisp, clean 3D CAD model, and to see someone interacting with this "perfect" design – all the health and safety elements and the human aspect – really opened my eyes. I think that real-world aspect is often completely absent for designers. Having it could only improve the understanding and the relationship between the developer and the designer, and what designers are capable of."

Nick Howard,
Partner and Principal Engineer
at Empire Engineering

Designing beyond the CapEx costs

Many designers feel that there is too much focus on CapEx and bringing down foundation weights which excludes opportunities for innovative designs that could impact on other phases of the OWF life cycle.

Currently about two thirds of an overall offshore windfarm budget is allocated to CapEx and 30% to OpEx. Design engineers will always design for efficiency. However, foundation designers tend to agree that many developers' dominant focus during the CapEx stage is on reducing the weight of the foundation designs, which inhibits any real design innovation that could have greater impacts on OpEx costs. From the developer's point of view, most gains in terms of OpEx would be in relation to optimisation of the wind turbine rather than the foundation, since that uses the majority of the O&M budget.

Within the time and cost constraints of a project, independent design teams are rarely able to be innovative while remaining competitive, which limits the innovations and optimisations they could realise for developers. This is where the companies with long-term in-house design teams have an advantage.

> "It's hard for independent design teams to realise innovation within a project because there are financial and time constraints, so within a project isn't the ideal time to be doing innovation. There are too many external pressures to allow that kind of blue sky thinking to occur. I think maybe there's a bit of responsibility on both parties – developers and designers – to try and bring innovation outside of the project and find budget funds from other sources for innovation."

Nick Howard,

Partner and Principal Engineer at Empire Engineering

Increased cooperation between turbine and foundation designers

How the wind turbine design process tends to work now is that foundation and turbine designers work within their separate packages with only a small overlap in the ILA.

Closer collaboration between the two groups would offer untapped opportunities for optimisation and innovation of both foundation and turbine designs. Take floating wind as an example: to accelerate the development of the design and commercialisation of floating foundations, which could potentially be more cost-effective for bigger turbines than fixed-bottom foundations, everyone stands to gain from increased cooperation. It's a win-win situation.

A diverse workforce and multi-disciplinary teams

Diversity of disciplines, experience, cognitive abilities, culture and identity in offshore wind can increase the probability of a breakthrough and locate more potential innovations. There is plenty of evidence to indicate that diverse teams can be more innovative and productive.

Even though offshore wind attracts a lot of enthusiastic environmentally-minded talent from top universities, diversity does not happen easily in most engineering firms in the offshore wind sector. We believe that increased diversity and multi-disciplinary teams could only benefit our industry, support full life cycle design and present us with unexpected opportunities for optimisation using technologies ranging from artificial intelligence to robotics.

> "The key to addressing many of the challenges in relation to foundation design is collaboration and feedback loops that encompass all players across the full life cycle of offshore wind projects. We need to be open to learning from everyone in the process – it's all relevant."

Karl Davis,
Managing Director of Empire Engineering

Conclusion

This is an exciting time for the offshore wind industry, as both the public and political support as well as the commercial appetite for alternatives to fossil fuels accelerate. There are most definitely challenges, and they shouldn't be underestimated. Getting it right is critical for all of us.

Fortunately, there are many opportunities to do so. There are countless dedicated and skilled professionals stretching the boundaries of our technical knowledge, adapting and extending the possibilities of existing technologies and developing new ones. The next decade promises to be a very interesting and fast-moving one for the offshore wind industry.

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