TKI WIND OP ZEE
Topsector Energie

Long-term outlook on developments in foundation technology

By BVG Associates
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Executive Summary

The Dutch offshore wind industry supply chain has successfully grown in recent years, focused primarily on the building and installing of monopile support structures, which account for 80% of European offshore wind capacity installed in the last five years.
Design and manufacturing innovations and economies of scale have continued to preserve the competitiveness of the MP ecosystem up to now, compared to alternatives. Technology changes, such as increases to the average turbine rating and average site water depth, and the emergence of alternative foundation concepts could threaten the position of monopiles, however.

This report provides insight into the nature of future offshore wind foundations through the following:

- Description of the present state of the art (including the outcome of recent research projects) for the most promising alternative support structures for wind farms on sites with an average depth of 40-60 m and 60-100 m. In doing this, also pay attention to possible disruptive technologies.
- Analysis of the LCoE for these techniques and the cost reduction potential.
- Indication of the water depth where the business case for alternative support structures starts to become competitive with the business case for fixed-bottom support structures and the speed at which potential cost reductions can be realized.
- Analysis of the strengths and weaknesses of the Dutch offshore wind industry (including all links in the supply chain) for the development and roll-out of these promising technologies.
- Formulation of recommendations to strengthen the competitive position of the Dutch offshore wind industry in the market for alternative support structures.

Technology assessment

We considered four foundation types: monopiles, jackets, gravity base foundations, and steel floating semi-submersible. For each, we summarised the characteristics, technical design drivers, main variants, pain points, and innovations that can be expected in the next few years.
Although the monopile is the most mature of the designs, there is a considerable pipeline of innovation in response to industry pain points. They will be larger, cheaper, faster to manufacture, and easier to install in the coming years.

Reference foundation designs

For each of the four foundation types, Ramboll provided a generic reference design estimate for North Sea site conditions and a generic 15MW turbine. Dimensions and masses were estimated for a set of water depths. The estimated masses enabled the different foundation technology types to be costed and compared.

Potentially disruptive innovations

This is a term used to describe designs for foundations that are significantly different from the four types profiled in the technology assessment. Floating foundations have the greatest number of potentially disruptive designs, perhaps because this is still a new area that has not matured and has been made to converge by market forces.

Analysis of total installed cost

We analysed the manufacturing and installation costs of the reference designs to give the total installed cost at a range of water depths for an installation date of 2025, and again with a further five years of expected innovations. The result is seen in Figure 1.

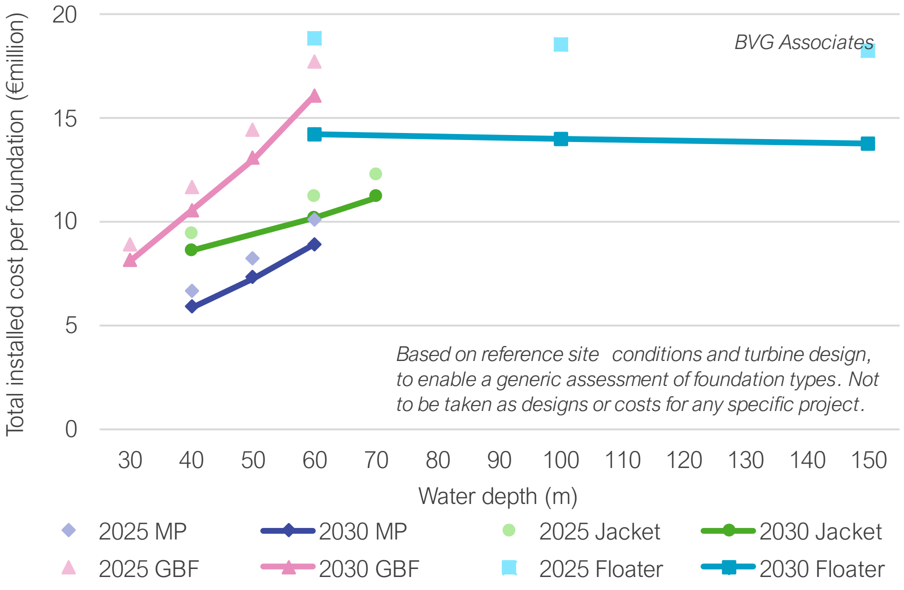

Figure 1 Total installed cost versus depth for different foundation types

It shows that MPs are competitive versus all other foundation types, but their cost rises steeply with depth. Jackets are more expensive, with gravity base foundations being the most expensive bottom-fixed type. Floating foundations, even after five years of cost reductions from expected innovations, remain more expensive than bottom-fixed, although the cost profile is almost flat for the investigated water depth range.
This chart does not show the variation in cost that is seen with actual site conditions, including ground conditions, wind, waves, and tides. Further variation results from

specific design choices that might be made and variations in manufacturing costs by location or over time. A large range of floating foundations design variants exists (material, layout, control systems, general arrangement, etc.), implying that even within a given foundation concept (here, a steel semi-submersible) cost uncertainty and potential for innovation are particularly high.
The potentially disruptive innovations were assessed qualitatively. We identified which ones we consider more likely to be successful, and therefore could be actively encouraged or monitored. The project did not set out to compare them quantitatively on a chart such as Figure 2

Competition between foundation types

The ways in which foundation types compete and innovations are relevant are shown in Figure 2. This shows preferred foundation types and major innovations by seabed depth and ground conditions. This is corroborated by what is seen in the market.

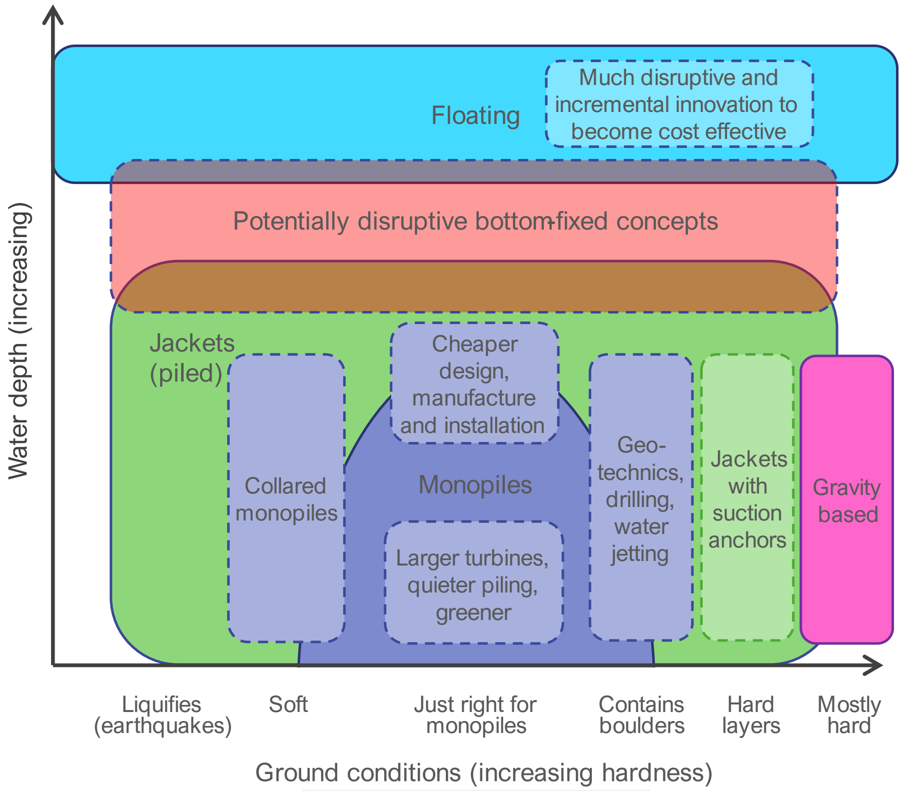

Figure 2 Competition between different foundation types, considering depth and ground conditions. Innovations and potentially disruptive concepts are shown in dotted boxes.

It can be seen that:

- MPs occupy a central position and are the preferred foundation type where ground conditions allow. They are competing against piled jackets for most depths at which bottom-fixed projects are being developed.
    - Innovations to enable piling of larger MPs and noise reduction are essential.

  - Innovations such as collared MPs and improved geotechnical investigations to locate boulders, can help MPs to compete further with jackets in non-ideal conditions.
  - Cost reduction will help MPs compete more effectively with jackets and could increase the depth at which MPs are viable.
  - There remains, however, a risk relating to the natural frequency. Designs must be specified to avoid or cope with wave and turbine driving loads. This becomes harder as turbine size increases and could become the limiting factor, though so far, the industry has continued to find control systems and other innovations to address what had been expected to be a barrier even at 10MW-scale turbines.

- Piled jacket foundations are the next most common foundation type and are normally used at deeper bottom-fixed sites and where site conditions do not suit MPs, for example, the ground is too hard or too soft, there are earthquakes or there are extreme metocean conditions
  - Suction anchors are more expensive than piles so are only used where there are hard ground layers that would add cost for piled jackets, and these layers are thick enough to allow suction anchors to be used.

- GBFs are not common today because they cost more than MPs, their sweet spot appears to be competing with jackets at shallower sites with hard ground conditions, and potential locations where there is no steel fabrication and a strong desire for local content.
- Floating foundations are generally more expensive than bottom-fixed and do not compete with bottom-fixed at the depths being used for bottom-fixed projects today. Their challenge is one of cost reduction to increase the size of the market where floating is the only option. This requires the discovery the of lowest-cost concepts, rationalisation of concepts, and standardisation of manufacturing and installation practices to build economies of scale.
- There are several disruptive bottom-fixed concepts for deeper bottom-fixed sites. It is unclear whether they will out-compete MPs and jackets at existing bottom-fixed water depths, or whether their role will be to increase water depths where bottom-fixed foundations are viable.

The Dutch foundations' innovation ecosystem

We assessed the ecosystem through interviews and desk research regarding Dutch companies and examples of recent foundation innovations. From this, we summarised strengths, weaknesses, opportunities, and threats, from which our recommendations were formed.

Recommendations

We recommend that RVO:

1. Ensures that the greater part of public funding supports MPs, as the most relevant foundation type for the foreseeable future, which need to be cheaper, larger, lower noise, greener, and better able to cope with challenging ground conditions. Ensures that the lesser part of public funding should support disruptive foundation concepts and innovation where there is little market pull.
2. Challenges its remit so that it could also fund innovations applicable to sites beyond the Netherlands.
3. Funds against a coherent roadmap of inter-related innovation areas and projects, ideally several stages of a project depending on results, rather than single stages.
4. Investigates the appetite and options for an offshore wind foundation test center in the Netherlands to reduce innovation lead times and attract innovators to the Netherlands.

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1 Introduction

The Dutch offshore wind industry supply chain has successfully grown in recent years, focused primarily on the building, and installation of monopile (MP) support structures.
Average turbine sizes have increased steadily, and the maximum economically viable depth of bottom-fixed sites has also increased. These two factors were expected to favour alternative foundation types to MPs, such as jackets, but jackets have lost, rather than gained market share. Design and manufacturing innovations and economies of scale have improved the relative competitiveness of the MP ecosystem up to now, compared to alternatives.
Average turbine rating and average site water depth will continue to increase, particularly as the industry achieves a multi-GW scale and the shallower sites get used up.
This report provides insight into the nature of future offshore wind foundations through the following:

- Description of the present state of the art (including the outcome of recent research projects) for the most promising alternative support structures for wind farms on sites with an average depth of 40-60 m and 60-100 m. In doing this, also pay attention to possible disruptive technologies.
- Analysis of the LCoE for these techniques and the cost reduction potential.
- Indication of the water depth where the business case for alternative support structures starts to become competitive with the business case for fixed-bottom support structures and the speed at which potential cost reductions can be realized.
- Analysis of the strengths and weaknesses of the Dutch offshore wind industry (including all links in the supply chain) for the development and roll-out of these promising technologies.
- Formulation of recommendations to strengthen the competitive position of the Dutch offshore wind industry in the market for alternative support structures.

This report sets out the answers to these tasks, which were carried out through a combination of desk research, high-level design, and cost of a set of reference foundation designs at different depths, and interviews. It is organised into the following sections:

Executive summary

1. Introduction (this section)
2. Technology assessment
3. Disruptive innovations
4. Foundation cost assessment, and
5. Technology acceleration for the Dutch foundation's industry.

The work has been led by BVG Associates with support from Ramboll.

2 Technology assessment

2.1 Overview

MPs have become the dominant foundation type for wind turbines for offshore wind projects. This is seen in **Fout! Verwijzingsbron niet gevonden.** which plots the foundation type for completed and upcoming projects, where known, globally excluding China.

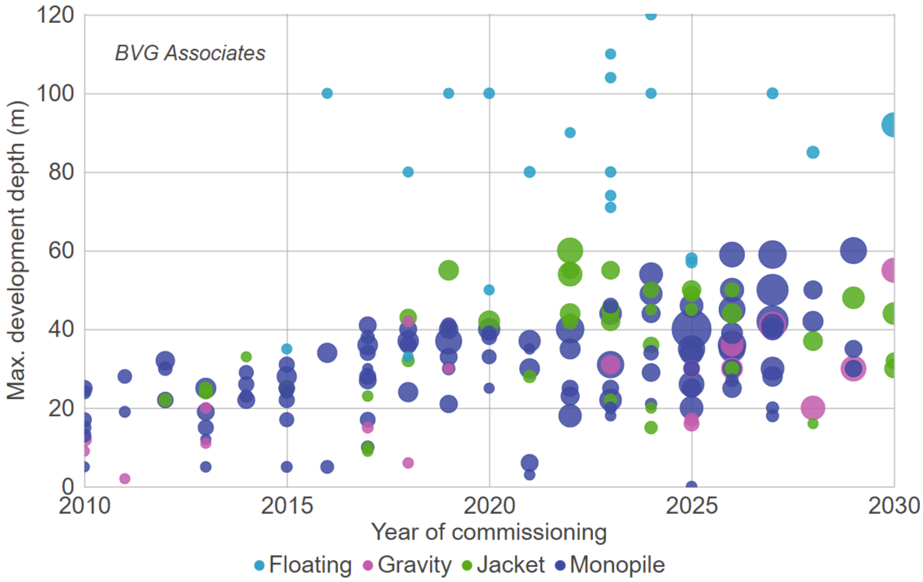


Figure 3 Foundation type versus maximum development water depth and installation date, for global projects excluding China. The bubble area is approximately proportional to installed capacity.

This section of the report assesses the current technical state of the art for the four major foundation types, MPs, jackets, concrete gravity bases and semi-submersible floating foundations. For each it describes:

- Description of characteristics
- Generic15MW reference design – what a typical 2025 installation is likely to look like
- Technical considerations
- Main variants
- Pain points, and
- Expected innovations, with a focus on incremental innovations.

Note, the use of patents is increasing, requiring third party engineers to understand these patents and work around them. For example, RWE has patents on its design for a collared MP. As it is generally possible to work around foundation patents, their ownership is not specifically described.

2.2 Monopiles

2.2.1 Description of characteristics

MPs have become the dominant foundation type in the offshore wind industry. They are a proven solution in water depths up to approximately 40m and are being actively considered for deeper sites. They are well understood from a design perspective, with codes and standards established, supported by extensive experience. These simple, large structures require specialist manufacturing facilities to roll steel plate sections and weld them into “cans”, before the cans are welded together to form a MP. MP mass however scales rapidly with turbine rating and water depth for current designs, which has limited their use to approximately 40m depths, up to now.

MPs will normally be used where ground conditions that are soft enough to allow piling while firm enough to give stability to the complete structure. Installation campaigns typically require heavy lift vessels to position MPs before specialist piling equipment drives the MPs into the seabed, though other solutions exist for specific conditions. Environmental mitigation strategies are often required for the impacts of piling noise on marine life.

Designs typically use a transition piece (TP), a secondary structure, between the MP and the base of the tower. A separate TP fitted after MP installation does not suffer from loading due to piling impacts and so can accommodate more complex welded and pre-assembled secondary steel than a MP.

Relatively few suppliers have the required capabilities for fabricating MPs and TPs, as they require specialised facilities. See Sif’s extensive facilities at Maasvlakte as an example, in **Fout! Verwijzingsbron niet gevonden.**.

Figure 4 MP laydown post-manufacture at Sif’s MP manufacturing plant at Maasvlakte 2, Rotterdam (Source: Sif).

2.2.2 15MW reference design estimate

The reference design comprises a MP with a TP bolted on after MP installation. The dimensions of designs for water depths 40m, 50m and 60m are shown in Figure 5. These designs are specified for central conditions characterising North Sea sites. The reference designs are appropriate for common installation techniques making them representative foundations for typical installation campaigns.

The reference designs are estimated for the reference site conditions and use a reference wind turbine design. They are outline designs and estimated quantities based on experience and without the detailed level analysis required for a specific project.
For further detail on the MP reference designs, see BVGA – Outlook on Fixed vs. Floating Wind Foundation Technology.i This includes reference designs for lower and upper-bound conditions, which show the potential range of MP and TP dimensions where metocean conditions, ground conditions and turbine mass differs from the central estimate

Masses for the central estimates, including TPs, at 40, 50 and 60m are 1,870t, 2,360t and 2,930t respectively.

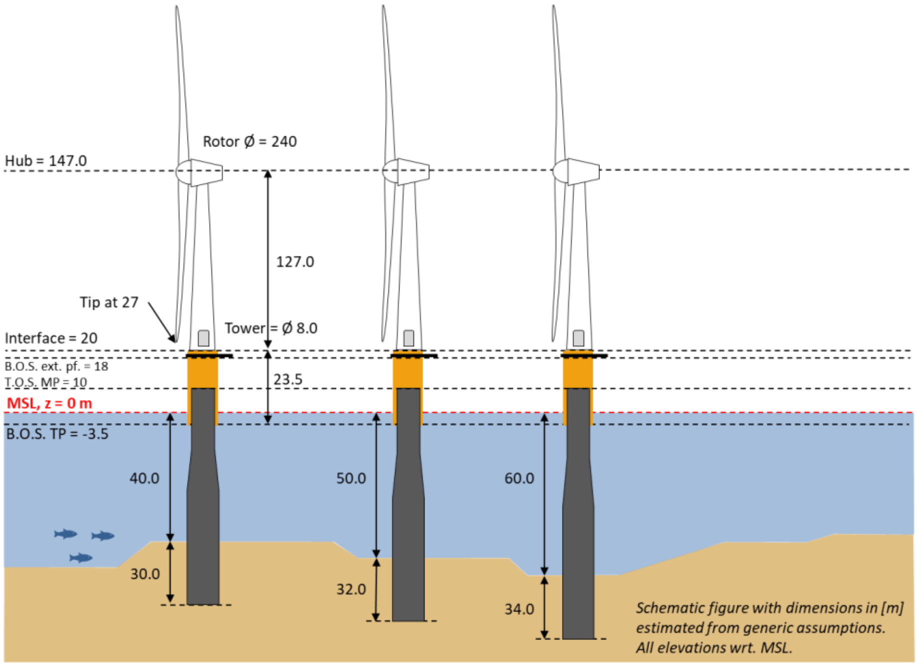


Figure 5 15MW reference monopile design. ***Note, the dimensions shown are for central conditions.***

2.2.3 Technical considerations

The key technical considerations for designing an MP are:

- Diameter/thickness (D/t) ratio. This is regarded as the key design metric to provide sufficient stiffness for site conditions. The use of larger D/t ratios (for a given MP diameter) can result in lighter structures, thereby reducing costs, but if the ratio is pushed too far, the structure will buckle.
- Natural frequency. Designs must be specified to avoid or cope with wave and turbine driving loads. This becomes harder as turbine size increases and could become the limiting factor, through so far, industry has continued to find control system and other innovations to address what had expected to be a barrier even at 10MW-scale turbines.
- Installation method. Design specifications are adapted to provide structural resilience necessary for the installation technique required for the site, typically: piling, boring, vibration or a combination of these.

- Jointing. Various jointing technologies are used to secure the MP/TP and TP/tower interfaces. These must be specified to withstand site specific loads.
- Manufacturing bottlenecks. Size constraints associated with manufacture can become a limiting factor with increasing MP size, for example, steel plate size limits, rolling capability and laydown space requirements.
- Installation bottlenecks. The availability of sufficient installation vessels with the required lifting capacity can constrain designs or decrease competition between installation contractors.

2.2.4 Main variants

Monopile / transition piece joint type

The key types are:

- Grouted. A well-established and widely used MP and TP connection secured and sealed using structural grout. The overlapping sections of the MP and TP are both structural, meaning increased mass versus bolted variants.
- Bolted. More recently, bolted flange joints have been used to secure the MP/TP interface. There are two main variants of bolted TPs:
  - Conventional length. The TP body and skirt are long enough to support the full length of the boat landing and the cathodic protection system to below the waterline. The gap between the top of the skirt and the bolted joint is grouted to prevent water ingress.
  - Compact length. The TP body is reduced to the minimum to support the array cables and house cable joints. The skirt length is reduced to the minimum required to provide environmental protection of the bolted joint, with the lower boat landing attached to the MP. HV equipment that might otherwise be housed in the TP is moved to the tower base.

See Figure 6 for examples.

Figure 6 Examples of MP/TP variants. Clockwise from top left: grouted (Hohe See, EnBW), conventional bolted (Arkona, E.ON), compact bolted (Triton Knoll, RWE innogy), and “TP-less” monopile (Hollandse Kust Zuid 1-4, Vattenfall).

TP-less

TP-less MPs are constructed with a single primary steel structure continuous to the tower base. Secondary steel items are slotted onto the MP structure using joints with no welding to ease offshore installation. The HV equipment is typically housed in the tower base. Adoption is being driven by the primary structure being lighter, although there are concerns about the future availability of installation vessels as TP-less designs require a higher and heavier maximum lift. See Figure 6

The choice of TP-less is usually based on a mutual dialogue between the developer or EPCI client and its consulting engineer and a trade-off is made based on risk and cost. Large European developers already using TP-less on projects include Ørsted, RWE, Shell and Vattenfall.

Work platforms

TP work platforms have typically been steel, but in a small number of projects, concrete variants have been used – See Figure 7. Concrete platforms have not been widely adopted despite being reported to be cost-effective, maintenance-free and durable.

Figure 7 Concrete work platforms (source: Aarsleff).

2.2.5 Pain points

Key pain points driving innovations are:

- D/t ratio. Efforts to reduce mass and cost have resulted in designs with increasing D/t ratio. Current design D/t ratios are typically approximately 120. Success in increasing the ratio is based on gaining a better understanding of installation and operational loads to avoid buckling.
- Jointing. Choice and specification of jointing technology (grouted/bolted variants). As MPs are deployed in increasingly challenging environments, joint strengths of current technologies will become a limiting factor.
- Installation. Vessel and crane requirements increase with increasing foundation mass, and key dimensions.
- Piling energy. The increased piling impact energy required as MPs become heavier requires the development of larger tooling, or alternative installation methods.
- Piling noise. The environmental impact of piling requires careful monitoring, with mitigations strategies required to protect marine life. Noise mitigation can cost €20m for a 500MW site. The environmental impacts of installation can be a limiting factor in consenting.
- Risk of refusal. Options to address pile refusal, if it occurs, are time consuming and expensive, for example, drive-drill-drive.
- Decommissioning. Cutting MPs at the mudline is expected. Full removal is not cost effective, as with several other foundation types.
- There is growing concern over the embodied carbon content of wind projects, and much of that is currently in the steel foundations.

2.2.6 Expected innovations

Design innovations

Design innovations include:

- D/t ratio: A principal area for innovation is increasing the D/t ratio to reduce mass and cost of MPs and TPs. The current D/t limit is approximately 120, however this figure is based on oil and gas design codes. A clear limit for offshore wind has never been defined in design codes. Given the lack of failures in MPs and TPs there is potential to increase d/t ratios to around 180. By way of comparison, offshore wind towers have D/t ratios greater than 250 but experience lower loads due to vertical transport and no piling. Commercial drivers are likely to be the determining factor in changes to the D/t ratio as designers respond to developers' pressure to drive down costs where risk appetites increase.
- Corrosion protection. Increased use of impressed current cathodic protection (ICCP), it may be required in sites where galvanic anodes do not meet standards.
- Coatings. Wider use of thermal metal spray to improve corrosion resilience and extension of coating lifetimes.

Materials research

A key focus is on fatigue resistance and S/N curve improvements. Existing codes were developed for smaller components with smaller wall thicknesses, so there is room for optimization for expected future component sizes.
Several research programmes and steel manufacturers are developing green steel production methodologies.

Monopile/ transition piece joint

As the wave loads impacting TPs increase, solutions to the limits of bolted MP-TP jointing will be required. Innovations in this area include:

- TP-less designs. These result in a lighter primary structure (no TP overlap) with no major joints but can take longer to install and have more secondary joints to maintain. Further innovation is expected. Several larger European developers including Ørsted, RWE and Vattenfall are using TP-less designs, but none use them exclusively yet. There are many examples of TP-less being developed in China.
- Tapered slip joints. These have been piloted at Borssele V, with contact between the TP and MP providing the connection.[ii]
- The C1 Wedge ConnectionTM. This won the Dutch Offshore Wind Innovation award in 2018, when it was known as Fistuca's Blue Wedge Connection. It claims to be a maintenance free joint that is faster and cheaper to install than bolting or grouting.[iii]
- Bolted X-joint. This is similar to a T-joint in that it has two rows of bolts, but different in that they are oriented at approximately 30° from vertical and cross each other. See Figure 8. Both rows are accessed from the same side of the joint. It came from a 2003 dissertation and is reported to be under development by SGRE.[iv]

A return to grouted jointing as the dominant approach may provide more scope to overcome the limitations of bolted flanges.

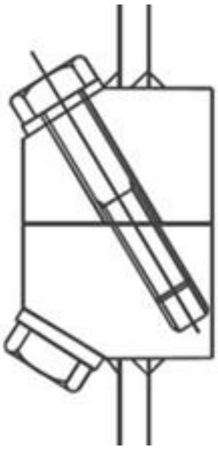


Figure 8 Bolted X-joint (Source: Alexander Jakubowski, 2003 dissertation).

Manufacturing innovations

Key innovations include:

- Increasing steel plate sizes. This will enable manufacture of larger MPs for deeper, more challenging conditions. Dillinger and Steelwind Nordenham have announced investment to enable production of super heavy steel sheet to increase XXL MP production.[v]
- Electron beam (EB) welding. This has the potential to dramatically reduce welding times. Use of EB welding has been announced for Sif's production of MPs for Dogger Bank and at new Haizea tower fabrication facility at Nigg.[vi], [vii]
- Improvements to post-weld treatments. Improvements to grinding, hammering, deep rolling and profiling processes are expected.

Installation innovations

See Figure 9 for examples of some of the following innovations:

- Piling energy. Current piling hammers are rated at 3,000 to 3,500kJ, with 5,500kJ hammers under development for larger MPs. The increased piling forces will impact MP design.
- Noise mitigation. In addition to existing solutions such as bubble curtains, piling suppliers and installation contractors are developing a variety of ways to mitigate noise transmission, some at source in the pile hammers.
- Vibration piling. This is being conducted as part of a research project at RWE's Kaskasi project.[viii] It is being discussed for many projects, so is expected to become more common. It is potentially faster, uses less of the pile's fatigue life and is perceived as more environmentally friendly than impact piling. Pile length may need to be increased to compensate for potential loss of stiffness, and the approach cannot be used for all soil types. TU Delft has led an RVO-backed Dutch consortium researching 'Gentle Driving of Piles'.[ix] This involves installing the pile by rotating about its central axis, as well as vibrating it along its axis.
- Long-impulse pile driving. IQIP's Blue Piling technology, as an example, may offer high energy, scalable piling suitable for XXL MPs with reduced underwater noise and installation fatigue.[x]
- Water jetting at the pile toe. Can be used to reduce driving loads, in conjunction with other installation approaches. GBM Works is developing this approach to reduce piling noise in conjunction with vibration piling.[xi]
- Drilling of piles. This is useful where there are special site conditions. It is at an early stage of maturity and has the potential to be optimised further.

Operational innovations

Key innovations include:

- Asset monitoring and life extension. This can be supported by digital twins.

- Simplifying / removing boat landing and personnel access. A solution has been demonstrated by Ørsted, using the Pict device. This has been ordered by Ørsted for its upcoming US projects.[xii]

Decommissioning innovations

Key innovations include:

- Hydraulic extraction. The HyPE-ST project researching use of high-pressure water within the MP to remove the entire pile. This would avoid cutting the pile and leaving the buried section in the seabed.[xiii]

Figure 9 Examples of piling technology. Clockwise from top left: IQIP's "Integrated Monopile Installer" noise mitigation system, AdBm/Van Oord's "Noise Abatement System", IQIP's Blue Piling technology and PVE's vibro hammer (source: suppliers' websites).

2.3 Jackets

2.3.1 Characteristics

Jacket foundations, as shown in Figure 10, use several widely spaced legs to give a structure with high stiffness. These legs are prevented from buckling by cross braces. Three legs have taken over from four become the norm. A transition piece at the top takes the loads from the tower base and transfers them into the legs – this is an integral

part of the jacket structure. At the base of each leg, a pin pile is normally used to secure the leg to the seabed via a grouted joint, though other solutions exist.
Jackets have a long legacy from oil and gas. Key characteristics include:

- Jackets are wider, shorter, lighter but more complex than MPs, with greater seabed footprint, but have higher fabrication costs per tonne
- Jackets can be used in challenging ground conditions, for example where it is too soft or too hard for an MP, using an appropriate anchor type
- Jacket cost increases more slowly with depth than for MPs, so tend to be used at greater depths
- Series fabrication requires industrial expertise to complete an average of one per week, the sort of throughput needed for a typical project, and
- Jacket installation is relatively complex and expensive compared to MP installation as it requires several process steps including piling (pre or post), jacket installation, jacket levelling and grouting.

Figure 10 Four-legged jackets en-route to the Wikinger wind farm (source: Iberdrola).

2.3.2 15MW reference design estimate

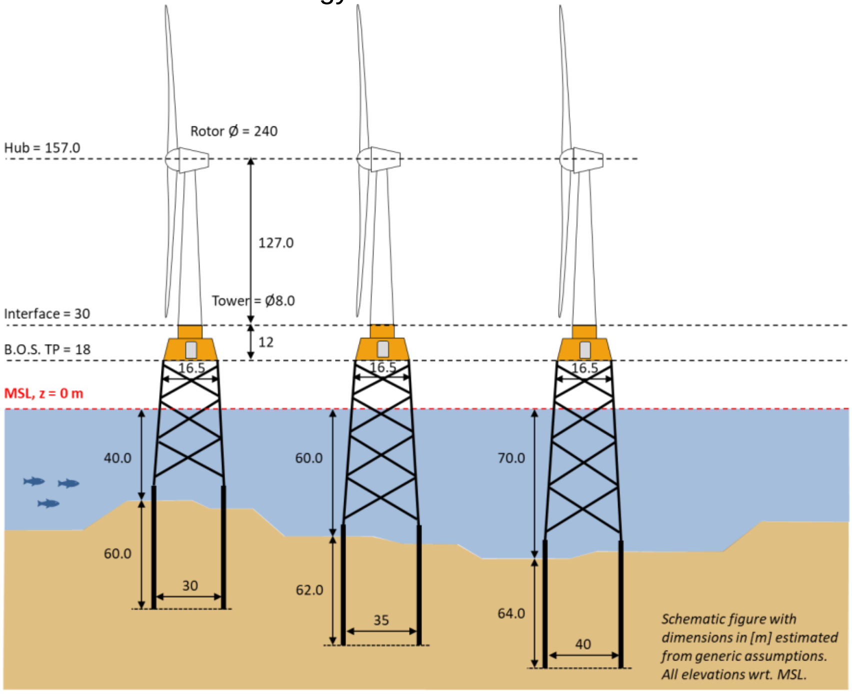
The reference design is a three-legged jacket with pre-piled pin piles. It has a welded transition piece which accommodates the tower access door and, within it, the HV electrical equipment.

The masses of jacket with TP and pin piles at 40, 60 and 70m water depths are estimated as: 2,525t, 2,883t and 3,116t. At water depth, 60m this is slightly less steel than for a MP at a site with central conditions.

The reference designs are estimated for the reference site conditions and use a reference wind turbine design. They are outline designs and estimated quantities based on experience and without the detailed level analysis required for a specific project.

Pin pile penetration, and so also mass, depends heavily on the soil profile. For extremely good soil, the penetration could be as little as 40m. For poor soils, it could be up to 80m.

For further detail on the jacket reference designs, see BVGA – Outlook on Fixed vs. Floating Wind Foundation Technology.[i]



Schematic figure with dimensions in [m] estimated from generic assumptions. All elevations wrt. MSL.

Figure 11 15MW reference designs for jackets.

2.3.3 Technical considerations

The key technical considerations for designing a jacket foundation are:

- Seabed conditions. This will drive the seabed interface type and detailed design.
- Loading. Seismic loads, for example, require longer pin piles along with stronger legs and possibly four-legged jackets.
- Natural frequency. This is less of an issue compared with MPs, as jackets tend to be relatively stiff and there is high flexibility to change frequency.
- Managing jacket complexity for different depths and ground conditions across a site. The set of variants used at East Anglia One, which shared a common footprint and piling template, is a good example although note that pin pile length is still likely to be site-specific.
- Vessel interface for OMS. This requires site and operator-specific consideration.
- Design for manufacture. The focus will normally be to limit the cost of the relatively complex welded features, although this is made more difficult as engineers

normally design for a range of factory capabilities as the jacket supplier is not known at the design stage.

2.3.4 Main variants

The main jacket variants are:

- Legs: three or four
- Bracing: Z, K or X, which are named after the shapes made by the cross-bracing, and
- Seabed interface: pre-piled, post-piled or suction anchors.

2.3.5 Pain points

Key pain points driving innovation are:

- Manufacturing. Is more challenging than for MPs, due to the more complex shape and larger overall size.
- Transport. A complete jacket is significantly larger than an equivalent MP, so adds to the cost of transport and installation.
- Installation. Campaigns require several stages, including piling, jacket installation, jacket levelling and grouting, which results in a relatively high installation cost.
- Installation. Vessel and crane requirements increase with increasing mass, and key dimensions.
- Installation. There can be degradation of the grouted connection from loads incurred before the grout has reached its full strength.
- Decommissioning. Cutting piles at the mudline is expected, full removal is not cost effective.

2.3.6 Expected innovations

Design

Note, there are many patents to negotiate in this area:

- Node design and optimisation. The use of cast steel nodes has the potential to provide a better shape than welding of tubulars, resulting in smaller tubulars on main legs and braces, for example the EUDP HI5Jack project [xiv]
- Wrapped composite joints. These could avoid welding of tubular joints, see Figure 12.[xv]
- Impressed Current Cathodic Protection (ICCP). Increased use for corrosion protection, it has the potential to be lighter, cheaper with less effect on seawater, although sacrificial anodes are still being widely used as they are well proven, see Figure 13Figure 13.

Manufacturing

Key innovations include:

- Automated welding of tubular joints and nodes. This requires predictable volume to justify investment.
- Electron beam welding. This is applicable to both MP and jacket fabrication.
- Post weld treatment. As for MPs, improvements are expected for grinding, hammering, deep rolling and profiling.
- Splitting of final assembly activity from fabrication yards. This has the potential to make better use of fabrication yard capacities.
- Automatic joint manufacturing to mitigate handling issues as assembled mass of prefabricated tubular joints increases for larger jackets in the future.

Installation

Key innovations include:

- Vibration piling. Increased use, as previously described for MPs.
- Suction caissons. Increased use, these have been used on projects including the European Offshore Wind Deployment Centre, Borkum Riffgrund, see
- Figure 14, and Seagreen. In future they are expected to be used where ground conditions do not permit conventional piling. They are good for speed of installation, noise and will allow full removal, but increase overall jacket dimensions for transport and installation.

Operations, maintenance and service (OMS)

Key innovations include:

- Asset monitoring and life extension. This can be supported by digital twins, to understand loads better for both design optimisation and for predicting and managing through-life reliability.
- Risk-based maintenance. This can reduce maintenance based on increasing knowledge of what is most likely to be needed.

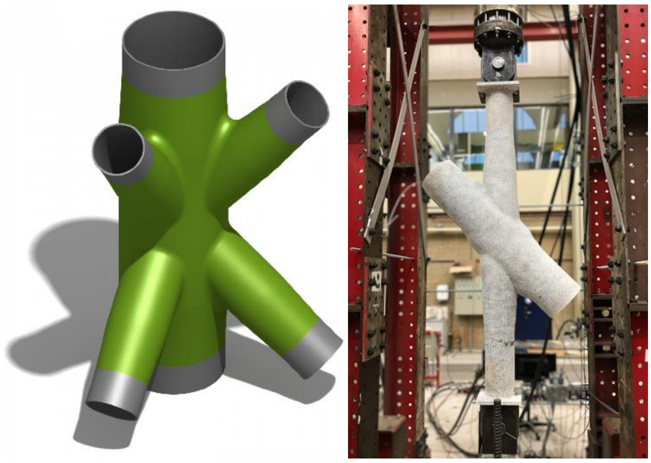


Figure 12 A wrapped composite joint design and a joint under test (source: GROW)

Figure 13 ICCP anode fitted on a transition piece (source: Corrosion.nl).

Figure 14 Jacket with suction anchors being installed at Borkum Riffgrund (source: Framo).

2.4 Gravity base foundations

2.4.1 Description of characteristics

Gravity base foundations (GBF), as shown in Figure 15, are based on well-understood principals originating from structures supporting oil and gas platforms. A GBF structure typically has a larger volume than an equivalent MP and it has a much higher mass than a MP or jacket. To date they have had lower uptake than MPs or jackets and have typically been installed in calmer, shallow waters (<20m).

Current and planned future usage of GBFs on larger projects is limited to: Fécamp in France where the GBFs are under construction, see Figure 17 and Empire Wind in the US where GBFs are being considered, although even here their use is reported to be in doubt.[xvi]

GBFs are suitable for relatively specific high-load-bearing soils due to the way loads are transmitted to ground. These include sites unsuitable for piling. Each foundation occupies a large area of seabed, which requires preparation to ensure it is flat enough. The design of GBFs typically use reinforced concrete for the primary structure with integrated cells (chambers) to take ballast once the foundation is sited. A cylindrical/conical shape provides for both a structurally efficient structure and the storage of ballast. Ballast of varying density can be used. The use of higher density ballast will reduce the size of a foundation, or a proportion of higher density ballast can be used in those foundations that see higher loads.

Construction by erecting formwork or slip-forming requires a large area and can take place on a quayside, in dry dock or on barges. Transporting and installing concrete GBFs can be challenging due to their relatively high mass compared to all other foundation types, with the dry mass of a 15MW GBF for water depth 60m being more than 10,000t. Due to craneage limitations semi-submersible vessels can be used to transport and install GBFs, or higher-volume versions could self-float and be towed out to site prior to installation.

The use of concrete, as a non-specialist construction material, can be attractive in markets seeking to increase local content, where the capability of the local steel fabrication industry does not support manufacture of MPs or jackets, or in response to high steel prices.

Once installed, concrete GBFs offer a low-maintenance and durable solution.

Figure 15 BAM Nuttall concrete GBFs for Blyth windfarm, using steel shafts (source: BAM).

2.4.2 15MW reference design estimate

Designs for four reference depths were provided for this analysis. All conformed to a standard ballast-filled conical design with slab base and cylindrical shaft to interface with the tower. The transition from cylinder to cone is gradual which allows post-tensioning to run continuously from base to the top. A bolted cage connection is used for the interface to the tower, as this is well proven. No skirt around the base is used (that can sink into the seabed under some ground conditions to create a suction caisson). Note, this design is not self-floating so requires dry transport to site. The design is seen in Figure 16.

The masses of the concrete structure with steel reinforcement and post-tensioning reinforcement at water depths of 30m, 40m, 50m and 60m are estimates as 5,800t, 7,700t, 9,600t and 11,800t respectively.

The reference designs are estimated for the reference site conditions and use a reference wind turbine design. They are outline designs and estimated quantities based on experience and without the detailed level analysis required for a specific project. Variation will also result from design choices, especially within the lower level of design maturity for GBFs compared to MPs or jackets.

For further detail on the GBF reference designs, see BVGA – Outlook on Fixed vs. Floating Wind Foundation Technology. [i]

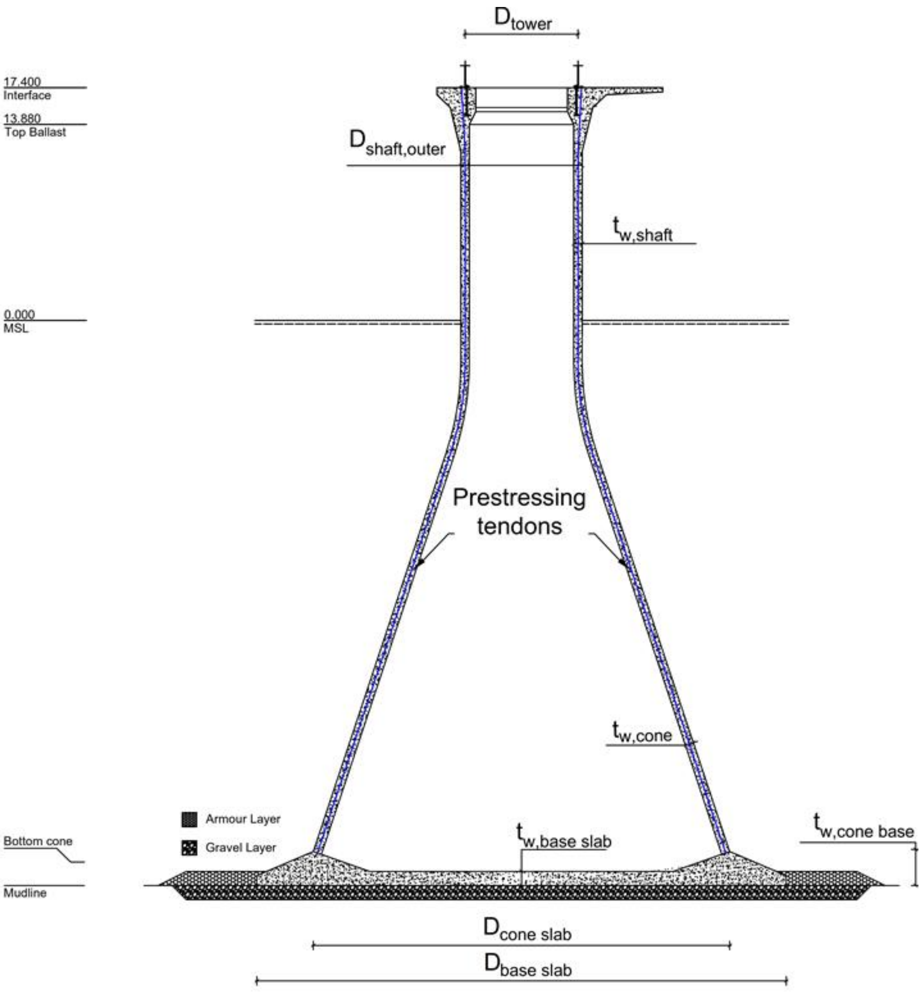


Figure 16 Concrete GBF 15MW reference design (schematic figure with dimensions in [m] estimated from generic assumptions).

Anticipated construction and installation approach

The design will be manufactured on a quayside or on barges. The base is cast first with protruding rebar. The cone and shaft can either use traditional formwork, slip-forming or jump formwork. Slip-forming is the most efficient for high volumes.
Manufacturers prefer to pre-tension from the base, so there will, ideally, be a pre-stressing pocket under the base. It may be possible to apply some tension onshore and complete the tensioning offshore, otherwise need to wait up to 28 days before concrete has reached full strength.

Transport to site will be by barge. Many changes, including additional volume, would be needed to enable this CBG to be floated to site with sufficient stability.
The seabed will be prepared in stages, typically: 1-1.5 m dredge, or several metres if soil has low bearing capacity. Lay sand and/or gravel layers. Check level and flatness before installation.

The GBF is then transported to site on a standard barge or semi-submersible transport vessel and lifted or floated into position. The ballast chamber is then flooded before the ballast material is pumped in. The GBF is finally secured by armouring around the circumference of the base slab.

A set of GBF designs for high density ballast (olivine green sand) were also developed. The use of higher-cost olivine allows for lower volume designs but is constrained by availability of this material close to installation sites. The reference designs using standard density ballast were chosen for this analysis, as high-density ballast is less widely available.

2.4.3 Technical considerations

The key technical considerations for designing a gravity base foundation are:

- Load conditions. Design loads include turbine, wave and seismic loading, and the effect of water depth,
- Seabed conditions These include flatness, soil type, soil homogeneity and scouring requirements.
- Foundation/ tower interface. This is the detailed design of the joint, normally concrete to steel.
- Tensioning. This is the detailed structural design and process to allow efficient tensioning. If partial tensioning can be carried out before the concrete has cured fully it may enable a reduction in the construction space required by allowing the structure to be transported earlier than it might otherwise be.
- Seabed preparation. This is the specification of the gravel sub-layer(s) and detailed design of the GBF-base where skirting can be considered.
- Installation approach. This is about deciding between the use of general-purpose transport and heavy lift vessels versus a float to site and sink approach.

2.4.4 Main variants

The main GBF variants are:

- Riser shaft. Steel or concrete.
- Ballast options. Standard density sand versus more dense options.
- Reinforcement. The use of pre-tensioning versus post-tensioning or a combination of both.
- Pre-cast. Whether fully cast in-situ or use of any pre-cast elements.
- Installation. Designed for conventional dry transport and installation versus float to site and sink, which requires a GBF with much greater stability.

2.4.5 Pain points

GBFs make up a small part of the offshore wind foundation market because they are seen as being higher cost than the alternatives. Most of the following pain points relate to cost rather than technical issues:

- Mass production. There are so few projects that have used gravity bases that there is no ecosystem of innovation that is driving standardisation, efficiency and economies of scale.
- Construction space requirement. The manufacturing and laydown space driven by the footprint and long cycle time is higher than other bottom-fixed foundation types.
- Relatively high mass. Construction sites require ground with high bearing capacity and high dock crane capacity, drydock or alternative to move GBFs from their construction location to be ready for transport.
- Installation vessels. Vessels that can lift 5,000-10,000t have high cost and limited availability.
- Sustainability. There is growing concern over the embodied carbon content of wind projects. Lower-carbon cements are already available, although there is no clear path yet to cement manufacture with zero embodied carbon.

2.4.6 Expected innovations

Key innovations include:

- Industrialisation of the construction process. This is expected to reduce labour and elapsed time and hence cost. As an example, see announcement by Ideol that it will partner with Bygging Uddemann to develop serial manufacturing for concrete floating foundations for offshore wind.[xvii] See also Figure 17.
- Industrialisation of construction logistics. Solutions are expected to enable movement of GBFs onland and from land to be ready for sea transport.
- Design for installation. Further innovation is expected on float-to-fixed (F2F) concept, examples include:
- Seatower's "Cranefree Gravity" GBF: a self-floating solution that uses tug boats for installation, see
- Figure 18,[xviii] and
- Arup/Costain/Hochtief's "Gravitas" GBF: a self-floating solution with no heavy lifting, no special vessels and minimised seabed preparation, see Figure 19.[xix]

The ultimate solution would include the turbine pre-installed on the foundation, but with low-cost transport solution providing sufficient stability. Much innovation is expected before common ways of transport and installation become established.

Figure 17 Industrialised construction of GBFs by Bouygues Travaux Publics at Le Havre for Fécamp (source: Bouygues).

Figure 18 Seatower's self-floating GBF being towed with an offshore met mast to its installation at Fécamp (source: Seatower).

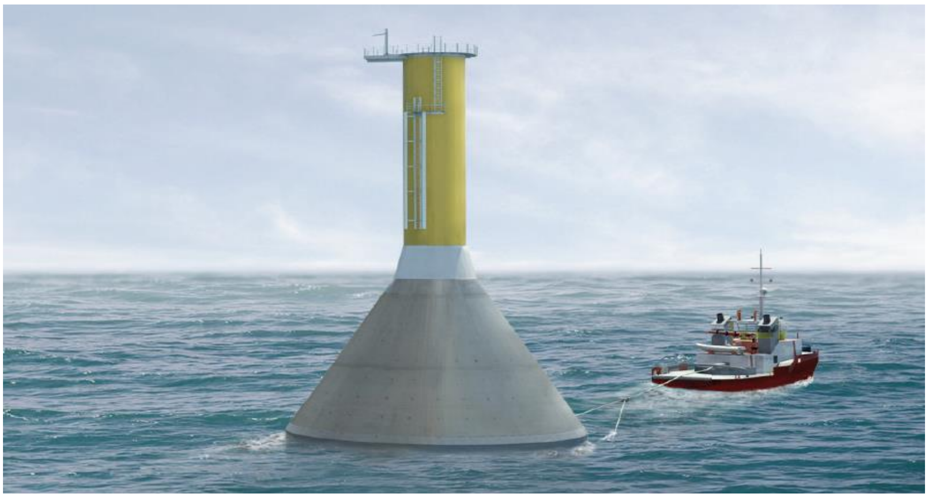


Figure 19 Arup/Costain/Hochtief's Gravitas self-floating GBF (source: Arup).

2.5 Semi-submersible floating foundations

2.5.1 Characteristics

There are at least 50 designs for floating foundations currently being proposed by technology innovators for offshore wind, with a wide range of different characteristics and performance. Figure 20 presents the four main floating foundation concepts. This section describes the strengths, limitations, and status for each of these.

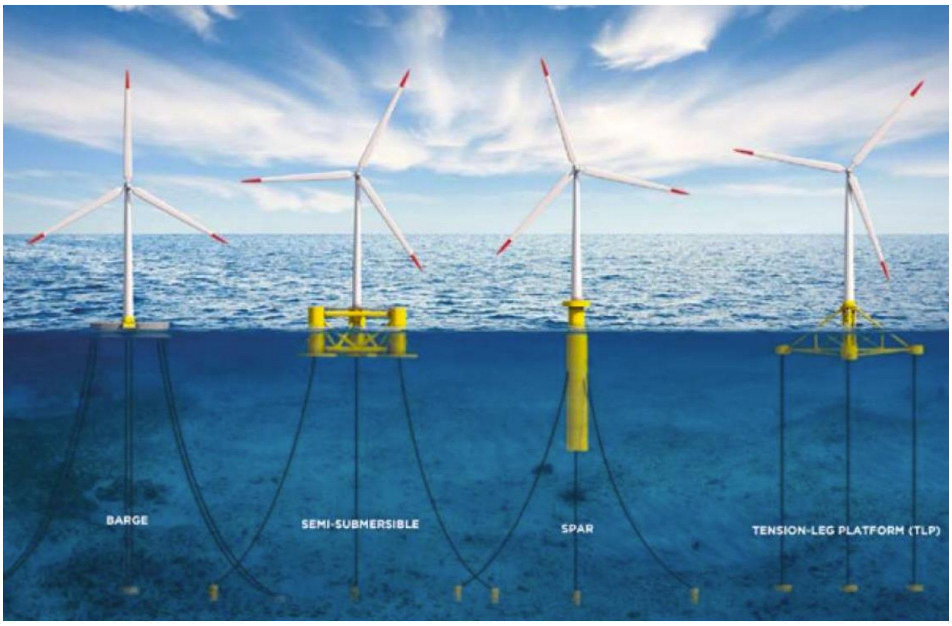


Figure 20 Floating turbine concepts (left to right): barge, semi-submersible, spar and tension leg platform (source: WindEurope).

Barge

Barge foundations have a single hull that pierces the waterline. The overall dimensions of the hull are smaller than an equivalent semi-submersible foundation, with a square (rather than elongated) shape to prevent motion of the turbine. The turbine can be erected onto the barge in a sheltered harbour then towed to the installation site because the combined structure is stable in transport. Barge structures are suitable for use in water to as shallow as 30m. Barges may experience large heave motions in extreme weather conditions when the wave period is close to its heave natural period.

Semi-submersible

Semi-submersibles are large structures based on assembly of multiple columns and pontoons. Designs are based on oil and gas experience, where they have a proven track record. Prototypes were first introduced in 2011 but design variants are yet to converge. They have high relative mass (intermediate between spars and tension-leg platforms) to provide sufficient buoyancy and stability. The large footprint also requires large storage and marshalling areas, dry and wet.

Semi-submersible hulls have low draft (compared to spars) that can be changed by ballasting for towing and operational conditions. This enables quayside turbine installation with the complete structure stable for tow-out and installation. Tugs and anchor handling vessels can be used in broad weather windows, reducing the need for specialist vessels.

Beyond their high relative mass, the main concern is that semi-submersibles experience large heave motions in extreme weather conditions when the wave period is close to their heave natural period. Semi-submersibles experience higher wave-induced motions than spars, but lower than barges.

Spar-buoy

Equinor installed the worlds' first small floating array, in 2017, of five 6MW turbines using spar-buoy foundations at Hywind Scotland. Each turbine sits on a 91m steel tube of up to 14.5m in diameter. When ballasted with dense aggregate to 11,200t, each spar floats with nearly 80m draft, chained down to three suction anchors.

Equinor is currently building a concrete version of its spar-buoy for the Hywind Tampen project. This project is made up of 11 SGRE 8,0MW turbines which will power the Gulfaks and Snorre oil fields. The sea depth is between 260 and 300m across the site.

Spar-buoy foundations receive stability as a consequence of their deep draft which makes them less affected by wind, wave and current compared to other floating foundation types. The turbine to hull assembly requires deep water adjacent to the quayside or sheltered assembly site, such as can be found in Norway but not so readily in other markets. The deep draft also limits options for tow-back for major-component replacement, if required.

Tension leg platform

The Tension Leg Platform (TLP) concept differs fundamentally from other concepts, since it is the tendon stiffness rather than the water plane area stiffness that dominates the vertical motions.

It benefits from the lowest structural mass and lowest platform motions of the three floating foundation types. The limited platform motions of a TLP structure can reduce the structural loadings on the turbine and array cables compared to other floating structures. TLPs are well established in the oil and gas industry but have not been used with wind turbines, up to now, on any commercial-scale demonstration projects. As the mooring system is critical to stability there could be reluctance to use it in areas prone to seismic loadings, or requirements to include redundancy in the mooring system.

The form of TLP that is expected to be used for floating wind turbine applications is a star-pontoon arrangement with minimal structure piercing the waterline and minimal steel mass.

A significant difference from the oil and gas industry is the need to erect a turbine on top of the TLP. If this were to be done in port it would not be stable on its own to transport to site (without a transport and installation barge), and if it were erected after the TLP had been installed it would require at least one floating-to-floating lift at sea.

The first full-scale demonstrator of OSW TLPs is expected to be installed in late 2022 at Provence Grand Large, in France, using SBM's design.

2.5.2 15MW reference design estimate

Each main concept has strengths and weaknesses, and the relative suitability varies according to location-specific factors. The most common main concept with widest applicability is the semi-submersible, which is why it has been chosen as the basis for the reference design. See example in Figure 21.

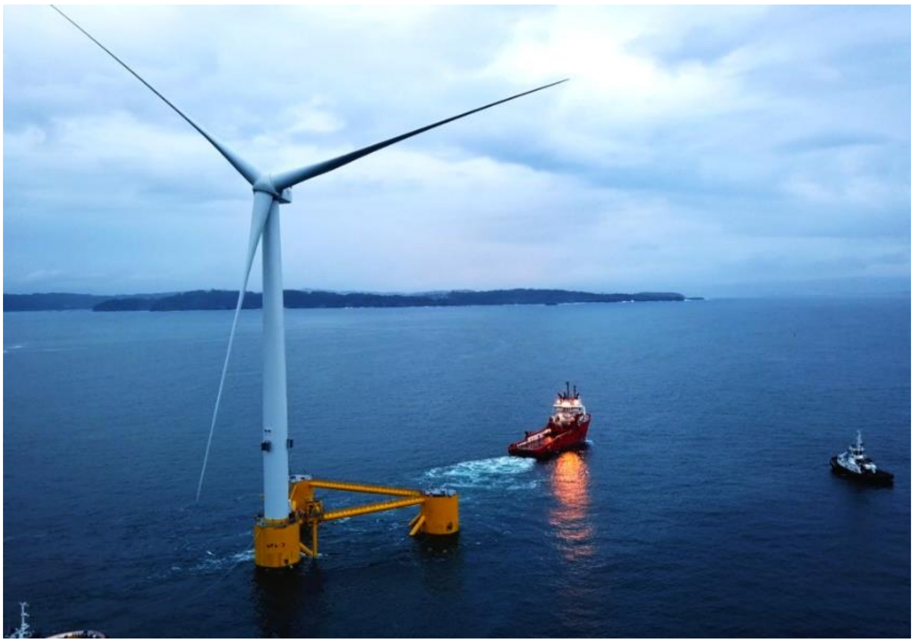


Figure 21 Principal Power's WindFloat semi-submersible and MHI Vestas V164-8.4 MW turbine under tow, Portugal (source: evwind.es).

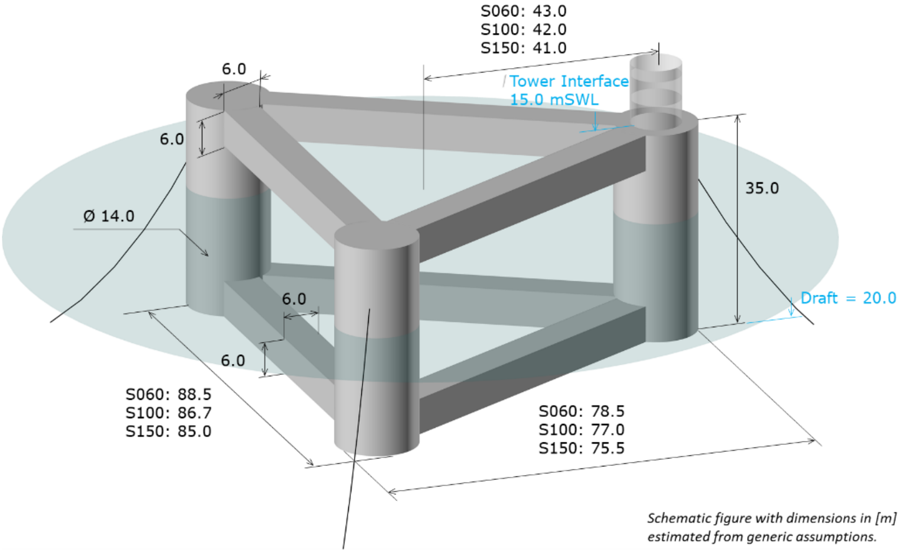
For this analysis, the reference design estimates are based on a generic semi-submersible consisting of three cylinders connected by truss elements and pontoons (at top and bottom of the cylinders, respectively) with eccentric tower placement. Dimensions estimated for the designs specified for 60m, 100m and 150m water depths are shown in Figure 22. Masses, excluding secondary steel, are 3,500t, 3,450t and 3,400t respectively for the floating foundation with a further 650t, 640t and 635t for the rope, chain and anchors of the mooring system. The reference design uses piled anchors.

The mass of the floating foundation decreases marginally as water depths and overall floating foundation dimensions increase. This is based on forces from the mooring lines which contribute to the restoring moment of the structure. Those forces depend on the angle of the mooring lines which change with on water depth.

The damping effects of the box pontoons’ large surface area eliminates the requirement for heave plates. Stabilisation can be provided by an active ballast system moving the centre of mass. Complexity of stabilisation features is likely to depend on specific site conditions. This reference design is intended as a central solution for the likely range of complexity seen in future markets.

The reference designs are estimated for the reference site conditions and use a reference wind turbine design. They are outline designs and estimated quantities based on experience and without the detailed level analysis required for a specific project. Variation will also result from design choices, especially within the semi-submersible concept.

For further detail on the semi-submersible reference design, see BVGA – Outlook on Fixed vs. Floating Wind Foundation Technology.[i]



Schematic figure with dimensions in [m] estimated from generic assumptions.

Figure 22 Steel floating foundation15MW reference design. Dimensions shown in metres and common unless specified for 60m, 100m and 150m reference depths.

2.5.3 Technical considerations

The key technical considerations for designing a semi-submersible foundation are driven by the metocean conditions, the choice of turbine and whether the main material is concrete or steel:

- Stability - Providing stability from extreme wave loading and avoiding natural frequency convergence of turbine structure and waves and creating restoring forces through waterplane stabilisation (pontoons or heave plates), low centre of mass, and active ballast systems.
- Tilt limit - Static impact on turbine energy yield and maximum loads at the tower base inform the need for active ballast systems should passive ballast be insufficient.
- Installation requirements - The maximum towing draft is especially relevant for heavy concrete semis, although not so much for steel semis.
- Tower design - The approach to tower design can impact hydrostatic stability of the floater, for example heavy stiff-stiff tower versus soft-stiff tower.
- Managing the number of floating foundation design variants across a site. Different water depths and metocean conditions across the site mean that a single design will not be optimum at each location, so trade-offs need to be made regarding number of variants, impacting manufacturing complexity and cost.
- Mooring and anchoring. Site-specific conditions determine the types of anchoring and mooring lines required, in a similar way to other floating foundation types.

2.5.4 Main variants

The main semi-submersible variants are:

- Material:
  - Concrete. Floating foundation sections can be pre-cast and assembled or cast in-situ via either static formwork or slip-form formwork, see example in Figure 23. Concrete is seen as having advantages for enabling local content.
  - Steel. The design for steel fabrication is primarily optimised for either:
    - Cylindrical structures, manufactured via rolling and welding, see examples in Figure 24, or
    - Panel construction, this type of construction is more typically used for shipbuilding and could be important for optimising the manufacturing process to local capabilities, see examples in Figure 25.
- Number of columns - The most common designs feature three or four columns connected either by pontoons and/or bracings.
- Tower configuration - Placement is either centric or eccentric. Eccentric has the advantage of reducing the maximum reach for turbine installation, as a centric 15MW nacelle lift is beyond the capability of most current land-based mobile cranes. Even if onshore cranes were available, the ground bearing capacity could become an issue at ports, hence, a crane vessel might be necessary for

assembly. Other factors to consider in this trade-off are that: an eccentric design can avoid an additional column, but a centric design is a more efficient structure to provide stability for all wind directions.

- Bracing - There are braced and brace-less designs.
- Counterweight - Some designs use separate counterweight or keel ballast, e.g. Stiesdal TetraSpar.
- Mooring system - There is a choice of whether to use steel chain (catenary) or synthetic mooring lines for hybrid mooring configurations (semi-taut or taut systems). Some synthetic materials may need additional qualification or certification for permanent mooring application. Note, tension leg platforms use a completely different type of mooring.

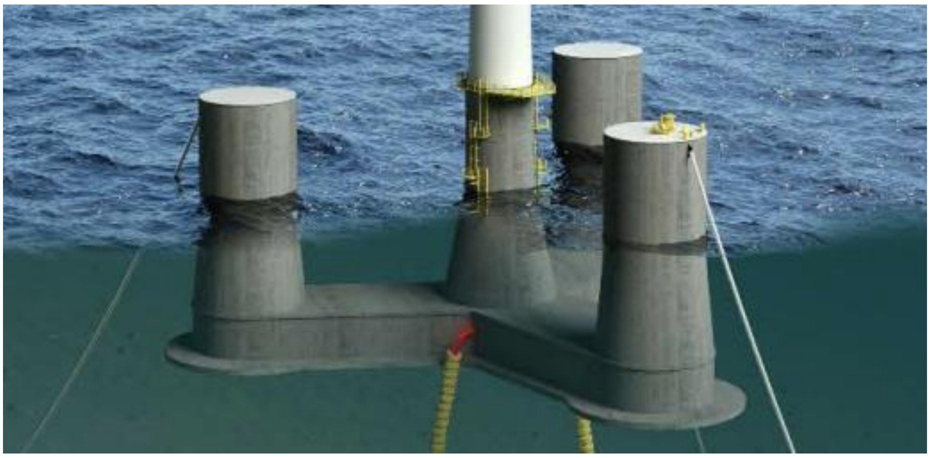


Figure 23 The OO-star semi-submersible concrete floating foundation designed for the Flagship project (source: Flagship project).

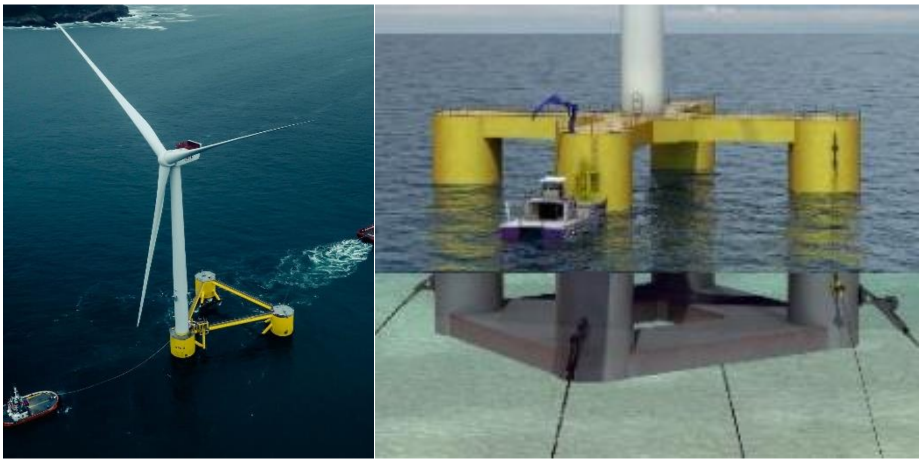


Figure 24 Principle Power’s WindFloat and Nautilus Floating Solutions’ Nautilus floating foundations (source: suppliers’ websites).

Figure 25 Gusto MSC's Trifloater and Equinor's semi-submersible (source: Gusto and Equinor).

2.5.5 Pain points

Floating offshore wind has yet to be deployed at scale and has some significant differences from bottom fixed. Differences, and pain points, are seen particularly around transport and installation, and for major repairable events.

Design and manufacture

Key pain points are:

- Complex transition of loads from tower into the floating foundation.
- Active ballast systems are beneficial, although Principle Power has a patent on its system.
- Larger structure dimensions are required for increasing turbine size.
- Manufacturing at scale is challenging, based on the large foundation space requirement.
- Transfer of the complete, high mass structure from land (for manufacture) to sea (for transport).
- Broad range of concepts leading to patent issues hampering scale of deployment for proof of concept and volume-based efficiency - large cost reductions are still required to achieve cost parity with bottom-fixed. It is too early to pick winners amongst the semi-submersible solutions with any certainty, let alone across all floating foundation types.

Installation and OMS

Key pain points are:

- Some floating foundation designs require shipyard-type construction, introducing the need for dry dock fabrication facilities instead of quayside assembly (as used by the Stiesdal TetraSpar).

- Crane requirements (lifting height, payload limits and outreach) for centric tower configuration are higher than for eccentric tower placement and cannot be met with mobile, land-based, cranes.
- Uncertainty about transport and installation and OMS strategies remains as deployment at scale for any concept has yet to be achieved.
- Active ballast system adds OPEX.
- Large volume structure with many joints in a dynamic environment introduces fatigue risks.
- Confidence in the reliability of dynamic power cables, for turbines, and especially for floating substations.

2.5.6 Expected innovations

Design and manufacture

- Shared anchors supporting multiple mooring lines and interconnecting mooring system solutions, i.e. mooring lines connecting multiple units.
- Novel materials for synthetic mooring lines in permanent applications, e.g., Nylon.
- Peak load reduction systems for moorings.
- Active ballast system developments.
- Simplification and optimisation to reduce the requirement for specialist fabrication and therefore increase industrialisation.
- Fabrication related, such as automatic welding techniques.

Installation and OMS

- Aspects of accessibility/transportability and workability.
- Connection and disconnection procedures and equipment., for mooring lines and array cables.
- Major component exchange strategies including tow-to-port or sheltered waters versus offshore on-site operations.
- Inspection requirements, i.e., time-based versus risk-based approach.
- Innovations in wind turbine control based on improved understanding of wind farm effects such as induced motions from operation in partial wakes and impact of floating foundation motions on energy yield.
- Asset integrity monitoring and the use of digital twins: to understand loads, improve designs and extend lifetimes.

3 Potentially disruptive innovations

3.1 Monopiles

Potentially disruptive innovations include:

- Collared MP - This has recently been prototyped on three piles at Kaskasi by RWE, see Figure 26, it adds support to the MP at the seabed and may allow the use of a MP where not previously possible.[xx]
- SPT's tri-suction pile caisson - This sub-sea foundation, see Figure 27, uses a structure that will sit on the seabed to join three suction piles to a vertical column that rises to the base of the tower.[xxi] The transition point from a centric column to a wider base is a major structural challenge, which handles higher loads the lower it is (relative to a typical jacket which does this above the water). It would be considered most promising if the lower section is in concrete.
- Slotted MP - A MP with longitudinal welding removed. Mentioned by RWE in its supply chain plan for Triton Knoll, but not seen elsewhere.[xxii] It introduces stress-raisers due to the absence of longitudinal welds.
- Universal Foundation's Mono-bucket - This was piloted unsuccessfully in 2019 when the two prototypes buckled during installation, but it is not known publicly why. After this, Fred Olsen withdrew its support from Universal Foundation.[xxiii] The concept has some loading upsides in terms of being stiffer and allowing lower-noise installation.

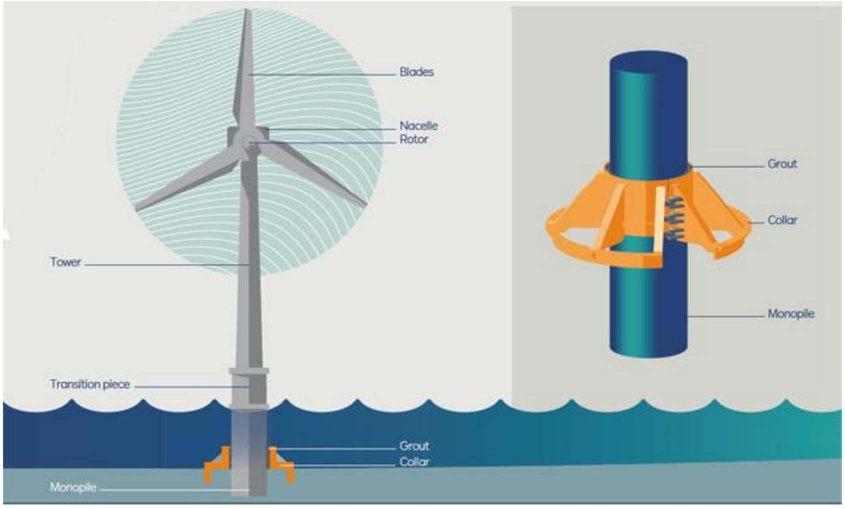


Figure 26 Collared monopile developed by RWE for Kaskasi (source: RWE).

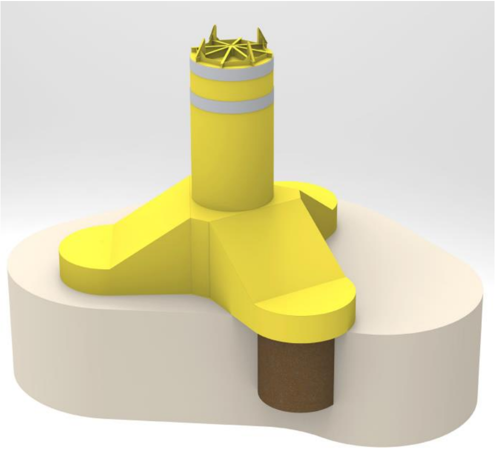


Figure 27 SPT's tri-suction pile caisson (source: SPT).

3.2 Jackets

Potentially disruptive concepts include the following, which are shown in Figure 28;

- Sif's Tripod - It was designed by Sif's in-house KCI-team and is effectively a value-engineered jacket structure, using fewer larger struts.[xxiv] It has a separate centric column to reduce the maximum lift. It is claimed to be a sturdier construction than the MP and easier to manufacture than a jacket.
- OffshoreTronic's Tripod Plus - This has a tripod base on the seabed, using piles and/or suction anchors, plus a MP section that slots in separately.[xxv] It is claimed to be suitable for depths up to 90m. The design has lots of overlapping steel in the joints which adds mass and cost.
- Stiesdal's TetraBase - This can be thought of as a simplified jacket.[xxvi] It has innovative joints enabling industrialised component manufacture, followed by rapid assembly at the construction base port. There is a trade-off between the benefits of industrialisation and the increased cost of the rapid joints.
- Keystone Engineering's twisted jacket. - This was proposed a few years ago, with claimed benefits of simplified manufacture, but has not been used on commercial-scale projects, other than for a couple of met masts.[xxvii]

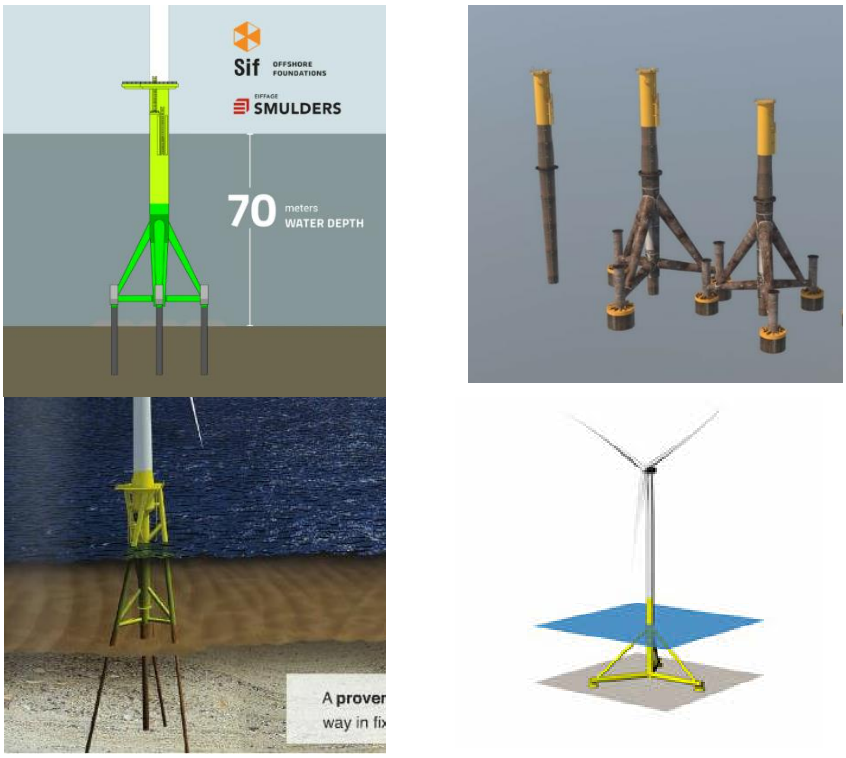


Figure 28 Potentially disruptive jacket designs. Clockwise from top left: Sif's Tripod, OffshoreTronic's Tripod Plus, Stiesdal's TetraBase and Keystone Engineering’s twisted jacket (source: suppliers’ websites).

3.3 Gravity base foundations

Potentially disruptive concepts include the following, which are all shown in Figure 29.

- OWLC’s Gravity Tripod - The base legs and transition piece are all made from concrete.[xxviii] The legs are spun pre-stressed concrete and are assembled to the base and transition piece using post-tensioning.
- ODE’s Articulated Water Column -This concept is included here as it has a gravity anchor at its base and is based on ODE’s experience with similar designs in the oil and gas industry.[xxix] It has recently been proposed for use at an Irish project.[xxx]
- Esteyco’s ELISA foundation - This is a float and sink GBF with a concrete telescoping tower.[xxxi] It has been prototyped in the Canary Islands. Its advantage is that it can be installed using a float and sink approach with the wind turbine already installed, although its complexity would be a limitation.
- MonobaseWind’s segmented GBF - This composite design allows for the turbine to be installed pre-tow. The segmented foundation allows elements to slide with respect to each other enabling efficient installation without specialist vessels.[xxxii]

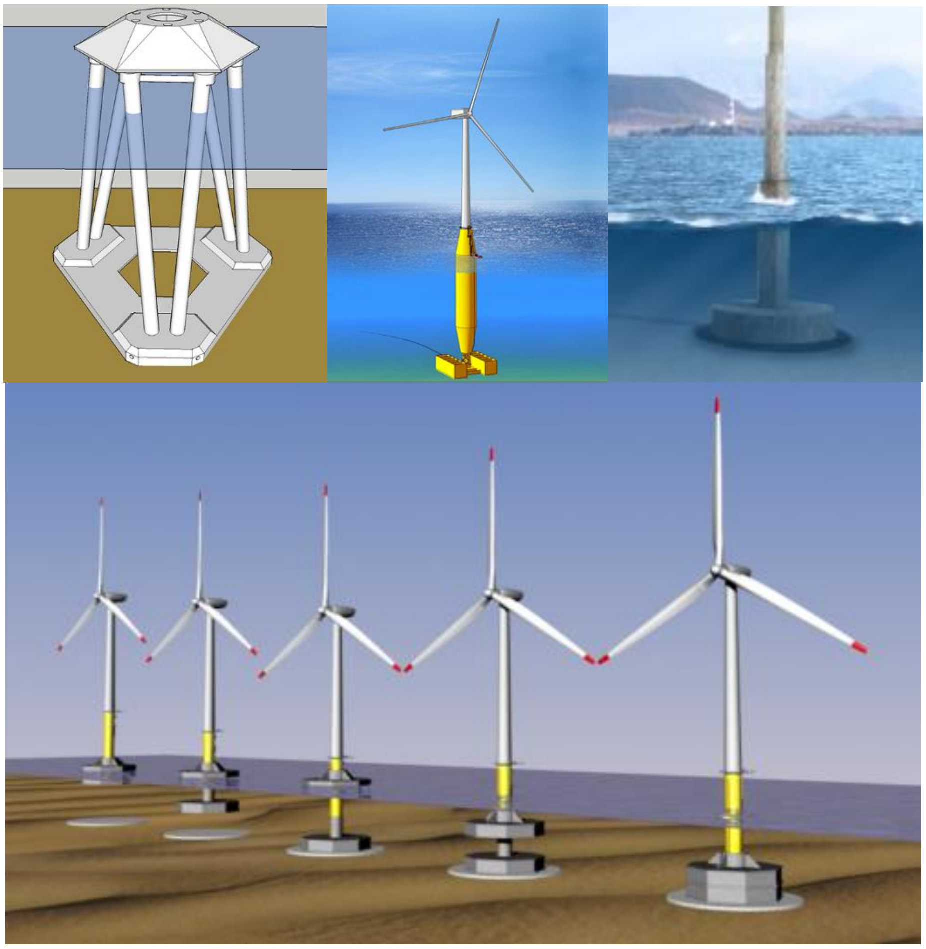


Figure 29 Potentially disruptive GBF designs. OWLC's gravity tripod, ODE's articulated water column and Esteyco's ELISA foundation, MonobaseWind’s GBF (source: suppliers' websites).

3.4 Floating, semi-submersibles

There are more potentially disruptive floating concepts than for bottom-fixed, as floating wind is still a relatively new area, The concepts included here as potentially disruptive are those that have not been demonstrated using a turbine of commercial scale yet. Many offer the potential for significant mass reduction, although a lesson from oil and gas is that the simpler the solution the better. The examples included here are intended to capture the major disruptive concepts but cannot capture every one as there are too many. Some could be used with semi-submersibles; others could replace them.
Potentially disruptive concepts include:

- Counterweight concepts - Examples include Stiesdal’s TetraSpar and Saipem’s Hexafloat, see Figure 30. These combine the benefits of a semi-submersible (shallow depth for transport) and a spar (stability from mass at depth).
- Pivoting about a single point - Examples include X1 Wind, Aerodyn’s Nezzy2 and Saitec’s SATH, see Figure 31. These use turret mooring/single point moorings,

which is already proven technology for Floating Production Storage and Offtake solutions (FPSO).

- Downwind rotor - Examples include X1's Pivot Buoy and Aerodyn's Nezzy2, see Figure 31 and Figure 32. These are typically enabled by a pivoting foundation and allow unconventional tower concepts such as tower braces, guyed towers or inclined towers.
- Multiple rotors - Examples include Hexicon, and Aerodyn's Nezzy2, see Figure 32. These are typically enabled by a pivoting foundation and have the potential to reduce the cost of the floating foundation and array connection per MW, having double the installed capacity on a single floating foundation.
- TLPs with vertical and/or inclined tendons - Examples include SBM's TLP and Gicon's SOF, see Figure 33. There is a lot of potential for mass reduction from the use of TLPs. Gicon's SOF also uses an innovative gravity anchor foundation to provide stability during transport and rapid installation.
- Vertical axis floating wind turbines - Examples include SeaTwirl's S1 and S2, see Figure 34. Vertical axis wind turbines on land have suffered from low coefficients of performance.
- Combined wind and wave energy devices - examples include Floating Power Plant (FPP), seeFigure 35.
- Floating offshore substations - Examples include BW Ideol, see Figure 36. When floating arrays are developed that are located too deep for bottom-fixed substations, at depths of perhaps greater than 100m, either floating or seabed substations will be required.

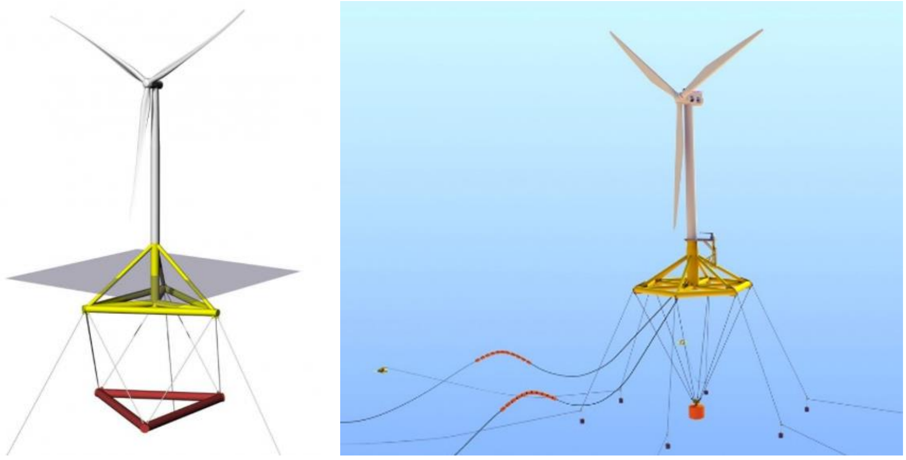


Figure 30 Floating foundations with counterweights: Steisdal's TetraSpar and Saipem's Hexafloat (source: suppliers' websites).

Figure 31 Floating foundations which pivot about a single point: X1’s PivotBuoy and Saitec’s SATH (source: supplier’s websites).

Figure 32 Floating foundations with multiple rotors: Hexicon’s TwinWind and Aerodyn’s Nezzy2 (source: suppliers’ websites).

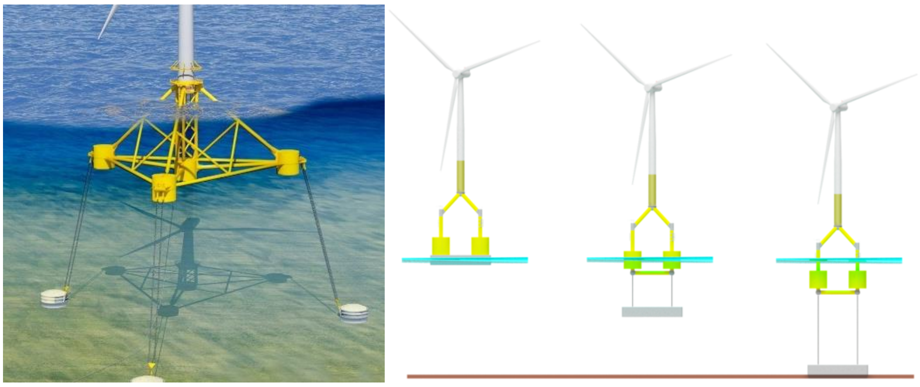


Figure 33 Tension leg platforms: SBM's TLP and Gicon's SOF (source: suppliers' websites).

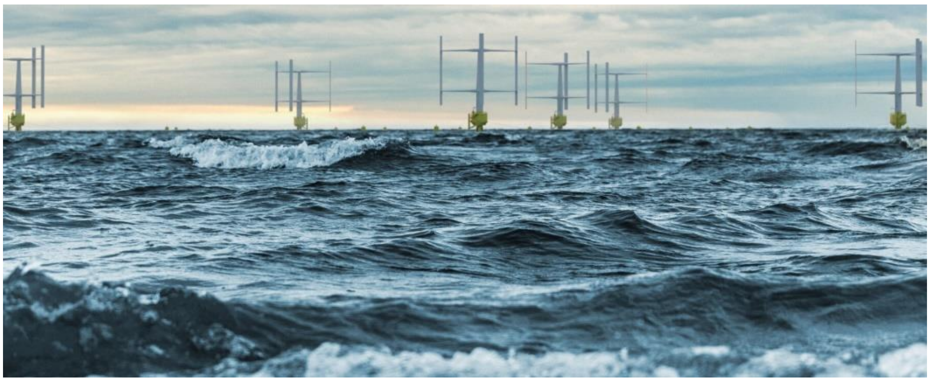


Figure 34 Vertical axis floating foundation: SeaTwirl's S2 (source: supplier's website).

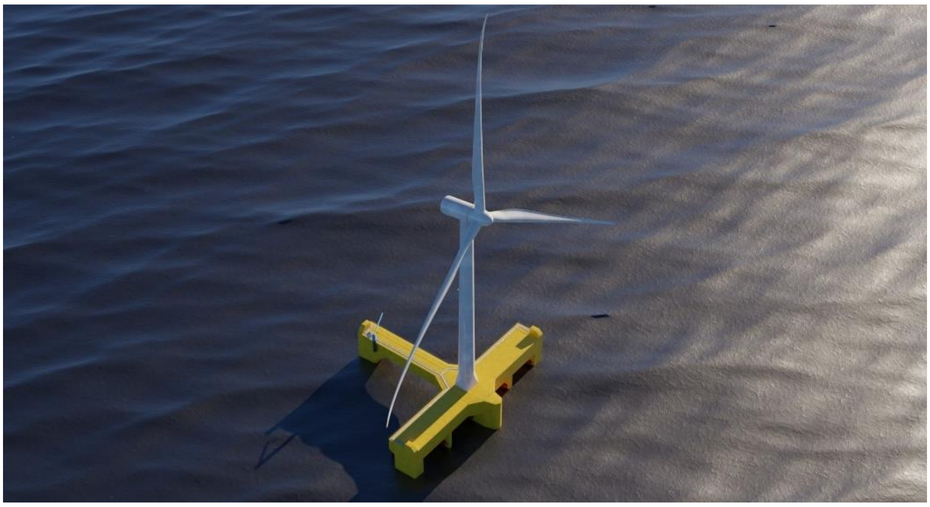


Figure 35 Combined wind and wave device: Floating Power Plant's platform (source: supplier's website).

Figure 36 Floating offshore substation: potential solution announced by Ideol in 2019 (source: Windpower Monthly).

3.5 Other

An interesting innovation is the use of subsea micro-piles installed using subsea robots, as proposed by Subsea Micropiles for floating anchorages. The use of a larger number of smaller piles would reduce the maximum piling noise.

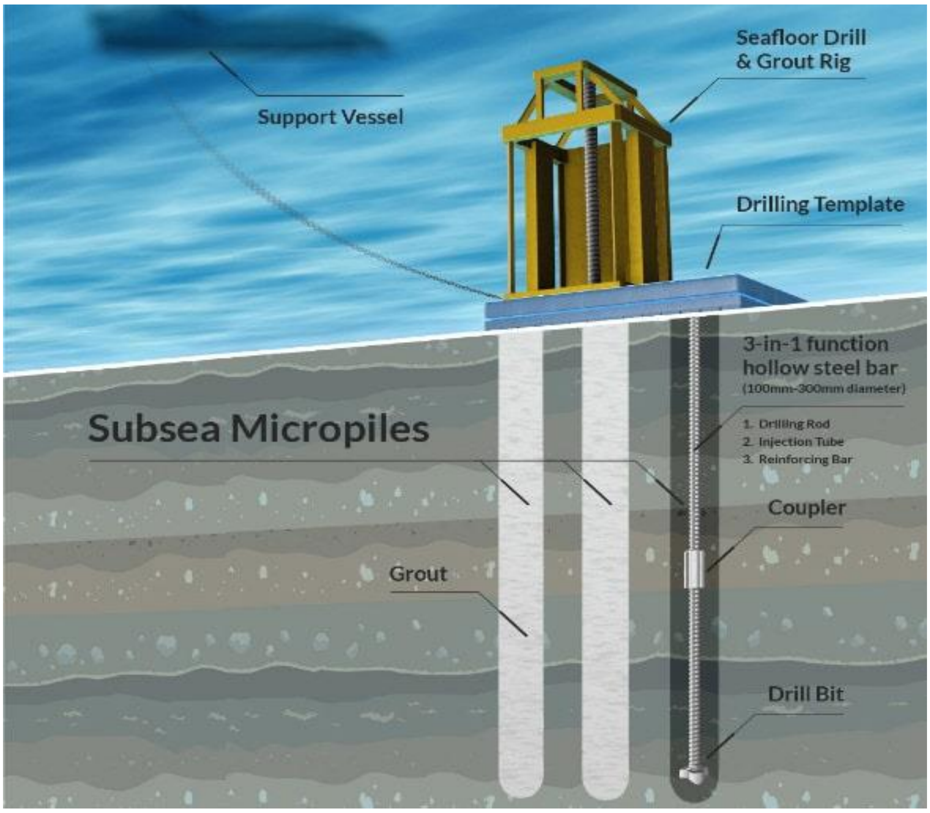


Figure 37 Micropile solution from Subsea Micropiles (source: supplier's website).

4 Foundation cost assessment

This section describes two cost assessments:

- The first is a quantitative calculation of the installed costs for the reference designs of the four foundation types explored, including expected innovations. We compare the installed cost of each design at different depths using a standard wind farm FID 2025 and compare these costs to FID 2030 to evaluate the impact of innovations on cost.
- The second is a qualitative assessment the merits of the potentially disruptive innovations identified, as there are too many to assess quantitatively.

4.1 Cost assessment of reference designs

4.1.1 Modelled offshore wind farm parameters

We defined key input parameters for consistent costing of the reference designs and installation campaigns. These are presented in **Fout! Verwijzingsbron niet gevonden.**. As transmission costs will be common across projects, and transmission connections are built for projects by the Dutch transmission system operator, we did not include the cost of transmission in the cost build up.

So that turbine generation capacity could be held constant across different foundation designs, we applied discounts where appropriate to reflect variation in wind turbine package costs based on different tower-foundation interface heights above sea level.

Table 1 Key wind farm input parameters

Parameter	Value
FID year	2025
Wind farm rating (MW)	500
Turbine rating (MW)	15
Distance to construction and O&M port (km)	60
Wind speed at 100m height (m/s)	9.5

4.1.2 Foundation cost modelling approach

We used reference designs for MP, jacket, GBF and semi-submersible design estimated by Ramboll as the basis for this modelling. The designs helped us build up a model of installed cost over five steps:

- **Step 1 - Foundation mass**

  The Ramboll reference designs were used to estimate the mass of the central variant for each allocated water depth, see

Table 2. The reference designs are estimated for the reference site conditions and use a reference wind turbine design. They are outline designs and estimated quantities based on experience and without the detailed level analysis required for a specific project. Variation will also result from actual site conditions and design choices, especially within the semi-submersible and GBF-concepts.

Table 2 Water depth-foundation combinations

Water depth (m)	30	40	50	60	70	80	100	150
Monopile		■	■	■				
Jacket		■		■	■			
Gravity base foundation	■	■	■	■				
Floating foundation				■			■	■

- **Step 2 - Component cost**
  We discussed with Ramboll the manufacturing approach for the 2025 FID cases for each design. We used our in-house cost/mass model to assign a €/tonne value for component manufacture for each foundation. This was based upon our extensive market trend analysis modified for the specifics of each reference design.
- **Step 3 - Installation costs**
  Based on our dialogue with Ramboll we defined the installation processes for each foundation type for 2025 FID. Using our in-house installation cost model, we costed installation campaigns for the reference wind farm. This enabled us to attribute a component installation cost for each reference design and water depth.
- **Step 4 - Total installed costs**
  We combined the component costs and installation costs to provide the total installed cost for each foundation type and water depth.
- **Step 5 - Innovated costs**
  We used the technical assessments in Sections 2 and 3 above to assign cost reductions based on modifying the learning rates in our LCOE model. We applied these cost reductions to the reference designs for 2030 FID keeping all other parameters constant. The result allowed us to compare the difference in installed cost based on anticipated innovations.

We used the modelling parameters from Section 4.1.1 and the modelling approach from this section to calculate costs for each combination of reference design and water depth. For example, using MPs at 40m depth and non-foundation costs from BVGA's cost model generates an LCOE of €50.5/MWh, excluding the transmission costs. Of this, the contribution of manufacturing and installation cost of foundations makes up 15%.

As the total installed foundation cost is a minor part of the total LCOE, for the purposes of comparing foundation designs we compare the total installed cost of each foundation, for the same 15MW reference turbine design, in the analysis that follows.

4.1.3 Foundation mass, 2025

The masses for the 15MW reference designs, for each water depth, are shown in Figure 38. To ensure comparability between foundation types:

- Masses include the major elements of the reference designs, for example the floating foundation type incudes the masses of the mooring system and anchors as well as the hull
- For the MP foundation type, the mid-case mass was used. The reference design included upper and lower bound masses to
- For the GBF, the mass of sand ballast is not included as it is not structural.
- Mass adjustments were made to ensure a fair comparison between foundation types. This was done by adding or removing some of the default tower mass for the jacket and floating foundation types, to:
    - Ensure that the nacelle was at the same height above sea level (and so would see the same wind speed and have the same annual energy production), which required extra height for the floating tower and reduced height for the jacket tower, and
    - Account for different tower loads, which are increased for floating foundations because of their movement and reduced for jackets because of their higher structural stiffness.

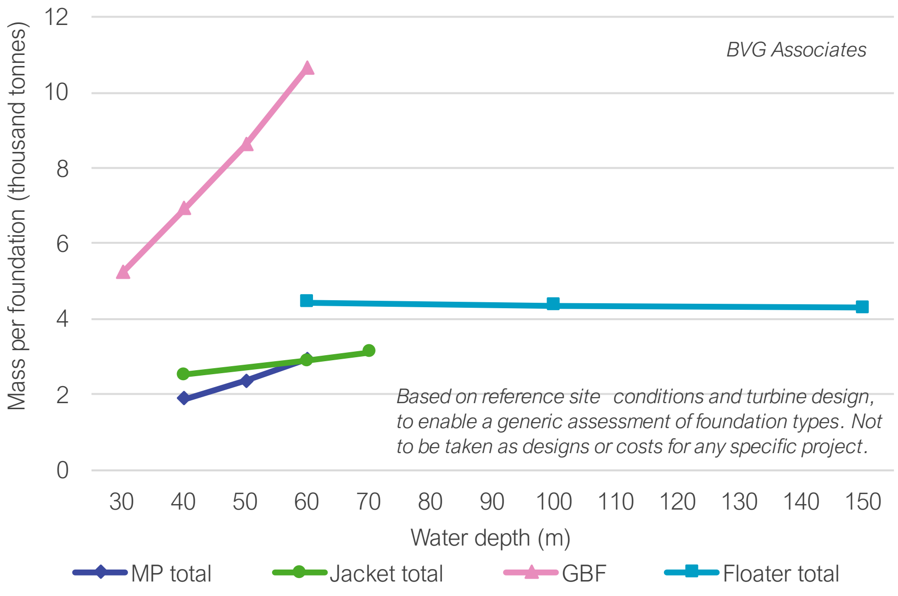


Figure 38 Foundation masses by depth for reference designs (FID 2025).

For these reference designs and site conditions it can be seen that:

- The mass of the gravity base foundation is much heavier than the other foundation types at the same depth as the primary material is concrete, rather than steel

- For the bottom-fixed foundation types, the mass increases with depth. The rate of increase with depth is lowest for the jacket, which is as expected as it uses its structure effectively
- The mass of the MP and jacket foundations converge at around 60m. At greater depths the mass of the MP is expected to accelerate steeply
    - Although not shown on this chart, for simplicity, MP mass for upper and lower bound site conditions can result in MPs that are slightly lighter through to almost twice the mass
    - Pin pile mass for jackets will increase with lower bound site conditions, but jacket mass will increase at a much slower rate due to challenging site conditions
- The floating foundation is heavier than the other steel foundations, MP and jacket, even at 70m. Its mass reduces very slightly with increasing water depth

4.1.4 Foundation manufacturing cost, 2025

The manufacturing costs for the 15MW reference designs, for each water depth, are shown in Figure 39.

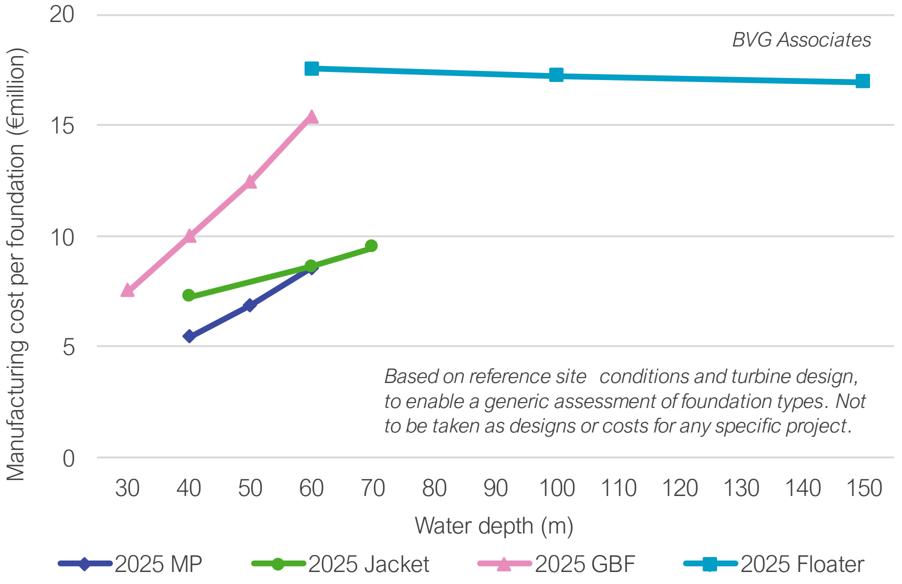


Figure 39 Foundation manufacturing cost per unit for reference designs (FID 2025).

These costs include the major elements, considered as part of the mass build up. These costs also include the increased or reduced cost for the tower adjustments described in the previous section.

It can be seen that:

- MPs have the lowest manufacturing costs up to 60m depth analysed. Although the cost per tonne to manufacture jackets is more than MPs, the cost per tonne of pin piles is less, so the costs of MPs and jackets converge at around 60m, again, and jackets have the lowest manufacturing cost from 60m to at least 70m water depth.

- The GBF is manufactured from concrete which has a lower cost per tonne than fabricated steel, although it is still more expensive than the other bottom-fixed foundation types at the water depths analysed.
- Floating foundations are the most expensive to manufacture at the depths considered.

The major challenges in calculating manufacturing costs for this study are:

- There is no standard cost per tonne for a given concept, as costs will depend on many project-specific and manufacturer-specific factors. This effect is mitigated by using average European prices we have seen from many projects over the last few years and by ensuring that the cost values we have chosen are approximately correct relative to each other.
- There was a jump of around 50% in steel prices in 2021 which has continued into 2022. It is not yet known to what extent this is temporary or will endure in the medium and long-term. To take account of this, steel prices have been increased by about half of the recent increase.
- There is little recent reference data for the cost per tonne of concrete foundation manufacturing, with only Fécamp as a recent commercial-scale wind farm. The value used in this study is based on several reports and has much more uncertainty relative to the steel prices than the steel prices have relative to each other.

4.1.5 Foundation installation cost, 2025

The installation costs for the 15MW reference designs, for each depth combination, are shown in Figure 40. These include the cost of vessels and associated manpower, critical installation equipment, and the materials used at the installation phase such as rock armouring for all foundation types and the sand and gravel used with the GBF. Per project costs, such as installation project management and marine coordination are expected to be similar across foundation types so are not included.

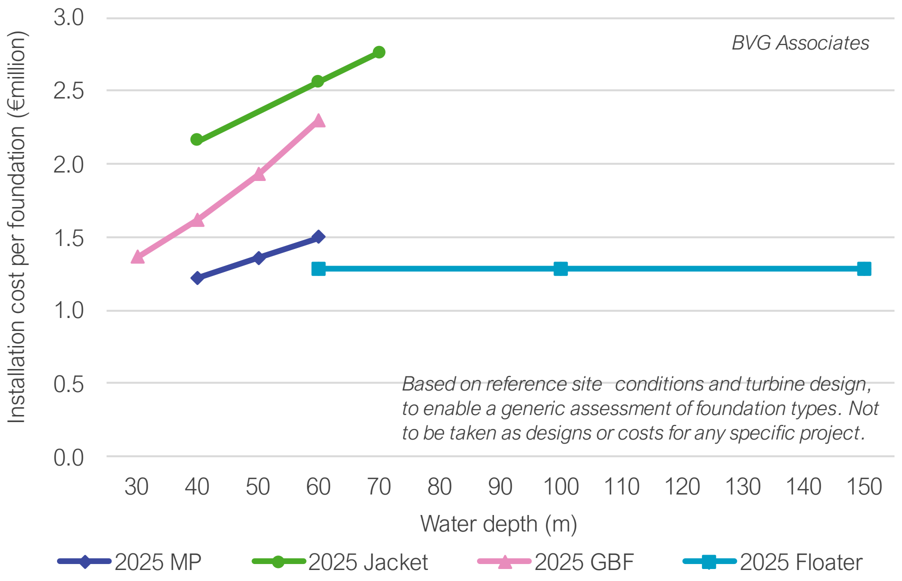


Figure 40 Foundation installation cost for reference designs (FID 2025).

It can be seen that:

- MPs have around the lowest installation costs, similar to floating foundations, and this rises with depth. The reference design uses an MP with bolted TP which can both be installed during the same visit of the heavy-lift installation vessel. The installation cost is only about 20% of the manufacturing cost for MPs at 40m water depth.
- Jackets have the highest installation cost. Jacket installation costs more than MP installation (including TP) because it requires a medium-lift vessel to pre-install the piles, then a heavy-lift vessel to install and grout the jacket.
- GBF installation costs are between those for MPs and jackets. The reference GBF-design is not stable for towing, so requires a heavy-lift vessel to lift it from a barge into the water at site. It also requires several smaller vessels to prepare the site, which becomes more expensive at greater water depth, where larger volumes of ballast are needed.
- Floating foundation installation costs are around the lowest, similar to MPs. No heavy-lift vessels are required, but several smaller vessels are required for anchor and mooring pre-installation, tow-out of the fully-integrated turbine and hull, and mooring system hook-up.

4.1.6 Total installed foundation cost, 2025

The total installed foundation costs, including manufacture and installation, for the 15MW reference designs, for each depth combination, are shown in Figure 41.

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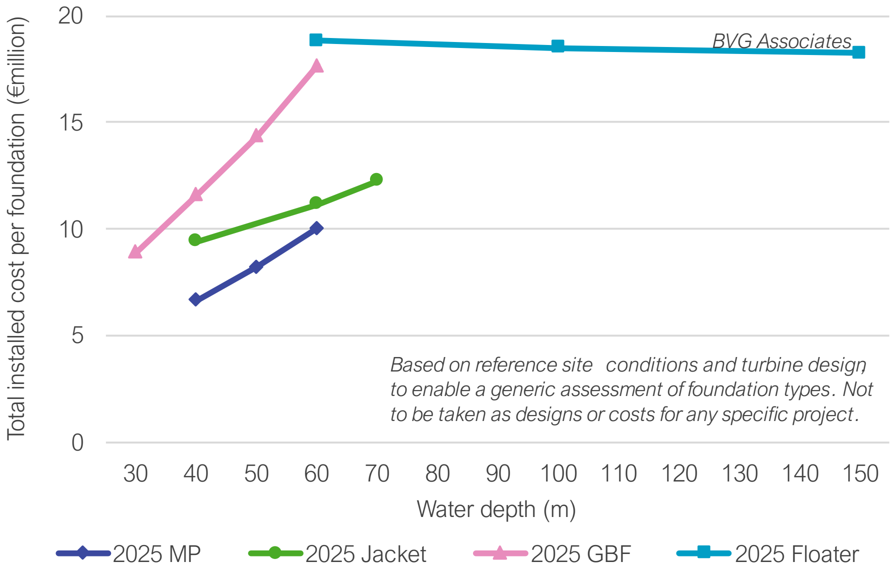

Figure 41 Total installed foundation cost by depth for the reference designs (FID 2025).

It can be seen that:

- MPs have the lowest total installed foundation cost. This is to be expected as MPs have a dominant position in the industry. For the reference site, assuming the mid-case site conditions, MPs have a lower total installed cost than jackets up to 60m. This is corroborated by what we see in current and recent projects using MPs, where both jackets and MPs are considered to depths of about 60m.

- Jackets are the next least expensive bottom-fixed option, always more expensive than MPs for mid-case site conditions. Their use is expected to be limited to where site conditions are unfavourable for MPs, for example where the ground is either too hard or too soft, or in earthquake zones. This is corroborated by what we see in current and recent projects using jackets, for example:
    - Seagreen: jackets with suction anchors used, due to hard rock layers
    - Saint-Breiuc: jackets with drilled piles used, due to hard rock
- GBFs are always more expensive than MPs but are competitive with jackets at water depths around 30m, where site conditions do not allow the use of MPs. This is the set of conditions at Fécamp, the only project in Europe where GBFs are used on a modern commercial scale project, with average depth of 30m and rocky ground conditions.
- Floating foundations have a higher total installed cost in 2025 than the bottom-fixed foundations for the depths that have been considered. We consider that FOW is a separate market that is relevant where the conditions do not allow bottom-fixed foundations. The two are not in direct competition, although this could change if potentially disruptive foundation concepts increase the depth at which bottom-fixed foundations are used, for example in the 70-100m range.

4.1.7 Total installed foundation cost, 2030

The total installed foundation costs - including five years of design and manufacturing innovations between 2025 and 2030 - for the 15MW reference designs, for each depth combination, are shown in Figure 42. This allows the effect of the innovations identified in Section 2, Technology assessment, to be seen separately the effect of changing turbine technology or manufacturing volumes that will be taking place separately.

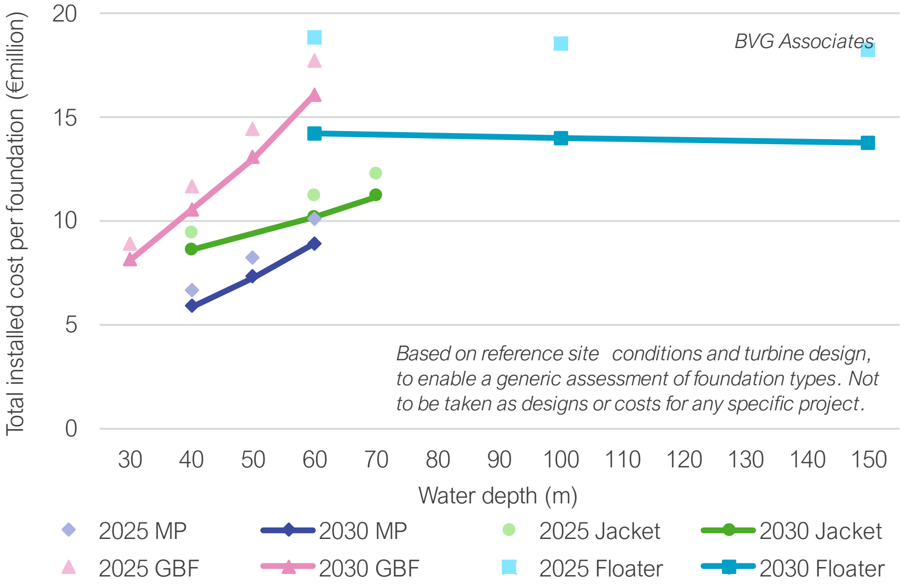

Figure 42 Total installed foundation cost by depth for the reference designs (FID 2030).

It can be seen that:

- The application of design and manufacturing innovations over a five-year period have reduced the total installed cost of all foundation types. The bottom-fixed foundations have all maintained their cost positions relative to each other.
- The cost of floating foundations has reduced by more than the bottom-fixed foundations. Although they remain more expensive than the bottom-fixed foundation types at the depths analysed, the difference is small enough that floating could be considered as an alternative in deeper bottom-fixed depths, say from 50m, where ground conditions are very challenging.
- For each of the bottom-fixed foundation types we estimate that cost reductions of 10-12% due to design and manufacturing innovations and 5-10% due to installation innovations will be achieved over the five-year period. We expect these to be drawn from the expected innovations described in Section 2, where more than enough innovations have been identified for each foundation type to sustain innovation of this magnitude of cost reduction. GBF will see the smallest change as there will be least volume in the market to drive change.
- For floating foundations, we estimate that cost reductions of 25% for design and manufacturing innovations, and 20% for installation innovations, will be achieved. These are both larger than for bottom-fixed foundations, as floating foundations start from a low level of rate of manufacture and design maturity and we see significant interest in the FOW-market to increase volumes and to invest in the innovation required to drive down cost.

4.2 Potentially disruptive innovations

In this section we have applied qualitative scoring to the potentially disruptive innovations described in Section 3. They are described against the four foundation types as in Section 3. For ease of cross-referencing, innovations are listed in the same order as in Section 3. We have assessed each potentially disruptive innovation against it’s potential for cost benefits in:

- Mass
- Ability to manufacture
- Ability to install
- Maintainability

We have assessed relative to the reference designs at the depths at which these solutions are being proposed. We have also provided an overall assessment of the impact on LCOE. These assessments have been made using the qualitative scoring criteria described in

Table 3 and the same colours have been used for the overall assessment on LCOE. This is intended as a high-level assessment to identify those potentially disruptive innovations of greatest potential within the constraints of this project, it is not a quantitative LCOE assessment.

Table 3 Potentially disruptive innovation scoring criteria.

Rating	Criterion (for mass, ability to manufacture, ability to install, maintainability and overall LCOE impact)
GG	We expect this innovation will make a very significant positive impact on this parameter (greater than 10%) for the overall foundation
G	We expect this innovation will make a moderate positive impact on this parameter (5 to 10%) for the overall foundation
Y	We expect this innovation will make no material difference either way for the overall foundation
A	We expect his innovation will make a moderate negative impact on this parameter (5 to 10%) for the overall foundation
R	We expect this innovation will make a very significant negative impact on this parameter (greater than 10%) for the overall foundation

4.2.1 Potentially disruptive innovations – monopiles

We have assessed potentially disruptive MP innovations as shown in Table 4. We see few genuinely disruptive concepts, which is understandable as this is the most mature of the foundation concepts. Of these we consider the most likely to be successful are:

- SPT’s tri-suction pile caisson - It appears to use a sensible combination of concrete and steel. It could extend MP-based foundations to increased water depth
- The collared MP - It has already attracted RWE’s interest. It only has application where there are specific, soft ground conditions.

Table 4 Qualitative assessment of potentially disruptive innovations for monopiles.

Alternative foundation type	Mass	Ability to manufacture	Ability to install	Maintain-ability	Comments	Overall LCOE rating
Collared monopiles	GG	A	A	A	Shifts mass from MP to collar to achieve stability in softer seabed conditions. Some additional fabrication, installation and maintenance complexity.	G
SPT’s tri-suction pile caisson	G	Y	G	Y	Allows for lower-noise installation than driven MPs. Is based on existing suction caisson technology. Overall mass of steel is	G

					expected to be lower compared to a MP. Requires design innovation for novel load transfer path at the seabed and joint at the base of the MP section.	
Slotted monopiles	Y	Y	A	A	Reduces welding; adds new challenges for fabrication (weld details at end of slots), handling and installation relative to state-of-the-art MPs, where it is already hard to avoid damage to MPs with high D/t ratio. Any fabrication benefits may be redundant with advancements in welding techniques.	A
Universal Foundation's mono-bucket	Y	A	A	A	Adds design and manufacturing complexity relative to an MP. For installation it avoids piling but is larger to transport than a MP and the prototype installation was not successful.	A

4.2.2 Potentially disruptive innovations – jackets

We have assessed potentially disruptive jacket innovations as shown in

Table 5. We currently consider three potentially disruptive innovations for jackets are likely to be successful. These all seek to extend the maximum water depth at which bottom-fixed foundations could be viable. They are foundations that are lighter than MPs would be at equivalent water depth, and they have simpler designs so should have lower mass, hence cost to fabricate, than conventional jackets.

Table 5 Qualitative assessment of potentially disruptive innovations for jackets.

Alternative foundation type	Mass	Ability to manufacture	Ability to install	Maintain-ability	Comments	Overall LCOE rating
Sif's Tripod	G	G	Y	Y	Combines elements of MP and jacket manufacturing techniques to extend the use of bottom-fixed	G

					foundations to deeper waters in a cost-effective way.	
Offshore-Tronic's Tripod Plus	Y	G	G	Y	Similar to Sif's tripod and includes a two-part joint which reduces the maximum component size and masse for installation. It is a solution that combines elements of MP and jacket fabrication to extend bottom-fixed to deeper waters in a cost-effective way.	G
Steisdal's TetraBase	G	G	Y	Y	Increasing industrialisation through simplification of jacket structures provides benefits across the supply chain from modular manufacturing, as long as joints do not more than reverse the benefits.	G
Keystone Engineering's twisted jacket	Y	G	Y	Y	Provides potential for simplified manufacture but may require further innovations for installation. This innovation is competing at water depths accessible through established designs and has not had success.	Y

4.2.3 Potentially disruptive innovations - gravity base foundations

We have assessed potentially disruptive GBF innovations as shown in Table 6. We currently consider that two potentially disruptive innovations for GBFs are likely to be successful. Each still requires cost reduction of concrete structures relative to steel, to succeed in the market:

- ODE's Articulated Water Column
- OWLC's Gravity Tripod.

Table 6 Qualitative assessment of potentially disruptive innovations for concrete GBFs.

Alternative foundation type	Mass	Ability to manufacture	Ability to install	Maintain-ability	Comments	Overall LCOE rating
OWLC Gravity Tripod	G	GG	G	Y	Combines elements of jacket and GBF foundation types. Modular manufacture of components is more efficient relative to the reference design and avoids the need for pumped ballast. The design cannot use float-to-site installation, so still needs large installation vessels.	G
ODE's Articulated Water Column	GG	G	G	A	The partially buoyant structure significantly reduces mass. It avoids lateral loading through the use of a hinge at its base and could extend the water depth at which bottom-fixed OSW is viable by many tens of metres.	G
Esteyco's ELISA foundation	A	A	Y	A	Offers simpler installation through the 'float and sink' installation approach with the turbine already installed. The ability to raise the nacelle in situ adds complexity which de-optimises the structural design for normal operation. The high degree of novelty introduces new risks.	A
MonobaseWind segmented GBF	A	A	A	Y	Offers simpler installation through the "float and sink" installation approach.	A

					The ability to move the foundation components relative to each other at sea introduces complexity which de-optimises the design for normal operations.	

4.2.4 Potentially disruptive innovations – floating

We have assessed potentially disruptive floating innovations as shown in Table 7. There are a greater number of potentially disruptive innovations in this section because floating wind has not reached a level of design and manufacturing maturity where convergence would be expected. We assess that there are several potentially disruptive innovations of interest:

- The TLP - This is the potentially disruptive innovation which we see has the potential to reduce mass significantly and so is expected to see development to address its installation novelty and challenges.
- Counterweights, rotating about a single pivot point and downwind rotors are all assessed to have a benefit to LCOE, either alone or in various combinations.
- Floating offshore substations - These are expected to be relevant for a part of the FOW-market that is in water too deep for a jacket foundation for the substation.

Table 7 Qualitative assessment of potentially disruptive innovations for floating foundations.

Alternative foundation type	Mass	Ability to manufacture	Ability to install	Maintain-ability	Comments	Overall LCOE rating
Counterweight concepts	GG	G	A	A	Reduces mass and provides benefits for float-out installation. Benefits could be offset by added complexity. Careful consideration must be paid to the dynamic behaviour. Examples: Steisdal's TetraBase, Saipem's Hexafloat.	G
Rotating about single pivot point	GG	Y	G	A	Reduces loads and mass by being loaded in one main direction. Speeds hook up. These benefits will be offset to some extent by added cost of the pivoting joint and its need for maintenance. Examples: X1 Wind, Aerodyn's Nezzy[2], Saitec's SATH.	G

Downwind rotor	G	Y	Y	Y	Provides small benefit to energy production from reduced rotor tilt, despite some wind shadow relative to upwind rotor designs. Loads from novel rotor loads could have knock-on impacts. Major wind turbine suppliers might not wish supply downwind variants. Examples: X1's Pivot Buoy, Aerodyn's Nezzy[2].	Y
Multiple rotors	GG	Y	Y	A	Reduces number of floating hulls. Reduced hull and mooring costs are balanced with additional design complexity. Uncertainty over turbine control and downtime requirements across paired wind turbines is introduced, for example, if there is a problem with one turbine will both need to be stopped? Examples: Hexicon, Aerodyn's Nezzy[2].	Y
Tension Leg Platform (TLP)	GG	Y	A	A	Reduces mass, significant mass reductions are plausible but must be balanced against greater complexity of loading patterns and tendon fatigue. Installation is expected to be more complex than for the reference design. Examples: SMB's TLP, Gicon's SOF and Pelastar's TLP. Is given a green overall rating because of potential to significantly reduce mass.	G
Vertical axis floating wind turbines	R	Y	G	Y	Typically, higher LCOE than conventional turbines and so case for them never really made, though companies have tried for decades. Potentially lower centre of thrust above waterline could help reduce foundation	A

					cost. The Sea Twirl design also requires deep water to transport. Examples: SeaTwirl's S1 and S2.	
Combined wind and wave energy devices	A	R	A	A	Tries to share substructure cost between wind and wave devices. It is often difficult to make a renewable generation device cost effective in a location that is optimum for it. As wave energy devices do not generate at cost close to grid parity anywhere, they are unlikely to be so in combination with wind floating wind turbines. Example: Floating Power Plant.	A
Floating offshore substations	G	G	G	A	Enables FOW in locations too deep for a bottom-fixed substation. Most aspects of the floating hull would be similar in concept to a turbine hull. Could be useful for a part of the market. Example: BW Ideol.	G

5 Technology acceleration for the Dutch foundations industry

This section presents our analysis of the strengths and weaknesses of the Dutch offshore wind industry for the development and roll-out of innovations and alternative foundation types. We make recommendations to strengthen the competitive position of the Dutch offshore wind industry, based on the synthesis of interviews with Dutch innovators and our own experience of OSW innovation in other countries.

5.1 Organisations and relationships

The Dutch offshore wind foundation industry has a strong market position. Maintaining this status requires the Dutch foundations ecosystem to continue competing effectively as the market continues to grow into new regions and technologies. This involves co-operation across design, installation, manufacturing, and maintenance.

Figure 43 shows the key functional roles that drive the innovation ecosystem. These functions exist either as the key activity of specialised organisations or within multidisciplinary companies that undertake a number of these functions. This means that the innovation process can occur entirely within single organisations, or via consortia of multiple companies. The complexity arising from the various combinations of actors in the innovation process means perceived inhibiting factors can depend on the perspective of the organisation.

A key strength of the Dutch innovation ecosystem is the strength of the relationships that have successfully formed between organisations allowing for innovation projects to be well resourced. In some cases, these relationships and consortia extend to international partners.

Beyond strong bi- and multi-lateral relationships between Dutch organisations the presence of industry-led bodies (e.g., GROW) and governmental bodies (e.g., TKI Wind op Zee) within the innovation ecosystem provides a focus for innovation project consortia.

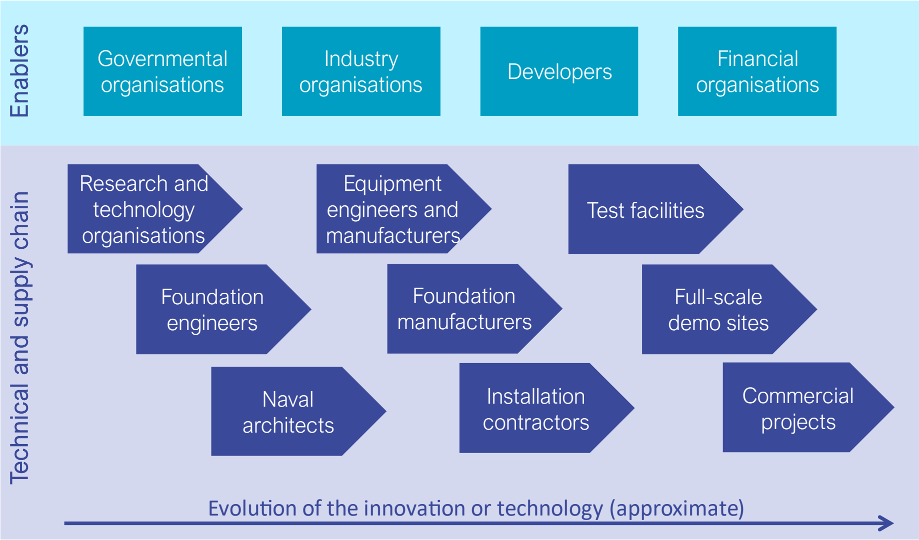

Figure 43 Key functional actors in the foundation innovation ecosystem.

Many Dutch businesses provide the functions shown in Figure 43. To characterise these, examples of organisations in each area shown in Figure 43, including GROW and TKI Wind op Zee, are shown in Table 8.

Table 8 Examples of organisations in the Dutch foundation innovation ecosystem

Type of organisation	**Description**	**Examples**	
Research and technology organisations	Support innovation projects with a range of technical research, engineering and testing capabilities.	- Deltares - Delft University of Technology	- Eindhoven University of Technology
Foundation engineers	Can either be within specialist organisations or form part of a foundation manufacturer's group.	- Ballast Nedam - KCI (now owned by Sif)	- Monobase Wind
Naval architects	Work closely with installers to ensure vessel functionality continues to develop, with many installers operating this function internally.	- C-Job - GustoMSC	- Royal IHC - Ulstein
Equipment engineers and manufacturers	Offer technical specialism for developing, manufacturing and operating equipment required for installation, sometimes renting it to contractors. There can be functional crossover with other organisation types which do this in-house.	- Ampelmann - Breman - CAPE Holland	- Huisman Equipment - Iv Groep - IQIP
Foundation manufacturers	Provide fabrication services supported by engineering functions and storage and marshalling sites.	- Sif	
Foundation installers	Offer services from specialising in vessel and equipment	- BigLift - Boskalis	- Mammoet - Spleithoff

	operation to broader organisations with comprehensive engineering specialisms for vessel, equipment, and foundation innovation.	• Heerema Marine Contractors • Jumbo Maritime	• Van Oord
Test facilities	Enable testing and demonstration of innovations at part- or full-scale.	• Borssele Wind Farm Site V • Future Wind	• MARIN • TNO
Government organisations	Governmental organisations supporting the development of the Dutch OW foundation industry including enabling innovations.	• Ministry of Economic Affairs and Climate • RVO	• TKI Wind op Zee • Wind and Water Works (portal)
Industry organisations	Non-governmental organisations supporting the development of the Dutch OW foundation industry including enabling innovations.	• GROW • Holland Home of Wind Energy • IRO	• Netherlands Maritime Technology • NWEA
Project developers	The ultimate 'clients' in the development of wind farms and transmission systems, leading the consenting, design, manufacture and installation processes, and being owner-operators.	• Eneco • Shell	• TenneT • Van Oord
Financial organisations	Provide financing, insurance and other financial services to projects and businesses across the industry.	• Green Giraffe	

5.2 Innovation development processes

To gain a better understanding of Dutch foundation innovation processes we performed desk research into companies and representative recent innovations. We also spoke to five companies, which were agreed between RVO and BVGA. This was to understand what was done, what worked well and less well, and to hear any suggestions for how this process could work better. We spoke with:

- CTO, equipment engineer and manufacturer
- Offshore R&D Manager, installation contractor
- Product Strategy Director, manufacturer
- Technical Director, equipment engineer, and manufacturer, and
- Product Development Manager, installation contractor.

In this section we identify three broad scales of innovation relevant to offshore wind foundations and use examples from the companies interviewed to bring to life the characteristics of what we call smaller-, medium- and larger-scale innovations. Although the examples are useful to characterise these different scales of innovation, the actual situation is often more complex. In particular, an individual company will make choices according to the particular innovation and its specific situation, for example, the level of its in-house resources and its financial strength.

Larger, disruptive, innovations

We characterise larger, potentially disruptive innovations as those which involve so much change that no single organisation could bring this innovation to market on its own. Organisations have to work with other manufacturers, installers, and developers on parallel, for example supporting innovations for equipment and installation strategies to enable a new concept. These parallel, supporting innovations may be needed to demonstrate operational and commercial viability at scale.

Such disruptive step-changes in foundation design may need to be developed through a range of research projects and then demonstrated in wind farm projects over a timescale of perhaps five to ten years before the novel concept is considered a mature technology in the market.

An example of such a large innovation is Sif’s production of TP-less MPs (see Section 2.2.4).

- The first project to use this design was Eneco’s Luchterduinen 129 MW wind farm which was commissioned in 2015. Sif and installer Van Oord worked together to design and manufacture a TP-less MP with a bolted flange tower connection capable of withstanding piling forces.
- While the TP-less concept offers overall reduction in mass and removes a critical joint, fitting secondary steel elements in the ‘splash zone’, offshore, adds challenges to design for installation.
- This design also requires developers to move some of their equipment from the TP into the tower base. A higher and heavier lift than using separate MP and TP is needed, which either requires installers to use larger vessels and larger MP handling equipment or could restrict installer choice.
- Sif has continued to develop the TP-less concept. It has worked again with Van Oord at Borssele 3 and 4. For Hollandse Kust Zuid it has worked with project partners Subsea 7 and Vattenfall to refine all aspects of the installation process prior to the installation of that project using ‘mock-up’ installation at its Maasvlakte 2 site.
- To optimise the fitting of secondary steel elements, Sif is developing “Skybox” see Figure 44. Skybox is a single-unit all-in-one solution for fitting secondary steel components to a TP-less MP in a single lift and using a slip joint. It is anticipated to be ready for commercial use in 2024.

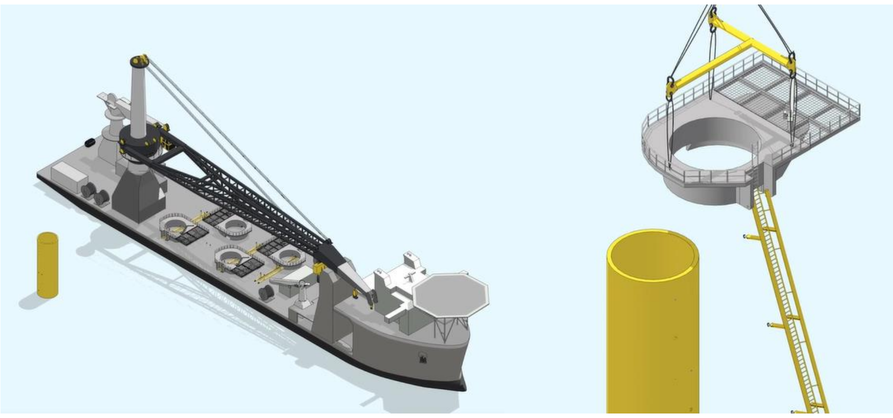

Figure 44 Representations of Sif's Skybox under single lift installation (source: Sif).

Medium-scale innovations

Medium-scale innovations can substantially change how foundations are manufactured and installed without fundamental changes to the foundation design concept. Even though the foundation concept is not changed, the changes to the manufacturing and installation processes are significant enough to need to be rigorously tested and demonstrated, which will lead to development timescales of at least five years. These innovations are, generally, complex enough to need inputs from several organisations to provide the specialist functions and resources to bring the innovation to market.

BLUE Piling Technology™ is an example of a medium-scale innovation for MP installation (see Section 2.2.6). It is an alternative to conventional piling hammers where impact forces are generated using a large water mass with a longer impulse period, instead of using solid masses. This results in lower pile wall vibration and is expected to reduce noise by more than 20 decibels (sound exposure level, SEL) when compared to conventional hammers. Reducing underwater noise at source will mean reducing or eliminating the need for further noise mitigation techniques. We consider that the characteristics of this innovation put it towards the larger end of the “medium-scale” innovations. There have been several key milestones in the development of this technology:

- In 2011 equipment engineers and developers Fistuca BV, a spin-off from the Eindhoven University of Technology and led by founder Jasper Winkes, began developing the BLUE Hammer technology. A small-scale concept was tested in partnership with Van Oord with funding from TKI Wind op Zee.
- After the successful prototyping, in 2016 Fistuca BV secured stakeholder investment from equipment manufacturers Huisman Equipment with further funding from RVO to manufacture a full-size BLUE hammer capable of driving the largest XXL MPs on the market.
- In 2018 The Carbon Trust Offshore Wind Accelerator (OWA) partners, alongside Dutch partners Fistuca BV, Van Oord, Shell and Sif contributed €3.2million to BLUE PILOT, with a further €2.7million of project funding from TKI Wind op Zee’s Topsector Energie programme. The project was designed to verify modelled

performance at full-scale using the BLUE 25M hammer and was successfully completed in August 2018 at the Maasvlakte 2 site using Van Oord's heavy lift installation vessel, Svanen.

- In 2019 Dutch equipment manufacturer IQIP announced it was investing in BLUE piling, see Figure 45, to bring the technology to maturity. IQIP has identified noise mitigation as a key strand of its innovation road map and joined forces with Delft University of Technology in 2020 to test improvements to the technology at small-scale at TU Delft.
- IQIP expects to test the improved concept at full-scale both onshore and offshore in 2022, which it expects will confirm readiness for commercial use.
- The ten-year development period is longer than we would expect for a project of this complexity and reflects changes in ownership as well as some unexpected challenges during trials.

Figure 45 BLUE piling under test (source: IQIP).

Some medium-scale innovations are developed by individual, large organisations. An example is Sif's application of electron-beam welding to MPs. Sif is bringing capabilities in-house where necessary to perform this work as it wants to protect any intellectual property, which makes collaboration under existing funding routes impossible.

Smaller, but still important, innovations

Smaller innovations are commonly aligned with incremental improvements to reduce cost, reduce lead times, improve safety or widen the use cases of equipment. These innovations are about doing the same thing, better. They are often developed as part of efforts to refine existing processes, part of equipment engineers' strategic innovation roadmaps or as a result of a specific project need.

The programmes for implementing these innovations are typically much shorter than those of medium and large innovations. This is because there is less complexity compared to larger innovations, a reduced need for demonstration at commercial scale (although there will still be the need for some testing and demonstration), and there are likely to be fewer knock-on impacts initiating the need for innovations elsewhere in the supply chain.

Alternatively, small innovations can be developed through consortia, such as the Bubble Joint Industry Project (JIP) being led by MARIN. The two-year project, coordinated by GROW, will involve 11 Dutch industry players including installers, equipment manufacturers and research bodies, and will be delivered under a €1.2 million budget. The eight work packages will provide the project partners with improved bubble curtain modelling and understanding. A ‘Best Practice’ reference document will be produced to describe the findings.

This project will support innovations in noise mitigation that are ongoing across the industry supporting smaller companies to undertake their own innovations and remain competitive in this area.

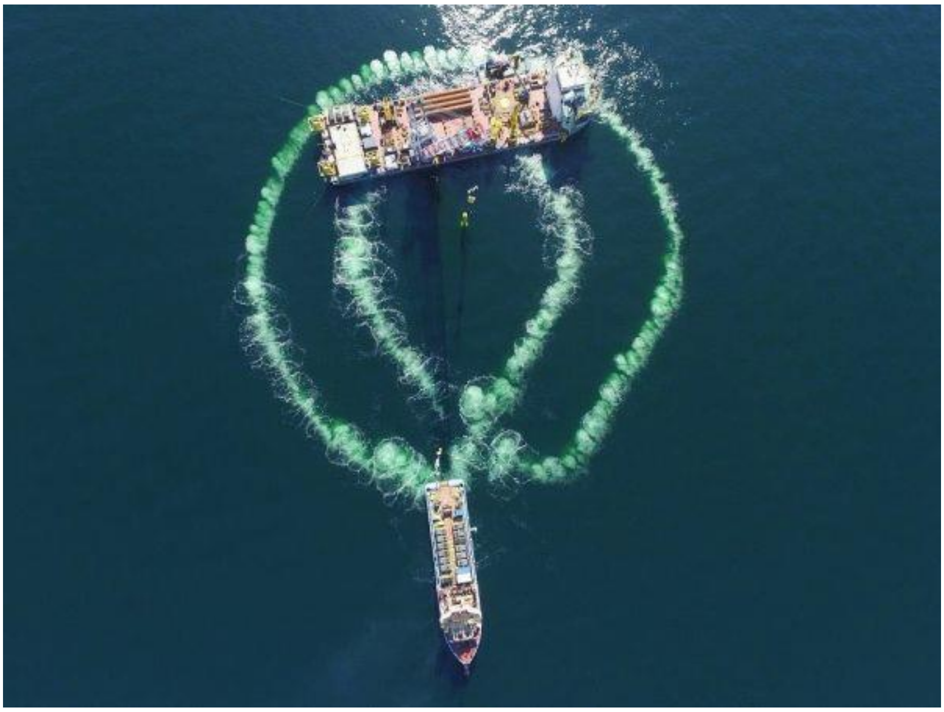

Figure 46 Bubble curtain at Wikinger Project, Germany (source: MARIN).

5.3 SWOT-analysis

This SWOT analysis is informed by the interviews and the research into the companies and projects described in Section 5.2, supplemented by BVGA's broader view of the OW foundations market. It addresses the end-to-end Dutch foundations innovation ecosystem, and not just RVO's role in it.

Strengths

- Generally positive view of a vibrant ecosystem at work:
    - Funding for foundations innovation via RVO subsidies and contributions via enterprises and research institutes, especially those organized in GROW.
    - Almost all the necessary elements (functions from research, through engineering to test and manufacture) are demonstrated in the Netherlands, helping relationships and communications.
    - Many of the businesses and research institutes are market-leading, with strong international reputations and deep pools of skills and experience.
    - Some businesses' strong records of successful innovation have built trust from end customers, who may allow accelerated application on commercial projects.
- RVO plays a useful role in supporting early-stage innovations, and in supporting research and technology organisations and smaller innovators.
- GROW partnership fosters collaborative innovation that are, typically, closer to commercialisation:
    - Highly knowledgeable partners, who are active in the industry, combine input to achieve consensus on a shared innovation road map.
    - Recognition that many projects need a collaborative approach and combined resources (engineering, testing, manufacturing) to be successful.
- All interviewees described proactive use of product and technology road maps to shape and steer their innovation projects.
- Opportunities have been made for testing and prototyping at full scale at Dutch sites, e.g., Borssele V and Haliade X prototypes.

Weaknesses

- RVO support programmes focus on innovation for the Dutch geographic market, and do not support innovation in non-Dutch offshore wind markets. Successful companies need to address the global market which has a broader ranges of site conditions than the southern North Sea and different solutions are sometimes appropriate, e.g., floating foundations for greater water depths, or earthquake loading.

- RVO programmes support projects based on how innovative the technology is, whereas the preferred objective of many businesses is on whether a key industry pain point is being addressed.
- RVO supports projects one stage at a time. This reduces the risk of unnecessary spend but can slow development, versus funding several stages in one go conditional on successful results.
- RVO projects are for consortia and not for individual organisations:
    - This can result in divergent interests and strains on projects, for example one party may be most interested in innovation for its own sake whereas another is more interested in addressing real world pain points, and
    - This does not help companies who have the necessary range of capabilities in-house, or those who do not want the IP generated to be shared with others.

Opportunities

- Seek to change the funding rules so that innovation that is not directly relevant to Dutch sites but is relevant to Dutch companies, can be supported, for example designing foundations to withstand earthquakes.
- Coordinate concurrent innovation projects to combine offshore test campaigns, which is an expensive part of many projects.
- Investigate a dedicated foundations test centre, up to and including full scale prototyping with turbine loading.
- Support innovations that are prototyped directly on commercial-scale projects to accelerate development lead times.
- Consider how knowledge sharing and personal interactions can be enhanced to maximise the benefits of cross-fertilisation of ideas and cooperation within the Dutch foundation ecosystem.

Threats

- Heavy reliance on a single company (Sif) as a “national champion” for foundation manufacturing. The industry needs its tier one suppliers to be strong companies, and there are no obvious alternatives.
- Focus on Dutch waters may make it harder for Dutch industry to compete in diverse site types internationally as the industry expands, including:
    - Deeper sites in the North Sea
    - US East Coast
    - Locations with less favourable ground for piling, and
    - Floating markets.
- Structure of subsidy programmes:

  - Smaller organisations may struggle to access support in the fast-paced ‘straight to market’ innovation competition space.
  - Requirement for consortia can lead to inefficiency and delay.
  - RVO’s Project-by-project focus makes it very hard to coordinate on shared offshore testing of innovations, that might otherwise be combined into one test and promote shared learning across more partners.
- RVO programmes appear dominated by Dutch innovators, with the involvement of foreign specialists in supporting roles only - take care that this does not reduce the benefit that foreign innovators can bring to the Dutch ecosystem.

5.4 Recommendations

The Dutch OW foundation industry has been highly successful in fostering leading businesses with excellent innovation capabilities. The dominance of MPs in the fixed foundation market has played into this success, with many Dutch companies having specialism in engineering, manufacture, and installation of MPs. Building on this success to keep Dutch companies at the forefront of MP technology should remain an important focus of innovation programmes.

New opportunities present themselves in the MP markets beyond the North Sea and in the emerging FOW market. Here designs have not yet converged, and Dutch businesses would benefit from ensuring that their major innovation programmes are aligned.

We recommend that RVO:

1 Ensures that the greater part of public funding supports MPs, as the most relevant foundation type for the foreseeable future in the Dutch and many other markets, which need to be cheaper, larger, lower noise, greener and better able to cope with challenging ground conditions; and that the lesser part of public funding should support disruptive foundation concepts and innovation where there is little market pull, for example disruptive floating concepts.
2 Challenges its remit so that it could also fund innovations applicable to sites beyond the Netherlands.
3 Funds based on a coherent roadmap of inter-related innovation areas and projects, ideally funding several stages of a project depending on results, rather than single stages; and that this roadmap coordinates with other national innovation roadmaps to get the greatest benefit from the available funding
4 Investigates the appetite and options for an offshore wind foundations test centre in the Netherlands to reduce innovation lead times and attract innovators to the Netherlands.

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