The next generation monopile foundations for offshore wind turbines

Manufacturing, design and handling challenges
Offshore wind production has grown exponentially over this century, but so far we have just witnessed the tip of the iceberg. With Climate Change pressing ever more and decarbonization becoming a rising policy priority in national and supranational agendas across the globe, offshore wind power will play a vital role in the transition to net zero. Before the end of this decade, it is expected to experience a 7-fold increase. Besides, if we are to remain on track with the Climate Neutrality target, by 2050, we should multiply by fifty today’s offshore wind installations.

The technical challenges are colossal, as we need to go bigger, further and deeper into the ocean. Before the end of this decade, we are likely to witness wind turbines of 20MW and more than 250m rotor diameter, with wind farms 200Km far from the shore. These figures seemed science fiction merely a few years ago... and they still do!

These monsters also imply larger supporting structures, and manufacturers are already working on the next generation of fixed foundations: XXL Monopiles with lengths up to 120m. These ultra-large structures require greater diameters and weights beyond 2,000 tonnes. They create tremendous logistical challenges in the manufacturing, handling, transportation and final assembly processes.

Current manufacturing standards are no longer valid as we push the technological boundaries. Weight reduction becomes imperative in the design of the next generation monopiles, and recent studies suggest that slenderness ratios up to 160 could be feasible. To prevent plastic deformation and damage when handling the cans, we need to rethink the whole fabrication process, including the supports design during the manufacturing, transport, storage and assembly.

Our experience in project management, design, manufacturing and assembly of fixed foundation structures in some of the most innovative offshore wind farm projects places Boslan in a privileged position to confront the technical challenges of the next generation monopile foundations.
The past decade has witnessed an exponential growth of the offshore wind market across the globe, with a 14-fold increase in the cumulative wind capacity installed worldwide, a Compound Annual Growth Rate (CAGR) of 22%, and a total of 35GW installed by the end of 2020. This accounted for 5% of total global wind capacity and 7% share of new wind installations.1

This is just the beginning, as offshore wind will be a crucial vector in the global response to climate change. Following The Paris Agreement,2 more than 130 countries have now set or are considering a target of reducing emissions to net zero by mid-century.3 In July 2021, the EU adopted a series of legislative proposals that intend to achieve climate neutrality by 2050, including the intermediate target of a 55% net reduction in greenhouse gas emissions by 2030.4 Offshore wind is becoming one of the pillars of these decarbonization policies,5 and its share of new wind installations keeps growing.6

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2. The Paris Agreement
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Figure 1. Cumulative Offshore Wind Capacity Installed Worldwide, 2000–2020. Source: IRENA (2021)

Figure 2. Global Offshore Wind Growth, 2006–2020. Source: GWEC (2021)
Offshore wind will maintain exponential growth in the coming decades. The GWEC foresees a 7-fold increase of installed offshore wind during this decade, expecting to reach 270 GW by 2030. This organization expects the volume of new annual offshore installations to more than triple in five years, from 6.1 GW/year in 2020 to more than 20 GW/year in 2025 (bringing its share of global new installations from 6.5% to 20%) and to double again in the second half of this decade, reaching 40 GW/year by 2030.7

![Figure 3. Global Offshore Wind Growth to 2030 (expected). Source: GWEC (2021)](image)

Noteworthy, the GWEC projections are insufficient to remain on track with the Net Zero Emissions by 2050 Scenario, and we may need to go significantly further. The IEA is calling for more substantial efforts, as it estimates that it is necessary to raise annual capacity additions to 80 GW/year of offshore wind by 2030.8 Likewise, IRENA’s analysis indicates that the world should reach an offshore wind cumulative installed capacity of 380 GW by 2030 to achieve an energy transition scenario aligned with the 1.5°C Paris Agreement target. Overall, more than 2,000 GW should be deployed globally by 2050.9

![Figure 4. Closing the Offshore Wind Gap by 2050. Source: GWEC (2021)](image)
The political, administrative and technological challenge is enormous. On the political and administrative side, the Covid-19 crisis may impact offshore wind deployment in the medium and long term, as some pre-development work such as permitting and environmental approval is being delayed.10 On the technical side, maintaining exponential growth of the offshore capacity will require more and larger farms in deeper waters and further from the coast, with bigger and more powerful turbines, and more complex, longer and heavier substructures and foundations. Fixed-bottom structures shall drive the sector’s capacity surge over this decade, while floating foundation technologies could drastically accelerate offshore deployment from 2030 onward.11

Figure 5. Offshore Wind Current and Projected Capacity in the 1.5°C Scenario, 2020-2050. Source: IRENA (2021)
CITIUS, ALTIUS, FORTIUS

Offshore wind turbines keep growing in power and rotor size, reaching milestones that were unbelievable not long ago. The world’s first offshore turbine farm, installed 30 years ago at Vindeby (Denmark), had turbines of only 450kW, with a rotor diameter of 35m. Both turbine power and rotor sizes have increased dramatically since then: in 2020 the average turbine rating for new installations in Europe reached 8.2 MW, while the average power rating of ordered turbines reached 10.4MW and the world’s record was in the hands of GE with its Haliade-X model, with 14MW and a 220m rotor.

Figure 6. Evolution of Wind Turbine Sizes over Time. Source: IRENA (2021)
And the race goes on, as Siemens Gamesa and Vesta have already announced models that reach 15 MW and shall be commercially available by 2024. The Chinese MingYang Smart Energy has gone one step further with the recent presentation of the MySE 16.0-242 prototype, which has a 242m rotor and reaches 16MW. Some experts predict that, “considering the increasing pressure for offshore wind to reach grid parity in Europe and China ... the next generation offshore turbine technology could probably be around 20 MW with a 275m rotor diameter by 2030”. This is equivalent to the length of three football pitches.

In parallel, wind farms are growing and moving further offshore towards deeper waters, enabling larger sea areas with more stable wind conditions, mitigating the visual impact on the coastline and preventing unwanted side effects on other economic activities. But this also implies increasing the construction and operation costs, as well as the technological challenges.

There are already wind farms up to 100 km offshore and deeper than 100m, and a new generation of wind farms, much further out, is in the pipeline. The evolution in the last few years is also remarkable: the average water depth and distance to shore of offshore wind farms under construction in 2020 was 36 m and 44Km respectively, compared to 22m and 33Km in 2014, just six years before.

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**Figure 7. Evolution of Rotor Size and Power Rating over Time.** Source: GWEC (2021), based on commercial offshore wind turbine installation

**Figure 8. Average Water Depth and Distance to Shore of all Offshore Wind Farms in Europe.** The size of the bubble indicates the overall capacity of the site. Source: WindEurope (2021a)
Fixed foundations are the most common type of installation in offshore wind farms, and by far the most mature technology. They are being routinely deployed in water depths of up to 40m (in some cases up to 60m deep), and at up to 80km from shore.23

Floating foundations are one of the recent developments in the offshore renewable energy industry, adapting various technologies used in the oil and gas sector. They enable access to waters beyond 60m deep and could potentially become a lower-cost alternative to wind farms with fixed foundations even for mid-depth sites (30–50m). Besides, they lower the impact on marine life.24 However, as of today this is still a nascent technology that will likely only blossom in the next decade.

Figure 9. Fixed Offshore Wind Turbine Foundations. Source: IRENA (2021)

Figure 10. Floating Offshore Wind Turbine Foundations. Source: IRENA (2021)
Monopiles remain the most widely used foundation structure for offshore wind turbines: by 2020, roughly 80% of all new and cumulative installations in Europe had adopted this technology. It is a popular solution due to its tubular structure, making it relatively easy to design and manufacture. However, the increasing size of turbines and deeper installation water depths require ever-larger structures, challenging designers and manufacturers alike.

Figure 11. Cumulative Number of Foundations Installed in Europe by the end of 2020, by Substructure Type.
Source: WindEurope (2021a)
Over the last few years, Boslan has developed a unique experience on fixed offshore wind turbine foundations, spanning various engineering disciplines at different manufacturing stages, including Jacket and Substation Design and Calculation, Civil and Electrical Works Supervision and Management, QA&QC, Testing and Commissioning, and Health and Safety.

Boslan’s flagship wind farm projects include the following:

✓ **Wikinger Project (2017)** - Offshore wind farm that supplies 350 megawatts (MW) to the German power grid. Seventy jackets (each weighing 620 tonnes) have been manufactured by Bladt Industries in Lindo (Denmark) and Navantia (Fene, Spain). Windar and Navantia have manufactured 280 piles in Spain, measuring 40 meters in length and 2.5 meters in diameter.

✓ **East Anglia One (Start date in 2020)** – Offshore wind farm with presence in the UK (North Sea) with a capacity of 714 megawatts (MW). 102 jacket type foundations were manufactured by Navantia (Fene, Spain), Lamprell (UAE) and Harland & Wolff in Belfast (Ireland). Piles were manufactured by Windar in Avilés (Spain).

✓ **Saint-Brieuc (Start of the operational phase expected in 2023)** - Currently under construction, this 496 MW offshore wind farm will be close to Saint Brieuc Bay (France). Navantia-Windar is manufacturing 62 jackets at Fene (Spain). Windar has manufactured the piles in Avilés (Spain). In line with the fabrication strategy adopted by the foundation’s manufacturer, Boslan is present at different locations in France and Spain, covering various roles related to Fabrication, Assembly, Transport, QA&QC and Health and Safety.

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**Boslan Working Sites and Manufacturing Partners – Saint Brieuc Project**

✓ **FENE (Spain) - NAVANTIA**:  
  • Fabrication of 62 transition pieces (TP)  
  • Fabrication of bracings and legs for 28 jackets  
  • Assembly of 62 jackets

✓ **BREST (France) - NAVANTIA/WINDAR**:  
  • Fabrication of bracings and legs for 34 jackets (Navantia)  
  • Fabrication of 186 stabbings (Windar)

✓ **AVILES (Spain) – WINDAR**:  
  • Preparatory works for 186 stabbings  
  • Assembly of 62 TP cylinders  
  • Fabrication of 186 piles
Load #12 of Jacket components to be transported from Navantia-Windar manufacturing facilities in Brest (France) for the final assembly in the Navantia facilities in Fene (Spain). Successfully completed last 06.04.2022. Photo: NAVANTIA
Manufacturers are already offering the next generation of ultra-large monopiles, the so-called XXL Monopiles, with lengths up to 120m, diameters of 10m and weights that reach 2,400 tonnes. The evolution is striking. Merely ten years ago, monopiles were recommended just for water depths less than 20-30m. An engineering paper on the monopiles published as recently as 2017 considered the then-average diameters of pile of 4.8m (max. 7m), average lengths of 51m (max. 85m) and average weights of 420t (max. 805t). In only five years those ranges have become totally outdated, as there are monopiles already delivered that surpass 1,700t, 8m diameter and 90m length. And this may be just the beginning, as factories are being adapted to be able to supply monopiles with an outside diameter of 15m, 130m in length, and more than 3,500t of total weight.

The increasing size of monopile comes with huge practical challenges, as all the logistics become far more complex. Component sourcing, piles handling throughout the fabrication stage, vessel fleet lifting capacity and hammering equipment need to be adapted to the scale of the next generation monopiles. This requires profound design and fabrication optimizations to ensure that monopiles rank as the most economical structure foundation type.
The most sought optimization is weight reduction. This is currently achieved with higher-strength steels; nonetheless, fatigue design aspects often prevent the general use of these materials. Besides, in addition to any technological progress with raw materials, design standards and industry rules of thumb need to be revised to keep up the pace for efficient and economical design at this grand scale.

Monopile Slenderness: The D/t ratio

As we design longer monopiles for more powerful turbines and deeper waters, ever-larger diameters are required. This implies increasing the steel thickness – to meet the Diameter (D) to Thickness (t) D/t ratio criteria set by the engineering standards on tubular structures. Thicker plates mean much heavier structures.

The current D/t standards are no longer valid for XXL monopiles. Until recently, design standards and engineering papers set the D/t ratio to values less than or equal to 100. Some more up-to-date standards set the new reference ratio to 120. But even with the 120 ratio, monopiles with diameters of 10m and above would become disproportionately heavy, given that any increase in the diameter (∆D) would translate into a relative increase of the weight close to the third power:

\[ \Delta W/W \approx (\Delta D/D)^3 \]

That is, if we hold the D/t ratio constant, a 25% increase of the monopile diameter (e.g. from 8m to 10m), would double its weight, and with a 50% increase in the diameter (e.g. from 8m to 12m) the weight would triple. See footnote (*)

This would not only be a massive waste of steel and money, but it would also multiply the manufacturing, transport and installation challenges. Tubular steel piles are typically shaped from plates using 3 or 4 rolls bending machines. Therefore, the main design parameters that gauge current workshops’ capacity are the can diameter, plate thickness, pile section depth and weight that workshops can handle. The handling and support of such heavy components throughout fabrication, without overstressing the cans or ovalizing them too severely, becomes of critical concern.

A 2019 study by Steelwind Nordenham suggests that monopiles with slenderness ratios up to 160 are “realistically feasible and applicable for deep waters and large turbines”, with pile diameters up to 11m and weights up to 2,000 tonnes. Its conclusions are somewhat controversial, and more research will be needed as we push the boundaries further and further. In any case, the Steelwind Nordenham study highlights a number of highly relevant considerations that need to be accounted for in the fabrication stage regarding the supports, transport, and storage.

(*) Here we are assuming a linear approximation for the relationship between the diameter and the length of the monopile,
\[ L = aD + b \]
where \( a \) and \( b \) are constant and \( b/D \ll a \).
\[ W = (aD_o + b) \Delta t \cdot L \rightarrow \Delta W/W_o = (\Delta D/D_o)^2 \cdot (\Delta t/t_o) \cdot (\Delta L/L_o) \approx (\Delta D/D_o)^2 \]
The linear approximation for the L-D relationship with \( b/D \ll a \) seems a reasonable estimate. See e.g. Negro (2017).
Supports

Supporting a 2,000-tonnes pile during the manufacturing process without damaging it is far from easy. We must guarantee that the support points do not cause bending, plastic deformation or any other type of damage to the can during the manufacturing process. More so given that XXL monopiles may have D/t ratios significantly above 100, which increase local bending and hoop stresses. To prevent plastic deformation on roller supports, the aforementioned study warns that their width and distance from the edge of the can are two key parameters to monitor.

Deformations can also occur due to dead load during the assembly process. This problem is aggravated at high D/t ratios, as we increase the can slenderness. Consequently, additional supports and lateral stiffeners may be required in XXL monopiles to keep the section’s round shape, as identified by the Steelwind Nordenham publication.

Transport and storage

Plastic deformations can occur, particularly for slender components, during the transport and storage of the cans. Cranes and custom lifting beams typically transport the cans or sections during fabrication. Similar to the roller supports, the self-weight of the can is likely to induce high local bending stresses at the contact area of the lifting and handling devices. The Steelwind Nordenham study shows that the risk of plastic deformation already exists for mild-slenderness ratios. Hence, lifting devices may need to be adapted accordingly.

The support structure requires to be adapted in all the section assembly fabrication steps. Steelwind Nordenham concludes that sections and monopiles beyond 1200 tonnes usually need to be supported at three or more points and highlights that special consideration must be given for support points near conical transitions since the stiffening effect of the cone shape may lead to higher stresses in these regions.

Pre-production planning ahead of fabrication, transport and storage operations will be critical for developing the next generation monopiles. Further investments are likely necessary to adapt current state-of-the-art fabrication processes and workshops to handle ever bigger, heavier and slenderer monopiles.
Baltic Eagle offshore windfarm is a 476MW wind project located in the Baltic Sea, approximately 75km off the coast of Rügen Island, Germany. It will have 50 wind turbines of 9.53-MW of unit power on monopiles, for an annual production of 1.9 TWh. It will meet the needs of 475,000 homes and avoid the emission of almost one million tonnes of CO2 into the atmosphere every year.

The foundations are being carried out by Windar and German EEW SPC. Boslan is supporting the manufacturing process in Avilés (Spain) for 50 transition pieces, as well as other parts in several locations.

The transition piece (TP) is made up out of a steel pipe construction and is the second part of a Wind Turbine Generator foundation, which is directly connected to the monopile foundation. The transition piece is secured to the monopile through a bolted connection and reinforced with grout after installation. It connects the wind turbine generator with the monopile and provides means to correct any misalignment of the foundation that may have occurred during installation, as the verticality of the monopile cannot be guaranteed after hammering. The transition piece is painted in yellow colour in order to improve visibility at sea after installation.
Boslan Working Sites and Manufacturing Partners – Baltic Eagle Project

WINDAR – Avilés (Spain):
- 50 TPs

NAVANTIA – Fene (Spain):
- Fabrication of 50 external platforms

SERASME – Gijón (Spain):
- Fabrication of 20 boat landings and 20 Access ladders

DIMIR – Langreo (Spain):
- Fabrication of 25 boltings and 25 intermediate platforms

TMG – Fene (Spain):
- Fabrication of 30 boat landings and 30 Access ladders

CALSOMATU – Fene (Spain):
- Fabrication of 25 boltings and 25 intermediate platforms

PREMONOR – A Coruña (Spain):
- Fabrication of 25 airtights

DIZMAR – Vigo (Spain):
- Fabrication of 25 airtights

FERRI – Vigo (Spain):
- Fabrication of 50 Davit Cranes

Baltic Eagle Project. First Transition Piece Fully Assembled. Photo: Windar
PART 5

ABOUT BOSLAN

In the last few years, Boslan has been in charge of the development of state-of-the-art offshore wind farms across the globe, covering the construction project cycle in projects such as Wikinger, Baltic Eagle, East Anglia One and Saint-Brieuc. Besides, Boslan has been working in Brazil for the last 15 years, transferring the expertise acquired in European offshore sites to its Brazilian affiliate.

Boslan’s practical and technical know-how in the design, manufacturing, assembly and handling of fixed foundation structures has made us a preferred partner for developers who need to confront the technical challenges of the next generation monopile foundations.

An ENGINEERING and CONSULTANCY FIRM with a MULTIDISCIPLINARY SPIRIT

BOSLAN is a Spanish company with over two decades of experience offering highly specialized technical, engineering and consultancy services. Headquartered in Bilbao, it has permanent offices in 9 countries and 750+ employees. It is currently running projects in 30 countries.

BOSLAN is organized into several areas of activity that coordinate and implement engineering, technical management, testing and commissioning works: oil & gas, power generation & networks, industry, architecture & urban development, IT and telecommunications.

Drawing on the multidisciplinary nature of the different departments and the vast experience acquired from the multiple and diverse projects, BOSLAN carries out comprehensive project management and implementation, supporting its partners and customers throughout the project’s lifecycle: Initiation, Planning and Design, Executing, Monitoring and Controlling, Closing and Commissioning.

R&D is at the core of BOSLAN’s DNA. This allows us to keep up with state-of-the-art know-how and take advantage of the most advanced design tools. BIM methodologies enable us to face each project holistically, guaranteeing an agile, timely and robust response tailored to the specific needs of the client and compliant with the highest quality requirements. Our goal is to continually surpass our customers’ expectations and become a trusted partner.


NOTES

1 Source GWEC (2021)
2 Source UN (2015).
3 Source UN (n.d.)
4 Source European Commission (n.d.)
5 Source European Commission (2020)
6 Source GWEC (2021)
7 Ibid.
8 Source IEA (2021).
9 Source IRENA (2021)
10 Source IEA (2020)
11 Source GWEC (2021)
12 Source Wikipedia (n.d.)
13 Source WTM (n.d.).
14 Source WindEurope (2021b).
15 Source GE (n.d.)
16 Source GWEC (2021)
18 Source GWEC (2021)
19 Source WindEurope (2021a).
20 Ibid.
21 Ibid.
22 Source EWEA (2016).
23 Source IRENA (2021)
24 Ibid.
25 Source WindEurope (2021a)
26 Source TNO (n.d.)
27 Source Steelwind Nordenham (s.d.).
29 Source Steelwind Nordenham (2019).
30 Source OffshoreWind (2022).
33 See Marson (2021), as well as DNV (n.d.), ISO (n.d.) and Norsok (n.d.).
34 Steelwind Nordenham (2019).
36 Steelwind Nordenham (2019).
37 Ibid.
38 Ibid.
39 Ibid.

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