

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

Technology Review of Tension-Leg Platform Floating Wind Turbines

Public Summary Report



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Floating Wind Farm

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EXECUTIVE SUMMARY

Tension-leg platform (TLP) designs have a number of advantages with respect to semi-submersible platforms, barges and spar buoys. They have the smallest mooring footprint of all substructure typologies and reduced motion responses in all degrees of freedom, with potential benefits in terms of lower cumulative fatigue damage and improved energy yield. However, in comparison to other substructure typologies, TLP solutions are rarely adopted in ongoing projects and their technology readiness level (TRL) remains lower to date. The reasons for this reluctance can be attributed to a limited understanding of the technology and to a number of challenges further discussed hereinafter.

Some of these challenges are technical in nature, such as complex mooring and anchoring requirements, whilst others are operational - namely transport and installation complexity. In particular TLP station-keeping systems are subject to high vertical loads, which therefore require much larger anchors compared to semi-submersibles, spars and barges. TLPs are also considered to present challenges in shallow sites with high amplitude waves, caused by the wave-induced variable water depth and the risk associated with the snatch load that typically follows a slacking event - a potentially catastrophic event in which a tendon loses all its tension for a short period of time - in harsh sea states. Tidal variation of the mean water level can significantly affect the pretension of the mooring lines and therefore discourage TLP solutions. However, innovations in mooring and anchoring systems may be able to overcome some of these issues offering project developers lighter substructures with a reduced mooring footprint.

Some of the perceived drawbacks associated with TLP solutions stem from unproven, anecdotal understanding of the technology, which the present study aims to confirm, or dismiss, as a result of an evidence-based investigation. The authors conducted an in-depth exploration of the industry's hesitancy towards TLP-WTs via an extensive review of relevant literature and direct stakeholder engagement with the aim of comprehensively understanding the underlying reasons contributing to the reluctance.

The primary drivers influencing TLP design and their associated mooring systems were outlined along with the challenges that need to be addressed to unlock the technology on a commercial scale. Key industry developments and novel technologies that hold the potential to facilitate the adoption and success of TLPs in the offshore wind sector were identified. The insights gained from these activities lay the foundation for informed decision-making and future strategic planning for TLP-based offshore wind technology.

Within the remit of the study the following key conclusions can be drawn:

- In comparison with other floating substructure concepts, TLPs encounter challenges such as maintaining towing stability, turbine integrations and hook-up complexity, and addressing wave-exposed surfaces, however solutions have been identified to mitigate these technical challenges. TLPs also boast notable strengths, characterised by their ability to exhibit limited motion responses, dynamic behaviour control through advanced mooring design, and a strong indication of potential weight efficiency gains – albeit dependant on site conditions, water depth among others. TLPs provide easier access over semi-submersibles and barges, generate a positive impact on the dynamic array cable reliability, and have a reduced seabed footprint. These strengths contribute to the appeal of TLP technology for floating wind applications, showcasing its potential to navigate diverse environmental conditions with enhanced stability and efficiency
- Key priorities in the development of TLPs encompass the implementation of modular substructure designs (albeit this is also true for other FOWT solutions), implementation of clear

offshore turbine integration strategies, optimisation of towing stability, and advancements in mooring and anchoring technology. These priorities underscore the industry's focus on enhancing the structural efficiency and stability of TLPs, ensuring their adaptability to various environmental conditions. The establishment of clear operational processes is deemed crucial not only for fostering industry confidence but also for minimising uncertainties associated with TLP applications. By prioritising these elements, the aim is to create a robust foundation for the widespread adoption and successful deployment of TLP technology in floating wind projects

- Given the early stage of TLPs in floating wind, and an existing reluctance towards their use, a single setback from any of the ongoing demonstrator projects could generate substantial delays in the development and deployment of the technology. Notable design advancements are being explored to improve the design and performance of TLPs and make them an attractive option for a range of development projects, with particular focus on towing stability (without the requirement for stability aids). Improved safety solutions (e.g. enhanced mooring redundancy) are proposed to mitigate risks, navigate unforeseen challenges and maintain a consistent trajectory of progress in the floating wind industry
- Within the considered lifecycle phases, TLPs propose several potential benefits when compared to other floating substructures. The generally reduced size of TLPs offer extensive benefits such as ease of manufacture and utilisation of storage areas within existing port infrastructure, which is crucial to the commercial scale deployment of Floating Offshore Wind (FOW). Although there is a level of uncertainty surrounding the stability during transport and installation, the substructure Original Equipment Manufacturers (OEMs) engaged in the framework of this project suggested that this is not a particularly impactful design constraint, nor a limiting factor for TLP deployment in general.
- A comprehensive review of mooring and anchoring sensitivities within TLPs has been conducted, emphasising well-defined design life and criteria. This provides a foundation for understanding the intricacies of the mooring systems employed in TLP technology. Encouragingly, innovations in mooring tendons and anchors show considerable promise. These advancements not only signal potential cost reductions but also offer significant development opportunities within the floating wind sector. The ongoing progress in mooring technologies underscores a commitment to enhancing the efficiency and reliability of TLPs, contributing to the continued evolution of sustainable energy solutions.

Comparative Numerical Analysis

As part of this project, ORE Catapult investigated the geometric and inertial properties of a range of TLP concepts - developed by Marine Power Systems (MPS) and Glosten - based on the IEA 15 MW reference turbine. The study assessed the dynamic behaviour of these designs under a range of offshore conditions, imposing key constraints like a fixed hub height (150 m), rigid-body substructure modelling, and a standard bottom-fixed controller, while allowing substructure OEMs flexibility in areas like tower geometry and mooring design. The designs were tested in various challenging environments, covering extreme wind and wave conditions, operational states, water depths (70, 150, and 900 m), offshore climates (benign and severe), and wind/wave directionalities. Shallow water (70 m) posed the greatest challenge; while both OEMs produced viable designs for benign sites, none succeeded in severe conditions—though it was suggested that a flexible substructure model could improve viability. Conversely, all designs performed well at 150 m, and only Glosten pursued ultra-deep water (900 m) concepts due to concerns raised by MPS over economic feasibility. The number of tendons also significantly affected platform stability; Glosten highlighted that five-arm systems allow for greater resilience during tendon slack events, maintaining stability even under partial failure scenarios, in line with DNV-ST-0119 guidelines.

Simulation results demonstrated the TLPs' robust performance across most scenarios. Tidal range had minimal impact—even at extremes—while motion responses, particularly surge and sway, increased with depth, offering potential insights for dynamic cable design. Mooring loads varied widely across designs, emphasizing the importance of individual design strategies. Tower excitation remained low, with no harmful resonances identified. Power output aligned closely with the turbine's expected curve, though controller strategy played a pivotal role. Overall, the findings support the viability of TLPs across a wide range of conditions, with the exception of severe shallow waters, where either physical or economic constraints limited success. Ultra-deep deployments are possible in favourable conditions and specific offshore sites. The work marks a significant step forward in understanding the capabilities and limitations of TLP wind turbine platforms, providing valuable data to inform future design and optimisation efforts.

Comparative Techno-Economic Analysis

Within the scope of this project, Offshore Renewable Energy (ORE) Catapult conducted a techno-economic analysis across multiple TLP designs. The analysis facilitates further investigation and understanding of the potential cost benefits of TLPs as a solution for FOW. The study examines unconventional tetrahedral and single column geometries. Allowing the evaluation of various strategies based on platform characteristics, specifically between those that exhibit stability for towing and those that do not. The latter leads to a greater reliance on offshore activities. For comparison, a semi-submersible base case was considered in the work, since this appears to be, at the moment industry standard.

This evaluation uses the ORE Catapult's in-house cost and economic model, combined with stakeholder engagement to capture more accurately the costs and assumptions associated with the technology, capturing the nuances of each design. Overall, this work aims to show the potential for TLPs, highlighting the benefits and drawbacks to allow developers to make easier, informed decisions.

A small base case wind farm was chosen to reflect the early-stage nature of TLP technology and its expected initial deployment. The evaluated TLP designs proved cost-competitive, generally outperforming semi-submersibles due to lower mass and fabrication costs. Discrete installation campaigns reduced vessel costs, while O&M was cheapest for towing-based designs within 100 km of the port. Beyond that distance, in-situ strategies were more cost-effective, aligning with industry expectations.

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NOMENCLATURE

ABS	American Bureau of Shipping	ORE	Offshore Renewable Energy
ALS	Accidental Limit State	O&M	Operations and Maintenance
CoE	Centre of Excellence	RNA	Rotor Nacelle Assembly
DLC	Design Load Case	ROV	Remotely Operated Vehicle
DNV	Det Norske Veritas	SOV	Service Operation Vessel
FLS	Fatigue Limit State	SWOT	Strengths, Weaknesses, Opportunities and Threats
FOW	Floating Offshore Wind	TRL	Technology Readiness Level
FOWT	Floating Offshore Wind Turbine	TLP	Tension Leg Platform
MPS	Marine Power Systems	TLP-WT	Tension Leg Platform Wind Turbine
OEM	Original Equipment Manufacturer	ULS	Ultimate Limit State

1 INTRODUCTION

1.1 Floating Offshore Wind Centre of Excellence

Established in 2020, the Floating Offshore Wind Centre of Excellence (FOW CoE) is a joint industry project (JIP), and as of writing this report, the industry, academic, and stakeholder partners are displayed in Figure 1. The collaborative programme was created with the vision:

'To establish an internationally recognised centre of excellence in FOW that will work towards reducing the Levelised Cost of Energy (LCoE) from floating wind to a commercially manageable rate, cut back development time for FOW farms, and develop opportunities for the local supply chain, driving innovation in manufacturing, installation and Operations and Maintenance (O&M) methodologies in floating wind.'



Figure 1 FOW CoE Industry Partners as of 2025

1.2 Project Overview

Phase 1 of this study, presented in Sections 2 through 4, encompass a comprehensive exploration of the offshore wind industry's reservations regarding Tension Leg Platform Floating Offshore Wind Turbines. To achieve this, a thorough examination of existing literature and designs has been conducted, supplemented by active engagement with partners and stakeholders. The research aims to gain an understanding of the system design prerequisites for TLP wind turbines and their associated mooring systems. Identifying the principal design drivers, challenges, and favourable operating conditions for TLPs was a key focus, shedding light on the intricacies of their integration. Additionally, the study aims to pinpoint priority industry developments and technologies that have the potential to facilitate the successful incorporation of TLPs in these projects. Addressing the unique challenges posed by less favourable offshore sites and metocean conditions, the research delved into investigating innovative solutions to mitigate tendon slacking, ensuring the robustness and reliability of TLP-WTs in diverse environmental contexts.

Based on existing literature and engagement, Section 2 details design requirements for TLPs at high level. This includes a review of existing research, TLP applications in oil & gas, and conclude by identifying challenges and opportunities for full-scale deployment of TLPs in floating wind. In addition to the operational configuration, the high-level stability requirements for self-stable towing configurations were also reviewed. Section 3 covers all lifecycle stages of a TLP-WT, from consenting and insurance to decommissioning, with a focus on the installation phase. This includes TLP-specific insights on manufacturing and the potential to unlock new local supply chain opportunities.

Section 4 investigates existing mooring and anchoring solutions specific to TLP wind, including synthetic ropes, inclined tendons and mooring load reduction devices among others. A review of the design requirements is followed by an outline of TLP-specific mooring and anchoring technologies.

Section 5 discusses the comparative numerical analysis supported by Marine Power Systems (MPS) and Glosten, which focussed on advancing the understanding of TLP wind turbines for floating offshore wind. Both OEMs, each with over 15 years of experience in offshore renewable energy systems, contributed detailed TLP designs for analysis. This collaboration allowed for a comparative evaluation of two distinct TLP concepts, offering valuable insights into their structural evolution and suitability for different offshore environments. The study provides a foundation for evidence-based assessments of TLP technologies, supporting their further development and potential deployment in the floating wind sector.

The final evaluation of this study examines the techno-economic comparison of various TLP designs against a base case semi-submersible in Section 6. A cost model was created to capture stakeholder engagement and assess the techno-economics of four innovative TLP designs - two self-stable and two hydrostatically unstable during towing. The design variations highlight strategic benefits, which are compared to the semi-submersible. The base comparison is conducted for a site in the Celtic Sea, focusing on identifying key cost drivers and the potential of TLPs for Floating Offshore Wind (FOW).

The report concludes with Section 7, where the main findings and knowledge gaps are discussed.

2 TECHNOLOGY REVIEW

2.1 Concept

Tension-leg platforms are positively buoyant floating substructures stabilised by taut mooring lines, or tendons, which are considerably stiffer than the mooring systems used for semi-submersibles and spar buoys. This increased stiffness leads to reduced platform motion under environmental loading, offering benefits in mitigating fatigue on the tower and array cables. However, as TLPs rely entirely on their mooring systems for both stability and station-keeping, they generally exhibit poor stability when afloat without tendon restraint. As a result, additional buoyancy aids or barge systems may be required for transport to and from offshore sites [1].

Semi-submersibles rely on waterplane area for stability, while spars use deep ballast to achieve a low centre of gravity. Their mooring systems primarily serve for station-keeping. TLPs, however, require mooring systems capable of ensuring both stability and positional control. Despite their promise, TLPs are the least mature of the main floating wind concepts, with only one full-scale demonstrator - the Provence Grand Large project - deployed so far [2].

Mooring systems for semi-submersibles and spars commonly use large-diameter steel chains, a well-established approach in offshore industries. Yet, concerns exist around the commercial scalability of such systems, particularly regarding the manufacturing capacity and availability of appropriate installation vessels. These challenges have prompted the exploration of taut and semi-taut systems using synthetic ropes. For TLPs, given the high vertical loads, steel chains would need to be entirely replaced with synthetic or alternative technologies.

Platform motion has a direct impact on turbine and cable reliability. Excessive movement can lead to damage of the tower, rotor-nacelle assembly, or array cables — especially in shallow waters where lazy-wave configurations are harder to apply. With their low motion response, TLPs offer a key advantage, potentially allowing for simpler catenary array layouts. However, while substructure costs may be reduced through lower steel requirements, this is often offset by the higher cost of the anchoring system [3].

2.2 TLP characterisation

TLPs are positively buoyant platforms, anchored vertically via a tendon system, although some variants use slightly inclined mooring lines. The excess buoyancy keeps the mooring system in constant tension. The substructure typically includes buoyant pontoons and columns, with upper sections connecting directly to the tower or via a column top frame or topside deck. The tendon system links the hull to seabed anchors, ensuring station-keeping. Two main design philosophies are emerging:

- **Deep-draught, single-column platforms:** Minimise fluid-structure interaction and promote manufacturability via simpler geometry, but less inclined to self-stable configurations for towing, in some cases requiring buoyancy aids or barges.
- **Shallow-draught, tetrahedral platforms:** Formed by assembling multiple components into a pyramid geometry, promoting streamlined quayside assembly and self-stable towing, though more sensitive to wave conditions.

These refer to operational draughts, not quayside draughts, which also impact the design. Examples are shown in Figure 2.

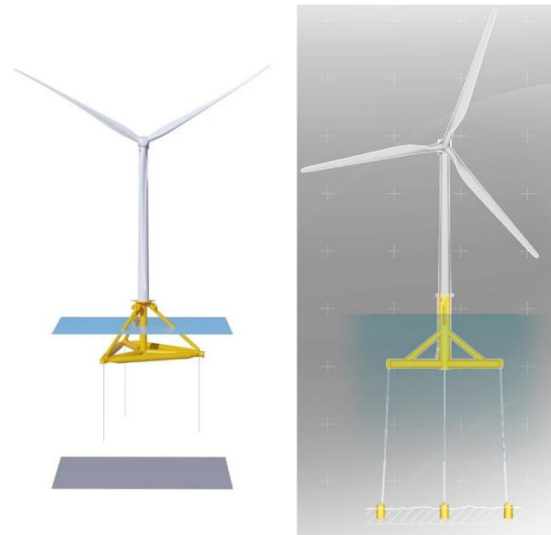


Figure 2 Examples of shallow-draught, tetrahedral TLP design (Stiesdal TetraTLP, left) and deep-draught, single column TLP design (SBM Offshore Float4Wind, right)

TLP floating substructures exhibit several distinctive characteristics:

- Vertical motion is governed by tendon stiffness rather than by water-plane area;
- Emphasis is placed on weight efficiency;
- While horizontal motions (surge, sway, yaw) are relatively unconstrained, vertical motions (heave, roll, pitch) are tightly restricted;
- Higher-order wave force interactions at various sum-frequencies may induce resonant (springing) or transient (ringing) vertical responses, increasing tendon loading;
- When tendon stiffness is sufficiently high, the platform's motion traces a path along a spherical surface — an effect known as “set-down” — creating a kinematic coupling between horizontal and vertical motions. This influences wave air-gap, tendon loads, and power cable behaviour [4].

With simple vertical tendons, the natural periods for horizontal motions are typically in the range of tens of seconds. However, more advanced mooring arrangements (including inclined or crossed tendon configurations in shallow-deepwater) can increase horizontal-plane stiffness, thereby raising surge and sway natural frequencies. In contrast, the stiff tendons constrain vertical motion so effectively that natural frequencies in heave, pitch, and roll are elevated to the point that the response in these degrees of freedom is closer to bottom-fixed turbines than to semi-submersibles.

These high vertical natural frequencies introduce dynamic interactions not present in semi-submersibles or spar platforms. The tower's flexibility can notably influence pitch and roll, while high-frequency excitations from rotor dynamics and aeroelastic responses of the rotor-nacelle assembly (RNA) can lead to vertical resonances, further increasing tendon loading.

Tendons

TLP-specific mooring lines are typically vertical, though slight inclinations are increasingly being investigated. Historically made from rigid steel pipes with extremely high axial stiffness, alternatives like steel wire or high-stiffness synthetic ropes are gaining attention. Functionally, the tendon system acts like an inverted pendulum: the TLP is held at a draft deeper than equilibrium, ensuring constant

tensile loading. This creates a horizontal restoring force when displaced. While vertical movements are tightly constrained, the system allows horizontal degrees of freedom within acceptable operational limits. Yaw stiffness is sufficient to resist moments induced by the RNA. Despite concerns, there is no evidence suggesting tendons may become twisted. Further details are provided in Section 4.

Control strategies

In TLP designs, the negative damping instabilities are primarily influenced by the surge and sway natural periods. As the dynamic behaviour of TLPs can be controlled via appropriate mooring system design, studies have shown that increased tendon inclination and the consequent enhanced horizontal stiffness in the mooring system can effectively mitigate the effects of negative aerodynamic damping without the need to change the turbine's controller parameters. This mitigation arises from the reduced motion of the RNA, resulting in fewer thrust oscillations, which in turn prevent the controller from making frequent blade pitch corrections. This ultimately leads to a more stable operation of the TLP-WT.

Inclined tendons

One notable advantage of tension-leg platforms is the enhanced level of design-driven control over the FOWT's dynamic response to external loading. Due to the stability of the platform stemming entirely from the mooring system, different tendon properties and geometries can change the entire kinematic chain, altering the motion dynamics without the need for complex and potentially expensive solutions such as active ballast.

One well-understood feature of TLP wind turbines is the direction of the pitching response to incident wind. As shown in Figure 3, pitch rotation is positive when the turbine is "pitching", as the turbine leans away from the wind or, in other words, the rotor moves in the direction of the wind. Pitch rotation is negative, on the other hand, when the turbine is "counter-pitching", as the turbine leans towards the wind [5]. One notable advantage of a counter-pitching configuration, is that the wind heeling moment can help offset the gravity-based tilting moment generated by the RNA's mass, reducing the bending moment applied to the tower bottom and the substructure [6].

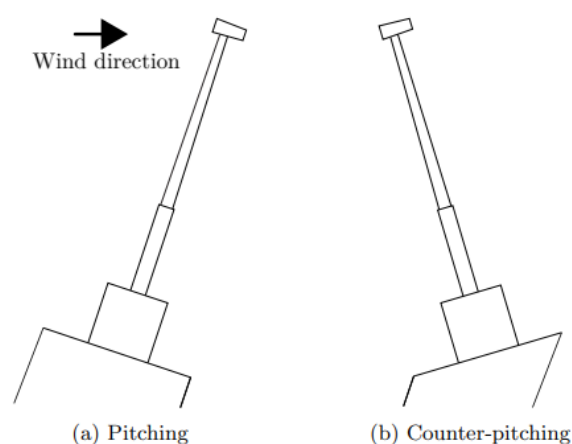


Figure 3 Pitching and counter-pitching wind response [6]

The pitching or counter-pitching behaviour of a TLP-WT can be determined by changing the inclination angle of the tendons. At the same time, inclined mooring lines increase the stiffness of the TLP-WT on the horizontal plane, which can be used to tune the surge and sway natural frequencies.

Figure 4 shows an example of the effects of inclining the tendons from vertical (90 degrees) to 74 degrees in a water depth of 100 m. The example was generated using a steady 11 m/s wind speed. While the surge response reduces with the inclination angle, the pitch transitions from a pitching response (positive angle), through a counter-pitching zone (negative angle) and back into pitching.

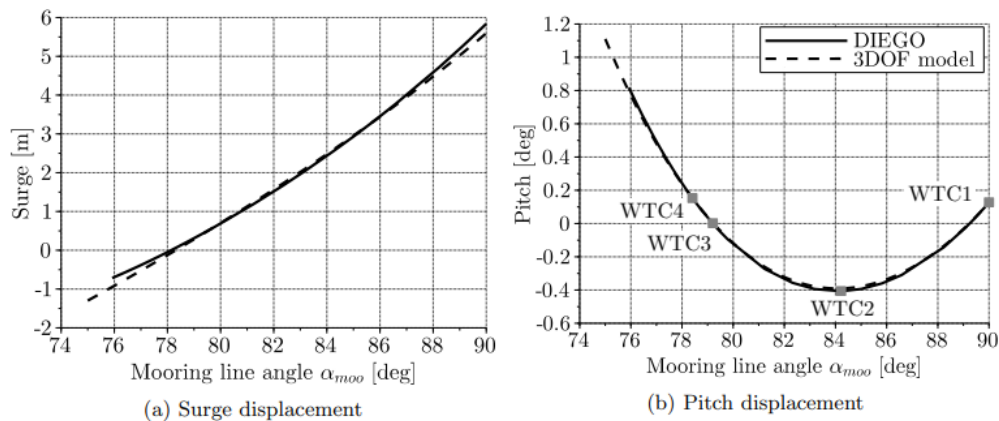


Figure 4 Static displacement of the DTU-TLPWT at different tendon inclination angles under a steady wind speed of 11 m/s [6]. Four Wind Turbine Configurations (WTCs) were explored in the framework of the study

As the RNA of a counter-pitching TLP-WT leans toward the wind, the moment generated by its mass acts in the opposite direction with respect to the heeling moment generated by the wind. This generates a dynamic response to incident wind that is structurally favourable to the turbine tower and substructure, a solution that is understood to be currently explored by multiple OEMs.

Inclined tendons, while beneficial for certain aspects of platform stability, come with some limitations. They are generally restricted to shallower water depths and result in increased tendon loads, necessitating larger tendons and more robust anchoring systems. These systems, in turn, impose higher vertical and horizontal loads on anchors, driving up costs. Installation is also more challenging, often requiring specialised connectors to interface with the platform and the seabed.

Benefits and Challenges of Site Conditions

A key advantage of floating offshore wind is the ability to install turbines in deep waters where bottom-fixed structures are not viable. While deploying TLPs in such locations introduces challenges — particularly around mooring system design and installation — many of these can be addressed using knowledge from the oil and gas industry, where TLPs are well-established. One particular benefit of deep-water deployment is the typically calmer hydrodynamic profile across the water column, which reduces loading on the mooring tendons [7].

Conversely, shallower waters - as little as 60 metres (around 70 metres for TLP-WTs) - may be attractive for floating wind deployment due to proximity to shore and infrastructure. However, these sites present unique technical difficulties. For substructures relying on catenary mooring systems, maintaining sufficient compliance becomes problematic under highly dynamic shallow-water conditions. Cable design is similarly affected: in shallow water, the limited vertical space complicates the integration of lazy-wave configurations needed to manage platform motions. TLPs, with their minimal heave and lateral excursions, offer an advantage by enabling simpler array cable layouts.

Shallow waters can also exacerbate hydrodynamic loading on both the substructure and its mooring system. Interactions between dynamic water motion and the seabed may alter ground conditions around anchors through scour and seabed morphology [7]. Additionally, tendons are exposed to more variable loading regimes due to increased hydrodynamic energy near the seabed.

Although TLPs allow some compliance in surge, sway and yaw, their vertical-plane responses (heave, pitch, roll) resemble those of bottom-fixed turbines. Proper tendon geometry and spacing must be ensured to maintain suitable natural frequencies - typically, surge, sway and yaw above 25 seconds, and heave, pitch and roll below 5 seconds [8]. Avoiding resonance with turbine frequencies (1P, 3P) and tower natural frequencies is critical. However, with larger turbines, the 1P frequency is lower, allowing a higher pitch and roll period limit. In practice, the 5-second threshold is stiffer than commonly used in current designs.

To prevent slack moorings - which can cause damaging snatch loads - the system must remain in constant tension. Snatch loading, considered an ultimate limit state for TLPs, can be particularly problematic when tension is suddenly restored.

Finally, variability in seabed conditions across large commercial wind farms poses further complications. Invasive geotechnical investigations (e.g., cone penetration testing and boreholes) are used to gather essential design data. As different anchor types may be required across a site, precision in anchor placement is critical for TLP-WTs due to their vertically oriented tendons.

2.3 Challenges and Opportunities

Table 1 shows the results of a SWOT analysis carried out to identify elements of TLP-WTs currently accepted as advantageous in comparison to other substructure concepts, as well as areas of underperformance, what can be improved, and external/uncontrollable potential threats.

Table 1 SWOT analysis

Strengths	Weaknesses
- Limited motion responses - Dynamic behaviour controlled via mooring design - Improved dynamic cable dynamics - Negative aerodynamic damping mitigated by design - Constant power control strategy - Reduced substructure size & primary steel - Reduced mooring footprint & seabed impact, enabling adjacent fishing activities - Higher and even energy yield with reduced (or no) tilt - Wider O&M weather windows - Smaller laydown area requirement in port	- Lower towing stability - Narrower transport weather windows - Complex & expensive Mooring & Anchoring - Subject to surface elevation variations (waves, tidal) - Need strong redundancy of station-keeping due to risk of capsizing in case of failure - Subject to springing & ringing - Anchoring sensitivity to earthquakes and soil liquefactions
Opportunities	Threats
- Modular substructure design - Steep learning curve can drive significant design improvement with experience - Synthetic mooring lines that are lighter, allowing for easier handling and transport. Further eased by reduced lengths compared to compliant moorings - Improved dynamics via advanced mooring geometry - Integration of novel technologies - Potential for significant improvements via clear definition of operational processes - Few proprietary topologies: accelerated commonality - Behavioural similarities with bottom-fixed turbines - WTG integration and major repairs potentially carried out in situ rather than requiring tow from/to port	- Design complexity. High cost to demonstrate designs hinders development and technical readiness - Possible need to carry out major repairs in-situ if weather does not allow tow-to-port - A single setback from undergoing demonstrator projects could stall TLP development for a long time - Limited number of proprietary designs: slower improvement of industry maturity - Growing maturity and confidence (and associated low-risk perception) in other FOW concepts may hinder the progress of TLPs

3 LIFECYCLE PHASES

3.1 Consenting & Insurance

TLP-WTs have recently demonstrated commercial viability for the first time at the Provence Grand Large site off the coast of France. Despite this successful installation, TLPs present unique consenting considerations compared to other substructure types, such as spar buoys and semi-submersibles.

One significant consideration for TLP development is the higher tension in the tendons, which exert vertical loads on the seabed. Consequently, TLP mooring systems typically require vertically loaded pile or suction anchors for station-keeping. The installation of driven or drilled piles may lead to significant environmental impacts, including noise pollution and disturbance to benthic species, as well as challenges during decommissioning when removing anchors. Developers must ensure that sites are properly decommissioned, and the difficulty of removing anchors could heighten risks for other marine industries. Generally, stakeholders have indicated that fishing and marine research would welcome TLP-WTs as they would avoid large catenaries scouring seabed and excluding fishing.

TLPs have a smaller seabed footprint compared to other floating platform types, due to their vertical tendon orientation and smaller platform size. They can more efficiently use the lease areas since they can be placed right up to the lease area boundaries, unlike designs with taut or catenary moorings which force the platforms to be placed further inside the boundaries to ensure the anchors stay inside the perimeter. These spatial considerations provided further planning flexibility, aiding the development and consenting process. Early intervention through stakeholder engagement and cross-industry collaboration during marine spatial planning is crucial to mitigating these risks.

The development and consenting considerations for TLPs are not exhaustive, and some will overlap with those of other substructure types. It is important to note that the consenting process may vary depending on the region of the proposed development and specific regulatory conditions. Given the relatively limited demonstration of TLPs to date, there is a strong need for continued research and stakeholder engagement to refine the understanding of the development and consenting process, particularly as the technology moves towards commercial-scale deployment.

Insurance

The dynamic cable systems, mooring systems, and floating substructures in FOW are still in the early stages of development, and as such, contractors and OEMs are expected to share a significant portion of the associated risks [9]. While floating platforms such as spar buoys, semi-submersibles, and barges have established performance records through pilot projects and commercial wind farms, TLP designs have not yet reached the same level of deployment and thus confidence. The successful installation of the SBM Offshore TLP in the Provence Grand Large project will help improve the understanding and viability of TLPs.

One of the main challenges in pricing and underwriting FOW projects is assessing the Possible Maximum Loss or Estimated Maximum Loss during transportation, testing, commissioning, and operations. TLP designs face potential catastrophic failure in the event of a mooring line failure, albeit it is acknowledged that other floating substructure concepts (semi-submersibles, spars) can face similar – if not harsher – consequences to the rest of the farm and other sea users in a mooring failure scenario. Although OEM decisions, such as redundant mooring systems, aim to mitigate these risks, the lack of a proven track record for TLPs remains a significant barrier.

Transportation and installation challenges also impact TLPs, with these platforms requiring - if towed - additional stability considerations compared to other floating substructure designs. These challenges, compounded by the complexity of towing to distant wind farm locations and dealing with variable weather conditions, further heighten the risk profile for TLP projects.

As the number of offshore wind farms increases and the industry gains more experience, confidence in the technology will grow. However, TLPs, still in the early stages of development, are likely to face higher insurance costs as OEMs absorb part of the associated risk. The ongoing commissioning of projects like Provence Grand Large will play a vital role in the maturation of the TLP concept, but achieving parity with other FOWT platforms will take additional time and development.

3.2 Manufacture & Assembly

3.2.1 TLP Substructure Primary Component Manufacture

Many TLP designs follow a very similar subcomponent manufacturing procedure as tubular, steel semi-submersible structures. This modular approach using standardised, tubular, subcomponents demonstrates the potential for commercial-scale production of TLPs. The subcomponent fabrication begins with a steel plate which is rolled into can sections, which are then aligned and tack welded together to create a cylindrical section as shown in the example in Figure 5.



Figure 5 Can sections and cylindrical sections at Welcon® factory [10]

Depending on the material, internal ring stiffeners may be added to the cans to prevent buckling. However, manufacturers will often use heavy-walled steel which does not require any additional members to prevent buckling [11]. In some innovative TLP designs, such as the Stiesdal® Tetra foundation which can be deployed in a TLP configuration, pin joints are then cast or forged and inset to the cylindrical sections before being welded into place (Figure 6). The circumferential seams are then welded using Submerged Arc Welding before the steelwork is blasted and coated in epoxy [11].



Figure 6 Stiesdal® Tetra component manufacturing at Welcon® factory [10]

The GICON-SOF TLP uses pre-stressed Ultra-High Performance Concrete (UHPC) for its tubular sections and buoyancy bodies, differing from steel TLPs in manufacturing. This approach simplifies production, making it cost-effective and efficient albeit requiring prior investment in dedicated fabrication facilities. The pre-stressing process, commonly used in bridge engineering, enhances the material's lifespan. The design also includes a concrete lowerable anchor, serving as a barge and ballast during installation.

3.2.2 Manufacturing Infrastructure Requirements

Due to the infancy of floating offshore wind (FOW) technology, there is limited experience in manufacturing components for FOW applications. While facilities for processes such as submerged arc welding, plate rolling, and reinforcement bar placement are relatively common, only a handful of facilities in the UK and Europe can perform all three processes required for FOW substructure production [12].

The design of TLPs may increase their compatibility with existing manufacturing facilities. A key difference between the subcomponent manufacture of TLPs and other FOW substructures is the size of the subcomponents being fabricated and handled. Many TLP developers aim to design tubular subcomponents with a similar diameter to the turbine tower sections, facilitating integration of TLP subcomponent manufacture into existing turbine tower manufacturing facilities. For example, Stiesdal® integrated the manufacturing of their Tetra foundation subcomponents into the turbine tower manufacturing facilities at Welcon®, creating the world's first fully industrialised offshore wind foundation. However, not all TLP designs follow this criterion, and those unable to integrate with turbine tower facilities often opt for dedicated manufacturing facilities.

3.2.3 TLP Substructure Assembly

The modular design of TLPs is advantageous for assembly. Each tubular section is manufactured and then shipped to the final assembly area, either at a dedicated facility or mobilisation port. Many designs only require a flat, open quayside area for assembly, thus eliminating the need for dry docks. For TLP designs requiring more specialised processes, such as the SBM Offshore® design used at Provence Grand Large, the central columns are upended and supported on stools, and the radial legs are aligned with the brace stubs and welded together using manual metal arc welding, as shown in Figure 7. Designs which feature diagonal braces will have them aligned using crawler cranes and welded using manual metal arc welding [11].



Figure 7 SBM Offshore® TLP Assembly in Eiffage Metal®'s yard in Fos-sur-Mer [13]

Pin-joints: TLP designs which feature pin-jointed tubular subcomponents, as shown in Figure 8, reduce the requirement for any special assembly processes such as welding or painting. This greatly simplifies the assembly process, only requiring the alignment of the braces around the central column followed by the insertion of fitted pins into the joints. Both of these processes can be completed using readily available mobile land cranes.

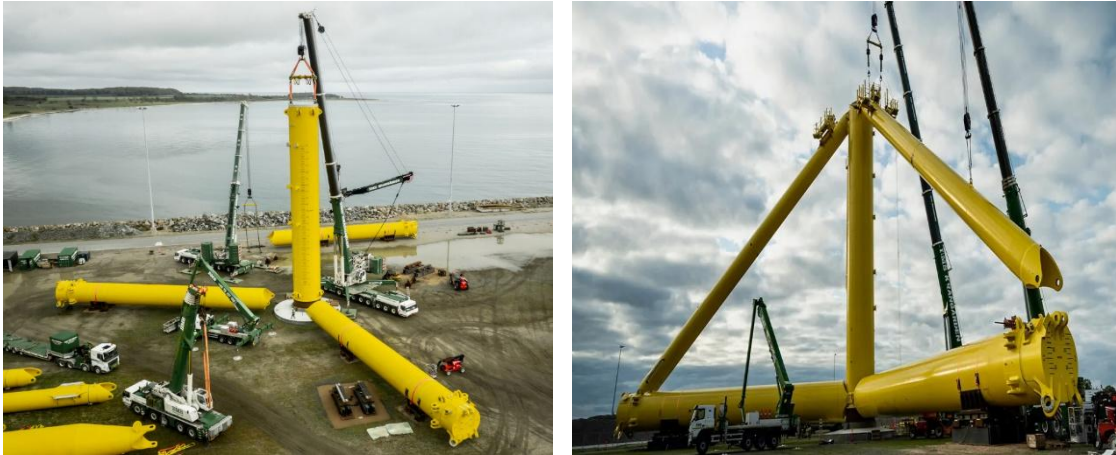


Figure 8 Attachment of radial braces (left) and diagonal braces (right) to Stiesdal® Tetra platform [10]

Concrete-based TLP: the concrete GICON design is assembled in two stages, firstly the diagonal braces are aligned around the transition piece and connected. Concrete elbow joints are added to the opposite end of the diagonal braces to complete the first sub-assembly.

The square base, assembled from concrete tubular sections and three-way elbow connectors, is placed within the slip-formed concrete anchor with the buoyancy bodies placed atop and joined together to create the second sub-assembly. A large gantry crane is then used to connect the two sub-assemblies and complete the assembly process, as shown in Figure 9.

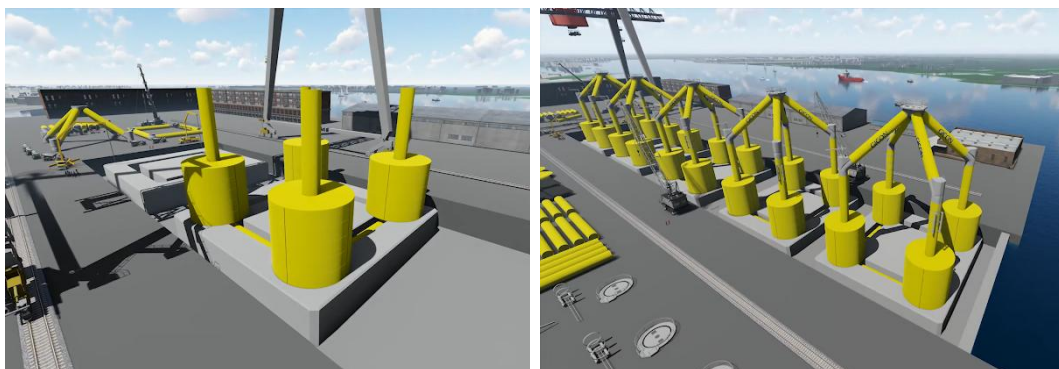


Figure 9 Visualisation of proposed GICON-SOF TLP assembly process

3.2.4 Port Requirements

The marshalling and assembly of floating wind turbines within the existing port infrastructure has become a notably limiting factor in the commercial-scale deployment of FOW. Substructure and subcomponent size have highlighted the current incompatibility of existing ports to accommodate the delivery of floating offshore wind at the capacity that is forecasted for the end of the decade. Figure 10 illustrates the key port characteristics required for FOW.

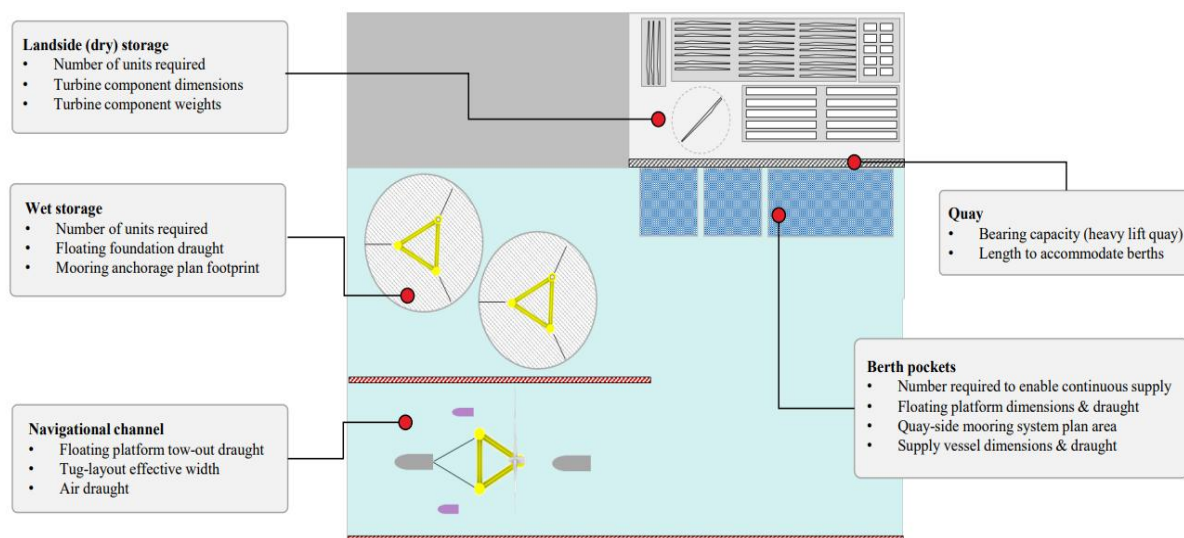


Figure 10 Schematic of key port characteristics for FOW delivery [14]

In a study conducted by ARUP [14], several key challenges were associated with port infrastructure and the deployment of floating offshore wind. The challenges that were highlighted were:

- Ports have a general lack of infrastructure for FOW delivery, particularly in turbine integration activities
- Project-by-project basis of FOW doesn't provide the level of commitment required for long-term investment in port infrastructure
- Large FOW components and assembled structures create several individual challenges
 - Movement within confined port environments
 - Identifying suitable wet storage areas
 - Identifying suitable land storage and assembly areas

Despite semi-submersibles remaining the preferred floating substructure, stakeholder engagement in the report revealed a notable shift towards TLPs, with over a quarter of stakeholders favouring this type of substructure [14]. This shift may be due to TLPs addressing several key challenges.

The generally smaller size of TLPs reduces port requirements. Their compact size, both when disassembled and fully assembled, allows for more convenient storage at quayside and in shallow ports, which is particularly advantageous in areas with limited port infrastructure. Additionally, the simplified assembly process of certain TLP designs eliminates the need for specialist machinery at the quayside, reducing potential future bottlenecks.

Landside Storage

TLP subcomponents will be transported from the manufacturing facility to an assembly area which will either be a dedicated separate facility or part of a mobilisation port. Once at the assembly area, the subcomponents will be stored until they are assembled. Upon completion of the assembly process, the substructures will either be stored quayside in a large flat open area, as seen at Provence Grand Large in Figure 11, or wet stored in the port before turbine integration or mobilisation to the site.



Figure 11 Provence Grand Large TLPs being stored quayside and floated off via barge [15]

The Arup study highlighted stakeholder confidence in the current UK port infrastructure for FOW marshalling and assembly. It was believed that existing ports could support a 1GW FOW development using 15MW turbines on semi-submersible substructures, with landside and bearing capacity needing minimal development. However, wet storage area would require more significant development.

Wet Storage

The smaller footprint of TLPs is not expected to affect wet storage significantly, as temporary moorings will be similar to other substructures, limiting their space-saving benefits. Many TLP designs are self-stable and do not require ballast during wet storage or tow, though less stable designs may need stability aids. There may be potential for wet storing fully integrated TLPs with turbines attached, but this would require additional ballast in some cases.

This process was demonstrated in the Provence Grand Large development (Figure 12), where platforms were assembled onshore, stored quayside, floated into port, ballasted for turbine integration, and towed unaided to the site for mooring and anchoring, demonstrating self-stability during tow.



Figure 12 Provence Grand Large turbines being towed after turbine integration [16]

3.2.5 Turbine Integration

In-Port

Of the limited demonstrations to date, quayside turbine integration has been the most common approach in FOW. This is usually conducted in a sheltered port using onshore land cranes. Ring cranes are believed to be the best option for this process, however, other land cranes, such as crawler cranes and tower cranes are also potential alternatives [14]. It is understood that the most efficient lift sequence is a one-tower, one-nacelle and three-blade sequence, with the limiting factor being crane capacity and the feasibility of lifting a fully assembled tower. Future lifting plans for larger turbines, 15MW and above, may consider lifting up to four separate sections per tower.

Floater movement has been a challenge associated with in-port turbine integration on floating substructures. TLP substructures show greater sensitivity to weather conditions during wet storage than semi-submersible structures due to their instability when unmoored. However, this can be negated similarly through the use of a temporary mooring or ballast system to ensure the stability of the platform during an in-port integration as shown in Figure 13 which demonstrates a similar in-port turbine integration process onto the Stiesdal® TetraSpar platform.

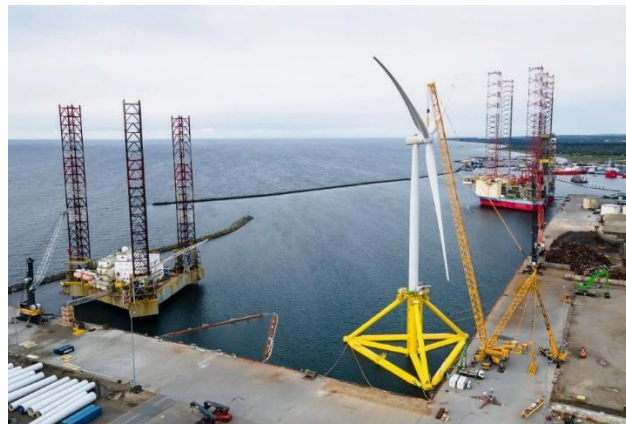


Figure 13 In-port installation of a turbine onto the Tetra platform by Stiesdal® [10]

Turbine integration can also be completed onshore in a dry dock or a flat, open area and floated out into the port using a barge to eliminate any potential stability issues. This approach is proposed by Bluewater® who utilise their Transport and Installation (TIF) frame which allows for turbine integration onto the TLP substructure in fixed bottom conditions. Once integrated, the frame is then used to aid stability during towing. The Bluewater® TLP and TIP, in both an integration and towing scenario, are shown in Figure 14.

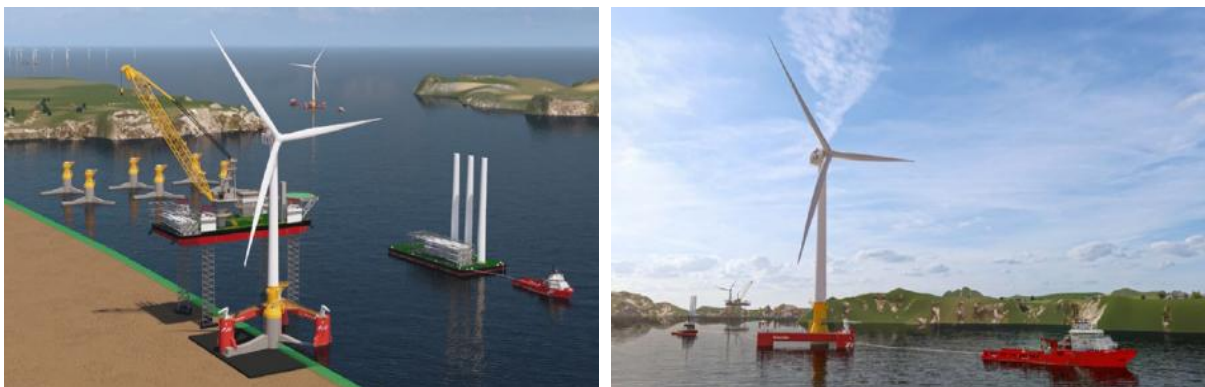


Figure 14 Bluewater TLP integration (left) and towing (right) using TIF [29]

The onshore integration approach depends on the availability of dry docks for fully assembled TLP structures and may lead to stability issues similar to wet storing turbine-integrated TLPs. Stakeholder engagement suggested that towing stability is less of a limiting factor than perceived. TLP transportation is further detailed in Section 3.3.

In-Situ

In-situ turbine integration is a method used more commonly in the installation of bottom-fixed offshore wind turbines. In the case of a bottom-fixed wind turbine, this approach consists of installing the monopile at the site, and then transporting the turbine components to the site for final installation. As the water depths seen in bottom-fixed offshore wind are generally shallower than those seen in FOW, a jack-up vessel can be used for the integration of the turbine onto the monopile. An example of this turbine integration technique is shown in Figure 15.



Figure 15 Jack-up vessel conducting an in-situ turbine integration for a bottom-fixed structure [17]

Once a TLP has been pre-installed, it behaves similarly to a bottom-fixed structure due to the stability provided by its highly tensioned tendons. Therefore, for TLPs deployed in shallow water sites, there is the option to transport the TLP substructure to the site and perform the turbine integration in-situ using a large jack-up vessel, providing the water depth is within the operational limits of the jack-up vessel. In this scenario, TLPs can be designed to be non self-stable (NSS) i.e. without towing stability as a design constraint. Results from the engagement with OEMs highlighted that multiple TLP designs will be capable of operating in 70m water depths with a 15MW or 20MW turbine attached. In this case, jack-up installation vessels such as Jan De Nul's *Voltaire* vessel, capable of operating in water depths of up to 80m [18], could be capable of completing the turbine integration procedure.

In deeper waters, where jack-up installation vessels cannot be used, developers are currently exploring the possibility of using heavy lift vessels with sufficient dynamic positioning (DP) capability to conduct the turbine integration process. In the absence of either a fixed platform or vessel, the process is further complicated by the risks associated with float-to-float lifting.

It is important to note that TLPs have additional considerations before turbine integration compared to other floating substructures. Pre-turbine integration, TLPs will be at peak buoyancy due to the absence of the downward force of the turbine acting on the platform. This will temporarily increase the tension in the mooring lines before the turbine is integrated onto the substructure. Therefore, specific design considerations may have to be made when pre-installing the TLP and the mooring tendons to ensure that they are capable of withstanding the additional buoyancy load caused by the omission of the RNA during pre-installation.

3.3 Transport & Installation

Compared to the other main floating substructure types, TLPs are generally a less understood area within the offshore wind industry as they can be an area with perceived increased risks or complexities.

3.3.1 Transport

Component Transportation

Transporting TLP components to the quayside for construction and assembly presents an advantage over other substructure types. The shallow-draught, tetrahedral TLP philosophy, with its smaller modular components, enhances flexibility in transportation due to reduced size and weight demands. The deep draught, single-column TLP philosophy with larger components is expected to pose different challenges when compared to tetrahedral designs, yet still offer a broader range of transportation options when compared to traditional substructure types. An example of this is the PelaStar TLP, which allows the loading of components for a complete substructure module onto a barge vessel. The arrangement used for the substructure components is illustrated in Figure 16.

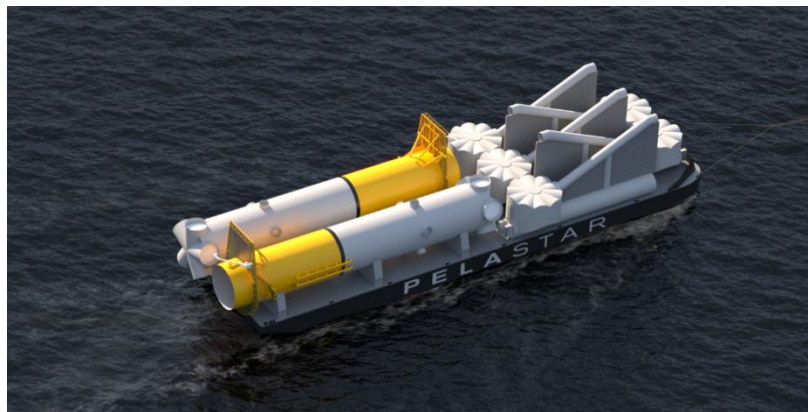


Figure 16 PelaStar component transportation [19]

FOWT Transportation

FOWT transportation methods can vary, with most demonstrators using the tow-out approach, where the floating substructure is towed to the site by an Anchor Handling Vessel (AHV) with a large bollard pull, supported by smaller vessels. This method can be time-consuming, as calm wind and wave conditions are needed, and vessel availability may be limited as FOW installation increases.

TLP transportation presents additional challenges due to its lower stability compared to other substructures. Since TLPs gain stability from mooring tendons and buoyancy, transporting them requires extra consideration [20]. Some developers transport the substructure by vessel, or tow it without the turbine integrated to lower the centre of gravity and improve towing stability. This increases costs, as large vessels are needed for offshore installation. To avoid these additional costs, developers often prefer quayside turbine integration, though towing with the turbine integrated results in stricter weather conditions.

To mitigate the high centre of gravity during towing, temporary ballast systems can be used. These ballast systems, typically large containers filled with seawater or dense aggregates, lower the substructure to the desired draft before towing or turbine installation. Once in position, the ballast is

removed and returned to port for reuse. Another option, adopted by PelaStar and past iterations of the MPS design, use distributed buoyancy modules to achieve the same stability.

In addition, TLPs can be dry towed on a heavy-lift barge and installed in situ. This approach eliminates the need for long wet-tow operations, avoids the stability risks associated with towing, and reduces sensitivity to weather windows during transport. Once on site, the TLP is offloaded, ballasted, and connected to its tendon system. Although this method introduces additional logistics for heavy-lift vessel coordination, it offers a potentially safer and more predictable installation pathway for large-scale projects.

OEM engagement revealed that towing with or without the turbine integrated can safely occur up to 4 metres Hs, with the installation and hook-up process being the primary limiting factor.

3.3.2 Installation

Mooring & Anchor Pre-installation

Pre-laying the mooring system for floating wind farms is the preferred approach to keep off the installation's critical path, avoiding bottlenecks and enabling simultaneous installation campaigns. While steel chain mooring lines can rest on the seabed, synthetics present a challenge due to potential abrasion, which could compromise rope integrity and cause failure [21].

For TLPs, maintaining the integrity of the mooring tendons is essential for stability, making wear avoidance a priority. To address this, buoys can be used to keep synthetic lines off the seabed during wet storage after pre-lay. In harsher conditions or during prolonged storage, lines may become tangled or suffer abrasion. To mitigate this, shared buoys can connect multiple lines near the waterline, easing retrieval during installation.

Installing anchors before the mooring tendons and TLP substructure enables a more efficient TLP installation. Suction and driven piles require specialised heavy lift vessels with heave compensation systems. Suction piles are deployed using the vessel's crane, where the pile autonomously penetrates the seabed before reaching the desired depth via a pump operated by a Remotely Operated Vehicle (ROV), ensuring a streamlined installation.

Driven piles, which require hammering or drilling, are similarly lowered to the seabed using the crane, with the pile self-penetrating under its own weight. A hammer or drill is used to reach the required depth, and while ROVs are not necessary for installation, they are essential for post-installation inspection.

Shallow water installations are less challenging due to easier anchor lowering and embedding. However, unforeseen challenges, such as harder seabed conditions, can delay installation. In rocky seabeds, drilled piles may be preferred over suction anchors [22].

Novel anchor solutions developed for floating wind could reduce installation time by using smaller piles and more efficient embedment methods, enabling operations in dynamic environments and challenging seabeds. TLP designs will have preferred installation methods, but pre-installing more components will likely improve overall efficiency. While all anchors will likely be preinstalled, different designs will dictate whether tendons can be installed with the substructure or separately.

Mooring Hook-up

The tensioning of mooring lines for TLPs is more complex than for other substructures, as all fairleads must be tensioned simultaneously while maintaining stability. There are two primary methods for hooking up a TLP to its mooring lines:

Ballast-Down and Deballast Hook-Up Method

This is a proven method for installing TLPs in offshore oil & gas, which can be adapted for floating wind applications. The TLP is towed to site in a shallow draft, then ballasted down (either by flooding compartments or using temporary weights) to align with the pre-installed tendons. Once connected, deballasting tensions the tendons and brings the platform to its operational draft and stiffness.

This method is suited for floating wind TLPs if tendon pre-installation is feasible and platform geometry allows adequate stability during ballasting.

1. Tow to site: TLP arrives on location in a buoyant, shallow-draft condition suitable for towing.
2. Pre-installed tendons: Tendons are already in place, held vertically using subsurface buoys or clump weights.
3. Ballast down: Ballast is added (e.g., seawater flooding tanks) to lower the TLP to its installation draft. The geometry (deep-draft columns or additional pontoons) ensures enough stability during this phase.
4. Tendon connection: One-by-one, tendons are connected to tendon porch interfaces using ROVs, divers, or guide systems.
5. Deballast: The platform is deballasted (removing water/weights), which pulls up on the tendons, applying the required tension and establishing restoring stiffness.
6. Operational mode: The TLP reaches final draft and is fully installed.

Winch or Jack-Down Method (Pull-Down via Anchors)

This method involves attaching the TLP to the anchors or tendons while in a high-buoyancy state, and then pulling the platform downward using mechanical systems such as winches, jacks, or hydraulic cylinders - with or without added ballast. This generates the necessary tendon tension by physically forcing the TLP downward into its final position.

Preferred when precision pull-down is required, or if platform ballasting is limited due to space, weight, or complexity. Also useful for modular or smaller TLPs where passive ballasting may not generate sufficient tendon pre-tension.

1. Transport to site: Platform arrives at site in high-buoyancy condition.
2. Anchor/tendon pre-installation: Tendons or mooring lines are already connected to foundation piles or suction anchors.
3. Topside connection: Tendons are attached to the platform's tendon porches while it's still floating at higher elevation (lower draft).
4. Mechanical pull-down: Use onboard winches/jacks to pull the TLP downward the tendons.
5. Optional ballasting: Ballast may be used to assist the pull-down or stabilise the structure.
6. Final position: Once at the correct draft, tendon tension is achieved, and the system enters operational mode.

Given the intricate nature of traditional TLP installation procedures and the potential for hull instability during submergence, efforts have been made to enhance the process. Several OEMs have begun to consider incorporating tensioning devices with pull-down lines within their installation procedures. These devices aim to streamline the de-ballasting process, which will be different for each specific design.

Feedback from TLP Substructure OEMs

The mooring hook-up process is design-specific and may necessitate specially tailored equipment. Substructure OEM engagement focused on the essential elements integral to the hook-up process for each TLP design philosophy, though details of their processes are understandably well-guarded and cannot be shared at this time. The OEMs acknowledged the complexity of the process but affirmed its confidence and reliability through the development of installation procedures and equipment tailored to each design type.

TLP designs incorporate installation methods that employ dedicated equipment tailored to their specific hook-up approaches. Notably, the utilised equipment is designed for removal and reusability in subsequent FOWTs. In cases where disconnection is necessary, the same installation equipment can be repurposed to reverse the installation approach.

This reuse of installation equipment carries significant economic advantages, allowing the costs associated with manufacturing these unique components to be distributed across the entire wind farm. Further discussions have indicated OEM's preference for pre-laid anchors and moorings, facilitated by buoyant tendons or buoys depending on whichever strategy best aligns with their platform.

The pre-tensioning stage of TLP installation must be accurately performed and monitored throughout the process. Tension can be monitored using a Tendon Tension Monitoring System, which may comprise of load cells positioned between a base plate and a flex element or strain sensors along the length of the mooring tendon [23]. Cable lay and pull-in

The array cable is typically laid once the TLP substructure and mooring tendons are installed before being pulled in and connected to the substructure. There is also the potential for the cable to be pre-laid prior to tendon installation. The cable is laid using a cable laying vessel (CLV) or a reel lay vessel equipped with portable installation equipment. Due to the improved station-keeping motions of the installed TLP compared to other floating substructure types, the dynamic cable pull-in may be easier to perform. However, the installation window for cable laying and pull-in operations will still be dictated by the safe operating limitations of the vessel.

3.4 Operations & Maintenance

3.4.1 Minor Operations and Maintenance Activities

Minor operations and maintenance (O&M) activities are crucial for ensuring the operational integrity and reliability of TLPs. Key components such as the substructure, mooring tendons, and dynamic cable system require proactive inspection and maintenance to minimise the need for major repairs.

Inspection

Given the importance of mooring system performance for TLP stability, increased inspection and monitoring activities are anticipated. The consequences of failure for critical components like mooring tendons or anchors could be severe, making TLPs more vulnerable than other, more stable floating substructures. Inspections will involve remotely operated vehicles (ROVs) to detect potential damage or defects. Increased safety factors and conservatism in wear tolerance are recommended to minimise failure risks, though this may lead to more frequent scheduled component replacement.

Inspection practices for anchors, such as suction and driven piles, will be adapted to monitor the anchor's top for corrosion, damage, or scour. The frequency of these inspections will rise due to the larger number of anchors and tendons needed for large-scale floating wind projects.

Turbine access

Maintenance activities may require access to the floating substructure, which presents challenges compared to fixed offshore wind structures. The reduced motion of TLPs allows dynamic crew transfers, similar to those used for fixed turbines. For distant wind farms, Service Operation Vessels (SOVs) are preferred over Crew Transfer Vessels (CTVs) due to their greater capacity to accommodate personnel. Access via an SOV involves dynamic walk-to-work systems with active motion compensation, providing more adaptability to rough sea conditions. Inshore, CTVs can be used for access, depending on the weather and substructure design.

3.4.2 Major Operations and Maintenance Activities

Major maintenance encompasses the comprehensive repair, replacement, or refurbishment of TLP components, including turbine blades, mooring tendons, and dynamic cables. Two primary strategies for major maintenance are tow-to-port and in-situ maintenance.

Tow-to-Port Maintenance and Off-station Management

Tow-to-port maintenance for TLPs presents unique challenges compared to spread-moored platforms. Due to their reliance on vertical tendons for stability, TLPs are inherently less stable during transport, making towing operations more complex and weather-sensitive. Unlike many spread-moored designs, most OEM TLP solutions require specialised onsite equipment—such as jacking systems or temporary buoyancy modules—for safe tendon disconnection and reinstallation. These additional steps increase operational complexity, cost, and downtime. Off-station management must also carefully assess the impacts of towing on tendon tension and dynamic cable integrity.

In-Situ Maintenance

To minimise downtime, in-situ maintenance is preferred. This method allows repairs to be conducted at the offshore site, avoiding the complexities of disconnecting and reconnecting tendons and cables. For shallow water, jack-up vessels, which operate effectively at depths up to around 80m [18] can be used for lifting operations. In deeper water, floating-to-floating lifts become more complex. The TLP's rigidity simplifies the lifting process compared to other floating substructures. In-situ repairs for TLPs in shallow waters mirror bottom-fixed wind operations.

Emerging lifting technologies, such as cranes attached to the FOWT tower or substructure (e.g. SenseWind, WindSpider, Koala), offer a promising solution for in-situ component replacement. These cranes, self-hoisting or self-climbing, reduce the need for additional vessels and simplify the

maintenance process. Their viability depends on available space and the stability of the substructure when handling the additional weight.

3.4.3 Additional insights from substructure OEMs

Recent stakeholder engagement has provided valuable insights into TLP deployment and maintenance. Key points raised by OEMs include:

- **Reversible Installation Methods:** Reversible installation methods offer flexibility, allowing for easier TLP deployment and retrieval. This contributes to more efficient installation and maintenance processes.
- **In-situ Replacement Preference:** OEMs favour in-situ replacement methods over the traditional tow-to-port approach, aiming to minimise production downtime and streamline maintenance.
- **In-situ Component Exchange Options:** Various in-situ component exchange solutions are being explored, including dynamic-positioning heavy-lift vessels and novel crane technologies. These innovations aim to address major maintenance challenges and offer more efficient alternatives.
- **Turbine Integration:** The absence of a tower and RNA reduces the weight of the TLP. OEMs have developed custom component integration and exchange processes to counterbalance this. Temporary ballast is sometimes used to ensure stability during integration, though its impact on different designs must be carefully considered.

These insights highlight the need for innovation, adaptability, and a deep understanding of the challenges involved in TLP maintenance and operation.

3.5 Decommissioning

Decommissioning a TLP typically follows a reverse of the installation procedure. Ballasting or other design-specific components are used for disconnection before towing the platform back to shore. If the turbine-integrated design lacks sufficient stability, steps will be taken to adjust or remove the superstructure before towing.

3.5.1 TLP Substructure

TLP substructures, which consist of smaller modular components, provide advantages during decommissioning. Their smaller size facilitates quicker dismantling and transportation compared to larger substructures, which may require extensive disassembly. Components can be transported to waste management facilities that handle smaller, industry-standard components, improving decommissioning efficiency. Waste management companies prefer designs with smaller components for their flexibility in handling.

3.5.2 Anchors

The anchor type selected to partner with the TLP design dictates the decommissioning method. Notably, the higher load which these anchors are expected to withstand necessitates the need for a specialised vessel or lengthy processes to complete the removal procedure. In some cases, for deeper reaching anchors, it was noted from industry engagement that the removal of these anchors may be more destructive to the marine habitat around the position of the anchor meaning the process may be simplified to the cutting or disconnection of the mooring tendon from the anchor. This is subject to the specific anchor type and whichever regulations are in place on that seabed.

4 MOORING & ANCHORING CHARACTERISATION

4.1 Design Criteria

4.1.1 Design Life

The expected design life for FOWTs is typically around 25 years [24]. The American Bureau of Shipping assert that FOWTs should have a minimum design life of 20 years [25]. Consequently, the design of mooring and anchoring systems is expected to be in line with these operational lifespans. This alignment is crucial to ensure that the structural integrity and functionality of the mooring and anchoring systems are preserved throughout the service life of the FOWT, thereby maintaining the asset's reliability and performance.

4.1.2 Design Load Cases and Environmental Conditions

The TLP-WT's design must be sufficiently robust to withstand the specific operational and environmental conditions of its intended site, accounting for the varying operational states of the RNA [25]. This complexity arises from the dynamic forces exerted by wind, waves and currents. To establish the maximum load capacity, site-specific combinations of these forces must be considered.

Key design considerations include:

- **Ultimate Limit State (ULS):** The structure must withstand the most extreme combination of loads, typically based on a 50-year return period of environmental conditions.
- **Accidental Limit State (ALS):** Environmental loads defined as 1-year loads can be assumed in conjunction with load factors for the ALS in the damaged condition in the relevant consequence.
- **Fatigue Limit State (FLS):** Tendon and tendon components be designed against the FLS. Minimum requirements for design fatigue factors depend on the materiel type and consequence class.
- **Severe Loading Conditions and Dynamic Analysis:** The mooring tendons must endure line tensions expected during a 50-year environmental contour sea state (parked conditions DLC 6.x) and operational conditions with lower environmental loads but higher turbine thrust at rated wind speeds (DLC 1.6).

4.1.3 Redundancy for TLP-WTs

Redundancy in TLP-WTs presents a compelling discussion point, as existing codes lack specific guidelines for these structures. While tendon failure is acknowledged to significantly impact substructure stability, the general guidance remains unchanged versus compliant moored structures.

DNV-ST-0119 [8] recommends that floating structures and its station-keeping system should be designed to consequence class 1, reflecting that the floating structure is unmanned during severe environmental loading (section 8.1.1.3). However for station-keeping systems without redundancy, the design should be carried out to consequence class 2. This reflects the risk for collision with adjacent wind turbine structures (section 8.1.1.4).

The redundancy of a TLPs station keeping system is dependent on what happens in the event of a tendon failure. If the loss of a single tether causes a capsizing risk then that the station keeping system of the TLP is a system without redundancy. If there is sufficient stability in the event of a line

failure then it will be subject to ALS load factors in the damaged condition (section 8.1.1.4). This will be very design specific as some TLP-WT designs will experience different responses in the event of a tendon failure.

ABS [25] state (in section 8-1/9) that a redundant mooring system is a mooring system where the strength criteria for the intact and one line damaged conditions are satisfied and the offset and motions of the FOWT are within design limits. Non-redundant is described as when under the damaged condition with one broken line, the FOWT cannot maintain its position or satisfy the strength criteria (section 8-1/11). The damaged condition with one broken line is to be assessed in accordance with DLC 9.1, 9.2, 10.1 and 10.2 for the redundant mooring system. For TLP tendons made up of steel tubulars the above DLCs are not applicable although the rationale is unspecified.

4.2 Station-Keeping Requirements

The station-keeping system in TLP-WTs mainly comprises the tendon systems, which anchor the floating structure to the seabed. The system ensures the wind turbine stays in its optimal position, allowing for efficient electricity generation despite environmental changes. Floating structures and their station-keeping systems must meet consequence class 1 requirements. This ensures the structural integrity of TLP-WTs under extreme conditions.

TLP tendons must be engineered for high stiffness and pre-tension, with a 15MW turbine typically requiring pre-tensions of around 1,000 tonnes. These design considerations control lateral movements (surge and sway) and minimise vertical and rotational movements (heave, roll, pitch) [8]. The aim is to limit the system's excursions, which reduces the dynamic cable's hang-off angle. Compared to other floating platforms, TLP-WTs benefit from their limited displacements.

Maintaining high pre-tension is crucial to counter buoyant forces and dynamic loads. However, excessive tension variability can cause temporary slacking, followed by snapping forces that could compromise the turbine's performance and structural integrity. Slacking may arise from environmental conditions, material fatigue, design flaws, or installation errors.

A potential mitigation strategy includes regular monitoring and inspection regimes. Advanced technologies, like digital twin systems, can provide real-time data, but may not detect tendon fatigue in time. Visual inspections can identify physical damage, but early fatigue detection remains a challenge. Proactive adjustments based on available data can help maintain optimal tensions.

Tendon failure can have severe consequences:

- **Loss of stability:** A tendon failure impairs platform stability, causing significant movement and potential damage.
- **Impact of corner tendon loss:** Loss of a corner tendon causes the platform to heel, compromising structural integrity and accessibility.
- **Increased tension on remaining lines:** Failed tendons add stress to the remaining lines.
- **Operational impact:** Excessive movement may reduce performance or cause a system shutdown.
- **Repair and recovery costs:** Addressing a failed tendon is complex and costly.

4.3 Mooring solutions

4.3.1 Mooring Tendons

TLP-WTs are anchored to the seabed using specialised tensioned lines, commonly known as tendons or tethers. These tendons function in a manner similar to the vertical mooring lines found in taut mooring systems. The principal difference lies in their material and design: tendons are traditionally composed of tubes that offer minimal compliance in the axial direction, effectively acting as an inverted pendulum. The station-keeping capacity of the system is thus determined by the tendon length and its pre-tension.

Tendons can take various forms, including [4]:

- Tubular members with threaded or mechanical connectors: These can be void, partially void or fully flooded and may be comprised of metal or fibre-reinforced composites
- Tubular or Solid Rod Members with Welded Connections: These are usually made from steel and are welded together to form a single, continuous tendon element
- Tendon Strands: Made up of high-tensile-strength wire or fibre strands that are bundled together, these tendons are designed for offshore installation as a single, continuous piece.

Traditionally in oil and gas applications, these tendons are made from high-strength steel. However, within the floating wind sector, there's a growing trend towards the use of synthetic materials. Companies such as Teijin Aramid and Avient Dyneema are pioneering this shift by producing innovative fibres like Twaron and DM20.

4.3.2 Water Depth and the effect on Mooring Tendons

The relationship between water depth and its impact on mooring tendon design warrants further examination for TLP-WTs. In deeper waters, there is an option to alter the hydrostatic stiffness properties of the floater to supplement or replace the stiffness traditionally provided by the tendons. This shift may necessitate a change in substructure design, favouring increased buoyant forces over the use of stiffer materials.

An alternative mooring system could integrate both steel pipes and synthetic systems. However, this hybrid approach may introduce additional risks, such as increased points of failure at the interfaces of the different mooring components. Moreover, the economic implications of using steel pipes become significant as the tipping point in design for operations in deeper waters is considered.

4.3.3 Platform Connection Systems

The topside connection, where mooring lines interface with the platform, varies based on the mooring material used, affecting attachment methods and maintenance needs. Synthetic materials, for example, may experience elongation, influencing the frequency of re-tensioning (if required by design). End terminations play a critical role in ensuring efficient connection and disconnection activities, which are vital for mooring system functionality and maintenance.

The design of the topside connection determines whether re-tensioning is possible, but having a permanent re-tensioning method introduces additional costs and maintenance challenges for floating wind applications. As a result, developers are exploring quick-connect solutions to eliminate the need for topside re-tensioning, with subsea-tensioning emerging as a promising

alternative. In this case, end terminations must ensure reliable connection and disconnection under subsea conditions.

4.4 Anchoring solutions

4.4.1 Anchor Types

Floating structures that utilise anchoring systems are subject to various loading scenarios. These can be exclusively horizontal, as is the case with catenary mooring lines, or a combination of horizontal and vertical, as seen in semi-taut and taut leg mooring lines. TLP-WTs primarily face vertical loads. This vertical load constraint is a key factor when selecting and sizing anchors for TLP-WTs. Another factor is the number of tendons as the more lines a TLP-WT has, the more the load is distributed, reducing component sizes.

Given these factors, certain anchors are not suitable for specific types of mooring system. For example, Drag Embedment Anchors are not feasible for TLP-WTs as they only handle horizontal loads. Vertically Loaded Anchors, which require dragging into position, are also eliminated due to a lack of precision when being installed. Consequently, the options for appropriate anchors narrows down to the following proven technologies: suction buckets, driven-piles, drilled & grouted piles, and gravity-based anchors.

Suction Buckets

Suction Buckets, also known as Suction Caissons or Suction Piles, are elongated steel cylinders that are open at the base and sealed at the top. Initially, these buckets settle into the seabed due to their own weight. Further embedment is achieved by evacuating water from the sealed end, generating negative pressure within the cylinder that drives it deeper into the seabed. These suction anchors are precise in installation and versatile in load angle adaptability – however feedback suggests suction piles may have to be modified for pure vertical loads, whether it be including a skirt in the design or by reinforcing the top structure of the pile.

Particularly effective in softer seabed compositions like clay, they can also be customised for sandy conditions, although they're not ideal for harder soil types. The Floating Wind project 'Hywind Tampen' has already employed 120-ton suction anchors [26]. However, their size dictates specific installation prerequisites, including adequate vessel storage, lifting capabilities, and ROV resources. They are costly to produce, transport, and handle. An example of the sizes of suction buckets used for offshore projects is shown in Figure 17.

Driven Piles

Pile anchors consist of elongated, hollow steel cylinders that are initially embedded in sediment and further driven into the seabed using hammers or vibratory equipment. An example of the type of vibrating hammers is shown in Figure 17. A guiding template may be employed for accurate placement – although seabed slopes may deem templates unusable. While these driven-piles are versatile enough for various seabed types, they can be problematic in harder conditions or in areas with cobbles and boulders. Designed primarily for vertical load applications, they are non-retrievable once installed. Decommissioning typically entails severing the part of the pile that protrudes above the seabed. Due to their lengthy and slender design, handling them often poses challenges for standard installation vessels, likely necessitating the use of specialised, costly construction vessels. Additionally, the noise generated during installation could pose environmental concerns, as the sound from the driving equipment may be disruptive to marine ecosystems.



Figure 17 Menck vibrating hammers [27] for driven pile anchors (left) and suction bucket anchors [28] (right)

Drilled and Grouted Piles

In conditions where the seabed is not suitable for driving, drilled and grouted pin piles may be used. These involve a temporarily cased drilled socket to enable the full-length placement of steel piles. While this method can be expensive and time-consuming due to the extended installation process, it is also versatile, allowing for use in challenging anchoring conditions. This opens up areas that may have previously been considered unsuitable for floating wind farms due to hard ground conditions. However, water depth can be a limiting factor due to the constraints of the umbilical and drilling equipment. Additionally, consenting implications—such as noise, pollution, and decommissioning—need to be carefully considered.

Gravity Based Anchors

The holding capacity of this type of anchor is generated both by the weight of the material used and the friction between the dead weight and the seabed. While they are commonly constructed from steel or concrete, some innovative approaches include filling a hollow shell with a variable-density fluid. Despite its simplicity and suitability for vertical loading across various seabed conditions, Gravity-Based Anchors are generally not considered a realistic solution for Floating Offshore Wind installations. The masses required for these anchors to function effectively are prohibitively large.

5 COMPARATIVE NUMERICAL ANALYSIS

As part of this project, ORE Catapult explored geometric and inertial properties of different TLP wind turbine concepts and evaluated their dynamic behaviour under various site and environmental conditions. The work was supported by MPS and Glosten by supplying 13 TLP designs, all based on the IEA 15 MW reference wind turbine. Some design constraints were imposed to provide a homogeneous design space and enable a direct and fair comparison of the solutions considered:

- Hub height was set to 150 m above mean water level
- Rotor geometry and properties
- Rigid-body substructure model
- Simplified tendons structural (Rayleigh) damping
- Bottom-fixed specific controller with minor changes, opposed to a bespoke controller accounting for each design's characteristic natural frequencies

Other design aspects were left for the substructure OEMs to explore freely. These include:

- Detailed substructure geometry
- Tower geometry and properties
- Mooring system material and geometry

A range of designs were developed and thoroughly tested under challenging conditions, encompassing multiple permutations of:

- Extreme wind and wave scenarios
- Operational states
- Water depths (70, 150 and 900 metres)
- Offshore climates (benign and severe)
- Wind/wave directionalities

Fatigue analysis was not included in this analysis but represents an important avenue for future work, especially with the application of DLC 6.4 and 1.2 climatology. To improve the accuracy and relevance of fatigue modelling, it would be beneficial for developers to provide detailed climatology data, enabling OEMs to optimise their designs and for ORE Catapult to conduct more focused testing. Enhanced modelling could also allow OEMs to better refine platform stiffness, turbine control strategies, and tendon materials, all of which would help improve the long-term durability and efficiency of TLP systems.

5.1 Numerical models

The turbine model used for this study was the version 1.1 IEA 15 MW offshore reference wind turbine (IEA-15-240-RWT v1.1) [1]. This was used opposed to the newer version, v1.1.3, as the latter was found to experience inconsistent wind load results.

The hub height of the turbines was fixed at 150m above the mean water level (MWL) for this study. This led to a restriction in the height of the entrance platform due to blade tip clearance requirements which vary by OEM. For this study, the OEMs have suggested to set the blade tip clearance as a minimum of 3m below the blade sweep based on turbine OEM requirements. The crane height was based upon a standard offshore davit crane from Palfinger (PF200) [2]. It was also necessary to keep the access platform above the 50-year wave crest to prevent ingress of water through the Heating-Ventilation and Air Conditioning (HVAC) louvres from a wave impact. Doors should be watertight and able to be impacted by waves. Survival condition allows for higher waves than the 50-year return, meaning wave impacts on the door is possible.

Figure 18 shows a schematic of these restrictions for the TLP designs.

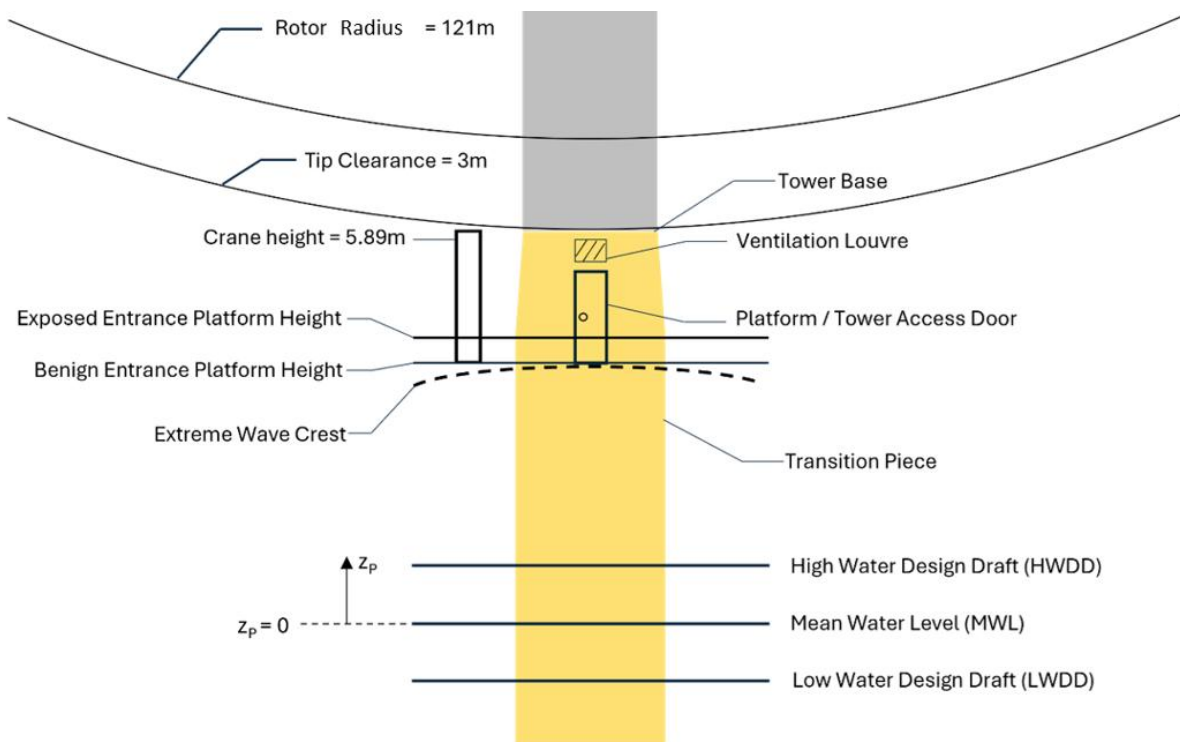


Figure 18 Schematic of the TLP tower base and transition piece displaying the 50-year extreme wave crest for a 150m hub height, where z_p is the z-axis of the platform and $z_p = 0$ is the MWL.

Set-down is another factor which impacts the height of the access platform, but has not been addressed for the designs in this study. Set-down in a TLP occurs when the TLP undergoes an excursion in the surge or sway directions. The TLP's system kinematics cause vertical submergence of the hull as the platform translates laterally. The TLP moves as if on the surface of a sphere with the radius of the tendon length. In shallow water, this can cause a significant increase in the hull submergence, impacting the gap between the maximum wave crest and the entrance platform. A solution to this in a real site design would be to raise the hub height of the turbine to move the entrance platform higher whilst maintaining the clearance between the blade tips and the entrance platform. However, in this study, the hub height is a parameter that the OEMs and OREC agreed to fix at 150m to maintain consistency in the comparative analysis.

The OEMs tailored the designs to environmental parameters specific to a benign and an exposed offshore site, obtained by applying DNV's definition of the design load cases (DLCs) 1.6 and 6.1 from the DNV-ST-0437 standard [4].

DLC 1.6 refers to the analysis of operational loads, i.e.:

- The wind turbine is operational and connected to the electrical grid;
- There are no faults of the TLP;
- The control system is active;
- A combination of different sea states are considered.

The DLC 6.1 refers to the analysis of a parked turbine, i.e.:

- The wind turbine is in stand-by mode, with the rotor either idling or at complete standstill;
- A 50-year return period for the environmental loads.

5.2 Modelling assumptions

For this study, the following modelling assumptions and limitations were agreed upon with the OEMs for the sake of simplicity and repeatability:

- **Rigid body substructure:** the platforms were modelled as rigid bodies opposed to flexible ones and hence deemed suboptimal by the OEMs. In reality the platforms would be flexible. Because for a TLP, the tower, platform, and tendons form a strongly coupled system in pitch/roll, the rigid body assumption has consequences on the global dynamics of the floating turbine, as outlined in Table 2:

Table 2 Consequences of rigid substructure assumption on global TLP dynamics

Impact	Rigid body substructure (modelling assumption)	Flexible substructure
Pitch/roll natural frequencies	The system is artificially stiffened resulting in higher pitch/roll natural frequencies. These higher natural frequencies mean that the resonant response of the platform is further away from the peak wave frequency range, resulting in lower wave-induced resonant loads.	A flexible substructure would generate a softer TLP system, reducing the pitch/roll natural frequencies and therefore shifting these closer to the peak wave frequencies.
Structural damping	A rigid substructure generates a direct positional constraint between the tendons' fairleads and the tower base, with nothing in between absorbing part of the excitations between the two. This further tightens the coupling between the turbine and the mooring system, with no damping to absorb part of the loads.	A flexible substructure generates additional structural damping, which would absorb part of the external loads - particularly those coupled with rotational DOFs about the horizontal plane (pitch and roll).

- **Simplified tendons structural (Rayleigh) damping:** a simplified damping model might not capture the complex structural damping of some tendon materials. Using more advanced damping models for those materials would allow the structural damping to be more accurately modelled. The increased damping provided by those models should help to reduce system motions and loads.

- **Bottom-fixed specific controller with minor changes**, opposed to a bespoke controller accounting for each design's characteristic natural frequencies. Even so, the turbines were checked against negative aerodynamic damping, which was negligible in all instances.

5.3 Scenarios and load cases

To explore a wide range of potential applications for TLPs, the OEMs have designed their models specific to the different offshore sites. The same three water depths were then explored for this study by ORE Catapult:

- Shallow - 70m
- Intermediate - 150m
- Ultra-deep - 900m

For each water depth, both a benign and an exposed site were considered. However, the combination of shallow water and severe climate was excluded, as it proved too challenging to develop a viable design while maintaining a rigid substructure in the model. A summary of the different sites and the metocean conditions investigated in this study can be found in Table 3.

Table 3 Summary of the environmental conditions utilised in this study

	Units	Based on DLC 1.6 (operational turbine)		Based on DLC 6.1 (idling turbine)	
		Benign	Exposed	Benign	Exposed
Hs	m	7.5	9.9	7.6	13.3
Peak Wave Period (Tp)	s	9.7	11.1	9.8	12.9
Gamma	./.	5.0	5.0	5.0	5.0
Wave directions	°	120 & 180	120 & 180	120 & 180	120 & 180
Max surface level (from MWL)	m	+0.50	+3.40	+0.50	+3.40
Min surface level (from MWL)	m	-0.50	-3.50	-0.50	-3.50
Reference Current Speed	m/s	0.15	0.14	1.0	1.0
$U(600, 10)$ Wind Speed (10mins @ 10m above MWL)	m/s	8.4	8.5	23.1	40.5
$U_0(3600, 10)$ Wind Speed (1hr @ 10m above MWL)	m/s	7.93	8.02	21.3	36.39
Turbulence intensity value	./.	0.077	0.079	0.116	0.145

5.4 Findings

This study aimed to compare the geometric and inertial properties of various TLP wind turbine concepts and assess their dynamic behaviour across different site and environmental conditions. MPS and Glosten contributed to this effort by providing a total of 13 TLP designs, all based on the IEA 15 MW reference wind turbine. While certain constraints - such as a hub height of 150 m above mean water level and assuming a rigid-body model for the substructure - were imposed, other aspects - including tower design and mooring systems - were left to the discretion of the substructure OEMs.

Water depth

The primary challenge for both OEMs was developing a viable TLP design for shallow waters. A water depth of 70 m emerged as a critical threshold, as designs were successfully produced for a benign offshore site but not for a severe site. Glosten suggested that the assumption of a rigid substructure was particularly conservative and that a flexible substructure model could have enabled a viable design even in severe conditions. In ultra-deep waters, MPS did not provide designs, citing concerns over techno-economic viability and the suitability of alternative solutions. Glosten, while acknowledging the challenges, remains confident that TLPs can be competitive, particularly with advancements in high-stiffness synthetic mooring materials. At a depth of 150 m, all designs performed well, demonstrating their suitability for such conditions.

5-arm solution

The number of arms in the tendon configuration plays a critical role in the stability of a TLP. In a five-arm system, Glosten indicated that one tendon can go slack without compromising overall stability, whereas, in a three-arm system, no tendon group can be allowed to go slack, due to potentially catastrophic consequences resulting from a complete loss of pitch stiffness. In a five-arm system, the centre of buoyancy remains within the area formed by the remaining four tendons, which can still uphold the TLP. Furthermore, when a five-arm system experiences slack events at two tendon groups simultaneously, the platform preserves some pitch and roll stiffness among the three remaining groups under tension. This is the logic behind the allowance for slack events in fibre rope tendons in DNV-ST-0119, Section 8.3.3.2 [3].

Simulation results

This project successfully addressed some of the industry's reluctance toward TLP technology in floating wind applications. Various designs were developed and rigorously tested under severe conditions, including extreme wind and wave scenarios across different operational states, water depths (shallow, intermediate, and ultra-deep), offshore climates (benign and severe), and wind/wave directionality (co-directional and misaligned). With the exception of the severe climate in shallow water and an MPS design in ultra-deep water - where economic feasibility, rather than technical limitations, was the constraint - all designs withstood the considered test scenarios.

- Tidal range proved to be a minor concern, with negligible impact in a 1 m range and only slight effects observed at a 7 m range, yet none that compromised operational capability even at the lowest tide. Even in storm conditions, where aerodynamic damping was absent due to turbine idling, motion responses remained limited. Surge and sway increased with water depth, whereas pitch and roll remained consistent across all depths, suggesting potential benefits for dynamic cable design.
- Mooring system loads were monitored at the fairlead, revealing considerable variations between different designs. This highlights the influence of design strategies and the adaptability of TLPs to diverse site and environmental conditions. Additionally, tower excitation levels were lower compared to the VoltornUS-S semi-submersible under similar loading conditions, with no observed resonant interactions between rigid-body motions, tower, and rotor.
- Power output was found to be dependent on the controller strategy but remained generally in line with the turbine's power curve. Further benchmarking against a semi-submersible would provide deeper insights into annual energy production (AEP) performance.

6 TECHNO-ECONOMIC ANALYSIS

6.1 Introduction

This section summarises the findings of a Comparative Techno-Economic Analysis evaluating TLP for offshore wind farms against a semi-submersible alternative. The study assesses the full life-cycle costs and revenues of both platform types for wind farms of equal size, with the goal of guiding offshore wind developers in making informed platform selection decisions. By comparing key financial metrics, the analysis highlights the value drivers unique to TLPs and identifies site conditions where they offer the most benefit.

The methodology involved evaluating various TLP configurations—particularly self-stable (SS) and non-self-stable (NSS) designs—focusing on their towing strategies from installation to decommissioning. The study explores trade-offs between platform stability and cost, helping clarify ongoing industry debates. Through this, it pinpoints the main cost influencers and outlines the degree of standardisation and optimisation needed to enhance the viability of TLPs in future offshore wind projects.

6.2 Methodology

This study has incorporated bottom-up cost modelling and industry consultation analysis. To carry out the analysis, five scenarios based in the UK were considered:

- Unconventional tetrahedral TLP self-stable in towing (T-SS)
- Unconventional tetrahedral TLP non self-stable in towing (T-NSS)
- Single column (3 leg) TLP self-stable in towing in towing (S-SS)
- Single column (3 leg) TLP non self-stable in towing (S-NSS)
- Semi-submersible (Eccentric turbine positioning)

To conduct the current analysis development of ORE Catapult's FOW Cost Model was required. To do so stakeholder engagement, including the supply chain, industry and project partners, to inform the cost model's technical, cost and financing assumptions was done, allowing a bottom-up approach. Employ a cash flow model was used to output LCOE in 2012 and 2024 prices along with other financial metrics. The cost model outputs and findings were then with the CoE partners and the model was finalised.

6.3 Cost Model

6.3.1 Model Structure

The core FOW cost model uses input data to calculate project costs, including DEVEX, CAPEX, OPEX, and DECEX, for various site parameters. LCOE and pre-tax IRR are calculated through a supporting model, with costs allocated to the most appropriate phase despite potential overlap, such as early CAPEX during development. Throughout the project, the ORE Catapult cost reduction pathway model was reviewed based on new insights from existing projects and stakeholder engagement.

The cost model requires a range of data inputs and assumptions, including representative FOW project configurations, costs, and cost drivers/macroeconomic cost factors.

Data Sourcing

Catapult reviewed and updated the existing FOW cost model data, identified relevant existing data sources (public, confidential, and from FOW CoE projects), and engaged stakeholders for feedback on specific cost data and assumptions. This approach ensured access to the most relevant data to support the project's success.

6.4 Technical Assumptions

6.4.1 Site Assumptions

Table 4 outlines the assumptions applied to the 150 m site base case model. A small wind farm size was selected since a similar approach to other technologies such as semi-submersible and spar starting with a smaller number of turbines for the initial sites.

Table 4 General assumptions of the modelled cases.

Site Parameters	Unit		Site Parameters	Unit	
Project Lifetime	Years	25	Site Condition	-	Severe
Number of Turbines	-	7	Turbines Rating	MW	15
Reference Location	Text	Celtic Sea	Wind Farm Capacity	MW	105
Distance to shore	km	65	Hub Height Mean Wind Speed	m/s	10.60
Water Depth Average	m	150	Substructure Material	-	Steel

6.4.2 Overview of Technical Assumptions

The technical data for the reference projects can be seen below in Table 5, this information was provided from both the OEMs involved in the project and the engineering team.

Table 5 Technical overview of the 150m water depth modelled scenarios.

Site Parameters	T-SS	T-NSS	S-SS	S-NSS	Semi-submersible
Mooring System	Synthetic Tendons	Synthetic Tendons	Synthetic Tendons	Synthetic Tendons	Chain Catenary with
Number of mooring lines/per turbine	6	6	6	6	6
Anchor Type	Suction Bucket	Suction Bucket	Suction Bucket	Suction Bucket	Drag-embedded
Number of anchors	3	3	3	3	6
WTG Integration Strategy	In-port	In-situ	In-port	In-situ	In-port
Major Repair Strategy	Tow to Port	Offshore	Tow to Port	Offshore	Tow to Port

6.4.3 Transport and Installation Assumptions

The required vessels for transporting and installing each floating substructure depend on whether full assembly occurs onshore or offshore. For semi-submersibles and self-stable (SS) TLPs, the fully assembled units are towed to site and connected to pre-installed moorings. In contrast, non-self-stable (NSS) TLPs are dry-towed to the offshore site using a dedicated barge, then deployed and moored before turbine integration, which is carried out offshore. While the high stiffness of the system makes this process similar to that used in fixed offshore wind, it necessitates a floating installation vessel rather than the jack-up vessels typically employed for fixed-bottom installations.

6.5 Limitations of the Study

While this study provides valuable insight to the topic, there are a number of limitations which are associated with the current work. Cost data collection can introduce uncertainty due to varying levels of detail from stakeholders and differences in cost line item definitions. When information was lacking, the author relied on internal data references to make informed judgments.

The analysis did not consider platform motions when calculating power or AEP, and weather downtime assumptions for floating platforms were generic, not accounting for stability differences or benefits from lower motions during O&M. Additionally, the O&M and construction ports were assumed to be the same, though they could differ in practice. Fuel costs for installation, O&M, and decommissioning were also neglected, as well as the site shape, with turbines assumed to be arranged in a grid layout.

Transmission assumptions include no offshore substation due to the farm's size, the use of HVAC for all cases instead of HVDC (despite increasing distance to shore), and a UK-average grid connection for a site in the Celtic Sea. It was assumed that all turbines and substructures are fabricated and assembled in the same UK port. Decommissioning was expected to follow the reverse process of installation, with similar cost trends.

For platform installation, self-stable towing configurations and semi-submersibles were assumed to require full vessel support throughout, while non-stable platforms could use independent installation campaigns for each vessel. Finally, no fatigue or structural analysis has been conducted by ORE Catapult to verify that these designs meet structural requirements.

6.6 Findings

Figure 19 presents the total cost breakdown as percentages, showing that CAPEX and DECEX contribute a lower percentage for NSS cost due to reduced mass and installation savings compared to SS towing configurations. Conversely, OPEX accounts for a larger share in NSS cases. Further details are discussed in the subsequent sections.

Development Expenditure

The DEVEX cost for each substructure is not expected to fluctuate heavily due to differing substructures. This outcome is expected, as costs related to development, consenting, surveying, engineering, and leasing are more dependent on site-specific factors than on the substructure technology used.

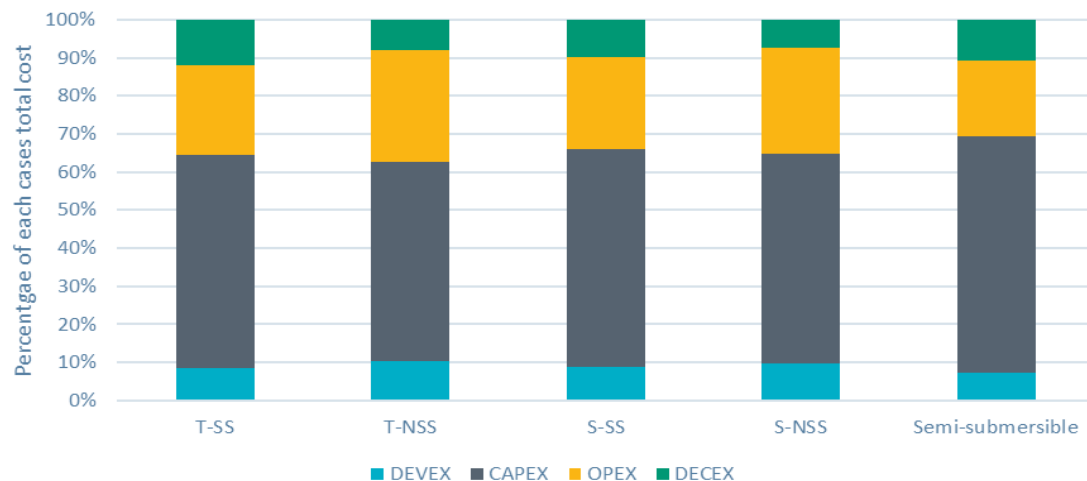


Figure 19 The total cost percentage breakdown for each scenario.

Capital Expenditure

The capital cost percentage of the NSS platforms was found to be lower than SS TLPs, and the semi-submersible is the highest. The percentage cost breakdown of the CAPEX can be seen in Figure 20.

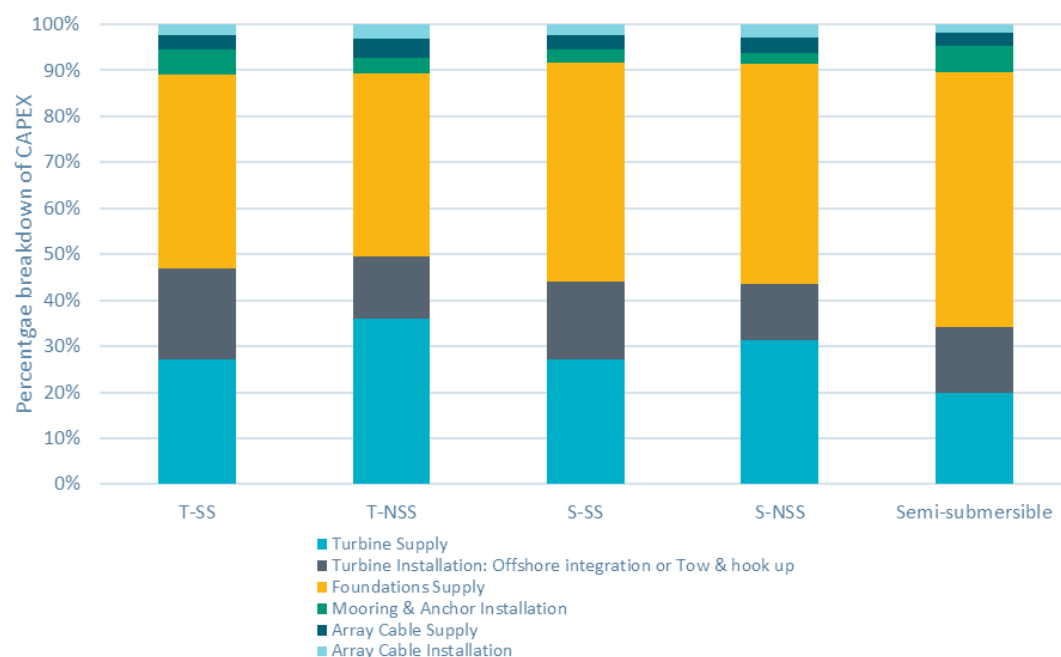


Figure 20 The capital cost percentage breakdown for each scenario.

The foundation supply cost consists of the substructure, mooring line, and anchor costs and is the largest portion of CAPEX. The key drivers of foundation cost were mass and the complexity and cost associated with manufacturing. The NSS platforms account for a smaller percentage of their total cost, this is linked to the benefit of either having lower mass or manufacturing compared to the semi-submersible, which is heavy and complex, leading to a larger contribution to the cost. Mooring line and anchor costs depend on the quantity needed, the total length of the mooring lines, and the mass of the anchors—factors that give TLPs an advantage over the semi-submersible in this work.

The installation of the substructure and turbine is typically a larger share of CAPEX for SS designs, as these units are towed fully assembled. This stems from the installation process which operates sequentially, necessitating the marine spread to be hired for an extended duration. When the installation is carried out offshore (as in NSS cases), the process can be divided into shorter campaigns, reducing the interdependence of activities and allowing for shorter vessel hire periods. Despite the offshore installation necessitating more expensive vessels, segmented campaigns, which can operate somewhat staggered yet concurrently, offer advantages. The towing installation is more sensitive to weather delays because a longer period of favourable weather is required. NSS also benefit from reduced onshore facility costs, since the majority of activities are carried out offshore, limiting the port space and equipment required compared to SS cases.

Mooring and anchoring installation cost is driven primarily by the number of anchors required, the deck space available, and therefore trips associated with the installation. For these reasons, the semi-submersible has a larger share of this cost compared to the TLPs.

Array cable supply and installation are relatively similar across the various TLPs, with a general reduction in cable length and installation time due to lower platform motions.

Other costs such as project management and contingency, are considered as a percentage of the overall CAPEX. Therefore, this cost fluctuates depending on the factors previously discussed, as well as the advantages of a lighter, less complex platform and cheaper installation methods.

Operational Expenditure

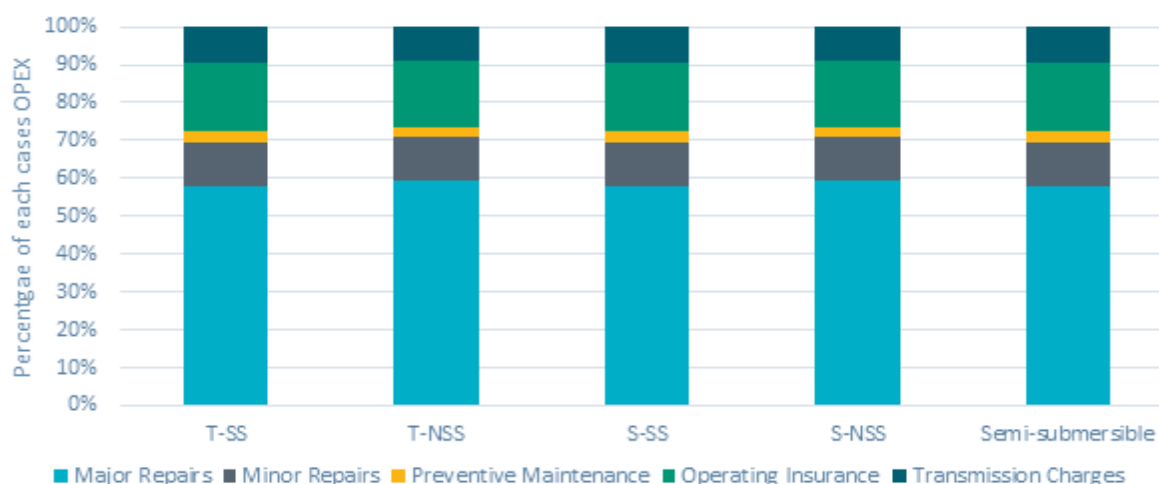


Figure 21 The O&M cost percentage breakdown for each scenario.

Figure 21, shows the percentage breakdown of the OPEX, highlighting very little variation between each substructure typology. The SS platform's major repair is marginally lower than NSS. However, this must be caveated, the current analysis assumes that the O&M port is located at the same distance—65 km from the wind farm—as the assembly port. Realistically, and evidently, this is not often the case with Kincardine offshore wind farm towing turbines to Rotterdam, taking over 90 days to complete a major repair. Varying the distance to O&M port finds 100-105km to be the distance at which in situ repair becomes the cheaper option.

Decommissioning Expenditure

Decommissioning is considered to be the opposite of the installation process within this work, so the trend seen in this cost are for the same reasons presented for installation costs. It is a simplification to assume these are the same however, this is a limitation of this work.

Annual Energy Production

The Annual Energy Production (AEP) is a key parameter since this is directly linked to revenue and LCOE. One of the main parameters which affects AEP are availability and losses. The availability on the other hand is expected to be different due to different O&M strategies implemented and specifically the vessel operating capabilities. When the major component replacement is carried out offshore, the vessels required have high rates. The vessel rates impact AEP since the availability is linked to the lost revenue per day and the vessel costs to determine the number of days downtime. The other impacting factors for towing are distance and availability of the port. The availability of SS will be significantly impacted by the distance to the O&M port, as greater distances lead to longer towing durations and reduce the likelihood of meeting the required operational windows. Additionally, port availability is expected to be a challenge due to the high volume of floating projects and existing maritime commitments.

7 DISCUSSION

7.1 Phase 1 Findings

The review of TLP technology, conducted through a combination of literature analysis, stakeholder engagement with various OEMs, and examination of design requirements and standards, yielded key insights into the strengths, weaknesses, opportunities, and threats associated with TLP applications in floating wind.

TLP-WTs are characterised by limited motion responses, which cable dynamics and therefore their structural integrity over time. The dynamic behaviour of the platform can be adjusted by design, changing the mooring stiffness and geometry. The mooring configuration can also mitigate the effect of negative aerodynamic damping and allow the adoption of a constant-power control strategy. TLPs offer benefits such as reduced steel content and mooring footprint, minimal seabed impact, enhanced energy yield with reduced tilt, and wider O&M weather windows.

Modular substructure design, optimised balance between towing stability and weight efficiency as well as advancements in mooring geometry and materials were all identified as priorities in technology development to unlock TLP-WTs on a commercial scale. Clear operational processes represent a key avenue for reducing uncertainties and boosting confidence in the technology across the industry. Load reduction devices and other novel technologies aimed at reducing the overall platform motions are being explored to generate milder loading cycles on critical components (particularly the dynamic cable, among others), leading to a lower LCOE in favourable conditions.

The design life and design criteria for mooring and anchoring systems are well-defined, accommodating the dynamic demands of wind turbines, which require rigorous dynamic analysis. Innovations in mooring tendons have shown particular promise, with advanced materials that can deliver enhanced strength profiles and superior fatigue resistance. There has also been success in integrating these tendons with quick-connection components, ensuring efficient compatibility with both the anchors and substructures. The choice of anchors, while contingent upon varying soil conditions, benefits from the establishment of quick-connection interfaces that streamline the installation process. The development of innovative anchors is poised to disrupt the market, offering significant reductions in both material and installation costs. Furthermore, a bill of materials was delineated for a TLP using traditional methods, serving as a baseline to compare against a bill of materials that incorporated these innovative approaches. This comparison underscored the substantial development potential for some of the applications reviewed.

Some technical challenges, notably towing stability, minimising wave-exposed surfaces of the substructure, and addressing the need to reduce the surface-piercing area, were found to be well-understood, while others require further research to appropriately evaluate their impact and possible mitigations. An overview of the identified challenges, and their respective solutions and mitigating actions, are shown in Table 6.

Table 6 TLP-WT challenges, solutions and mitigations

Challenges	Solutions & Mitigations
TLP-specific loading and dynamic behaviour: sum-frequency quadratic wave loading and third-order wave loading can generate resonant effects with TLP-WTs, respectively known as springing and ringing	Appropriate design and tendon stiffness, careful modelling choices and thorough tank testing to capture phenomena that could be missed or difficult to recreate in a numerical environment
Increased risks associated with co-location: Collision with other marine users may result in catastrophic failure, presents a development and consenting challenge	TLPs' small footprint presents an opportunity for benefit from co-location, provided thorough consultation with relevant marine users and governing bodies is conducted to ensure sufficient clearance between TLPs and neighbouring activities as well as sufficient redundancy in mooring design
Hookup and installation challenges: The complex nature of hooking up TLPs at site and sufficiently tensioning them to the necessary pretensions poses a challenge	Convergence towards a small number of established tensioning methods. Furthermore, the inclusion of quick connection systems and in-built tensioning systems may simplify the hookup and installation process
Transport: Due to the lower stability during transport in comparison to other substructure types, TLPs face stricter weather windows for towing and in some cases require temporary ballasting both in tow and at site	Research and development into existing less stable designs to improve stability during tow-out and installation, or opt for dry-towing and in-situ WTG installation strategy However, OEMs have indicated that this is not as great an issue as perceived; although a semi-submersible could be towed out in a harsher environment, the hook-up process would not proceed during that environment anyway
Shallow and ultra deep water: A misconception exists about the unsuitability of TLPs in shallow water, while ultra-deep water applications present unresolved knowledge gaps	OEM engagement has indicated that depths of as low as 70 m are possible with 15 - 20 MW turbines, providing a viable option immediately outside of the bottom-fixed depth range Ultra-deep applications need to be investigated in more detail to identify challenges and determine feasibility of deployment
TLP-WT Tendon technology: Synthetic fibres show promise in replacing steel wire rope and pipe for use in mooring tendons. However, the performance and properties of these materials are not fully understood over 25 years	Conduct further research and testing of synthetic materials to validate their long-term performance (e.g., creep resistance)
Anchoring methods for TLPs: Traditional anchoring methods are very large for TLP-WTs due to the high expected vertical loads involved	Explore innovative anchoring solutions, like Triton anchors, UMACK, Schottel Swift and Subsea Micropiles, that offer better mass-to-holding capacity ratios and which are suitable for vertical loading
Lagging TRL levels and lack of demonstrations: There is a wide landscape of TLP designs and concepts with very few advancing sufficiently through TRLs to market or demonstrator readiness	Having many different TLP designs complicates standardisation efforts, leads to a fragmented supply chain and disperses the focus on innovation. Concentrating resources on fewer designs could enable better allocation of research, optimisation and development of selected designs

Challenges	Solutions & Mitigations
Effects of TLP Specific Loading on the Anchor: Due to limited number of demonstrators, the long term TLP-specific anchor loadings are relatively unknown	Identify key factors affecting cyclic TLP-WT loading on the anchor over the design life, including different soil types and its implications for performance. Support studies for novel anchor designs to help with testing to improve confidence.

7.1.1 Knowledge Gaps and priorities for future development

Substructure mass

- A notable level of uncertainty has been identified in the expected size and mass of TLP-WT substructures. The existing literature and project scoping efforts reveal conflicting opinions, even among industry partners
- This uncertainty likely arises from the industry's current reliance on academic research, which may not entirely align with practical requirements and real-life applicability in terms of primary and secondary steel, leading to varied expectations within the sector
- Lower bounds of expected substructure mass are consistent among the OEMs involved in this investigation, while upper bounds diverge considerably – indicating uncertainty over how the steel content of TLP-WTs (in least favourable conditions) compare to semi-submersibles
- Further work has been carried out during this study to identify, with the support of TLP designers MPS and Glosten, the steel content outlook for tetrahedral and single column TLP geometries in different site conditions - as discussed in Section 7.2.

Cost

- While reducing hull mass is highlighted as a crucial factor for viability, obtaining precise figures is challenging due to the limited number of installed floating offshore wind turbines, making statistical data unreliable
- Insights from bottom-fixed offshore applications offer a preliminary understanding, providing a general comparison between floating and bottom-fixed designs
- TLPs face challenges in terms of cost, due to lack of maturity in general and particularly in the demonstration phase due to the expense of one-off installations, making them currently less financially viable than alternative platforms. However, their performance and weight advantages make them more favourable for economies of scale compared to other platforms
- Overcoming the TRL barrier is crucial to unlock the full potential of TLPs. EDF and SBM have taken significant strides in breaking down these barriers through projects like Provence Grand Large, contributing to the advancement and increased viability of TLP technology
- This section of work provided cost insights from the literature, which was further developed by building a detailed cost model in Section 6 and applying it to a representative site, enabling a comparison between TLP and semi-submersible platforms. The conclusions are discussed in Section 7.3.

Operations and Maintenance

- The specific impact of TLP motions on the well-being and safety of O&M personnel receives insufficient consideration, raising concerns in the context of floating wind
- Guidance on power cable dynamics, software calibration, performance validation, and testing is limited, leaving critical aspects insufficiently addressed
- Synthetic tendons, tower design, and the interaction of floater or mooring control systems with wind turbine systems all suffer from inadequate standards, underscoring the pressing need for enhanced guidance in these areas
- Much of the work surrounding the vessel selection for in-situ maintenance scenarios in deep water sites remains relatively unexplored. As the water depths may potentially be out with the operating limits of jack-up vessels, a suitable alternative maintenance approach must be developed
 - The stakeholder engagement revealed the proposed approaches for these deep water scenarios had been thoroughly considered. However, further detail on the methodology for the different design types and water depths could be investigated to address any underlying doubts which developers may have about the technology throughout its operating lifespan.

Expected loading

- Expected loading patterns for TLP-WTs of 15MW size have not been openly shared or made available in the public domain, with the few available values procured through academic and in-house projects. This is in reference to pre-tension values and maximum loading conditions.
- The stiffness properties of tendons remain closely guarded by advanced material manufacturers, thus not available for public dissemination
- The interaction between the mooring connections and tensioning apparatus of platforms, regarded as sensitive intellectual property, which obscures a full understanding of the mechanics of individual TLP systems

Anchors

- Uncertainties remain around the sizing of innovative anchor solutions, a pivotal element for cost-effective comparisons with traditional anchors
- The installation methodologies for these novel anchors are similarly undisclosed, preventing any attempt at a comprehensive installation cost analysis

7.2 Numerical models

This Work Package effectively tackled some of the industry's historical hesitancy toward the use of TLP technology in floating wind applications, specifically:

- The tidal range was identified as a relatively minor factor, with minimal impact observed on the TLP substructure dynamics at a 1 m tidal range and only modest effects at a 7 m range. These variations did not affect operational performance, even at low tide. During storm conditions, where the turbine was idling and aerodynamic damping was absent, the motion responses remained very limited. Surge and sway showed an increase as water depth increased, while pitch

and roll remained stable across all depths, indicating potential benefits for dynamic cable optimisation.

- Mooring system loads, measured at the fairlead, revealed considerable variations between different designs, underscoring the significance of design decisions and the adaptability of TLPs to diverse site and environmental conditions. Furthermore, tower excitation was found to be lower compared to the VoltturnUS-S semi-submersible under similar loading conditions, with no resonant interactions between the rigid body degrees of freedom, the tower, and rotor.
- Power output was primarily influenced by the controller strategy but remained broadly consistent with the turbine's power curve. A deeper comparison with semi-submersible designs would provide valuable insights into annual energy production (AEP) performance, aiding in the refinement and optimisation of future design strategies.

Several limitations of the study highlight areas for future research:

- Rigid substructure assumption
- The exploration of substructure and tower design, particularly focusing on fatigue and structural analysis, was not fully addressed and would benefit from a deeper investigation to refine steel content requirements.
- The limitations of anchoring systems, especially in relation to varying seabed compositions, need further exploration to ensure optimal performance in different marine environments.
- The study only considered linear hydrodynamic contributions, and higher-order hydrodynamics could play a crucial role in design optimisation, suggesting the need for a more comprehensive analysis.
- The dynamic cable requirements of TLP systems were not explored in depth, and further research in this area could enhance overall system efficiency.
- Whilst the study touched on performance metrics, a benchmark comparison of annual energy production (AEP) against semi-submersible platforms could provide critical insights into the competitiveness of TLP technology in real-world conditions.

7.3 Techno-economic Analysis

This study assesses the cost drivers of four TLP designs and their installation methods, comparing them to each other and a semi-submersible base case. The key findings highlight the main cost factors, benefits of TLP technology, and areas for further research and development. The main insights from the 150 m water depth base case are:

- The key driver for foundation supply cost is the platform mass, and secondly, fabrication cost, creating benefits for the presented TLP designs.
- The installation cost was found to be greater contributor to total cost for towing full assembled structures, despite less specialised vessels being required. The two reasons are the requirement for all vessels throughout the platforms' installation campaign, compared to carrying out discrete installation campaigns and the impact of WDT. This finding is qualified by the fact that turbine integration for a TLP is comparable to fixed offshore wind due to the platform's stiffness and limited motion. However, a float-to-float integration operation has not yet been executed in practice.

- OPEX is highly linked to distance to O&M port and is highest for offshore MCR when the site is within 100 km of the O&M port. In-situ MCR becomes more cost-effective when the distance exceeds 100 km. The MCR strategy is a key driver for the AEP, which affects LCOE and revenue.

Limitations of existing and current work, has highlighted several areas which require further attention:

- The current work only considers seven platforms. A number of benefits are anticipated at the GW scale, carrying out analysis at a large scale would be insightful.
- Assessing the impact of varying seabed typologies or angles is required to determine if and how the anchor supply and installation costs are impacted for TLPs.
- Consideration of site shape is required to determine if there is any benefit for TLPs since leased areas are typically non-uniform. This could be a benefit for TLPs since, as water depth increases, the footprint required for catenary lines can become very large and might impact the turbine spacing, and further power production.
- Inclusion of the cable in the model analysis would allow differences and potential benefits between a TLP and a semi-submersible to be captured more effectively, reinforced with engineering analysis.
- Determining the impact on the AEP due to the lower motions to find if there is any benefit for power production, or if the control system for the semi-submersible is effective enough to counteract the motions is key.
- The O&M cost modelling could be improved firstly by gaining a better understanding of the major repair rates for a TLP through engineering analysis. Analysis could identify any reduction in O&M cost, availability, and revenue gained. Secondly, performing analysis to determine the impact of lower platform motions on O&M, particularly for gaining crew access to the turbine.
- Installation and O&M logistics require detailed analysis to allow the nuances of each design to be captured and better understood. Finally, more detailed analysis on weather window availability and the impact on installation and O&M costs and logistics to understand the impact on WDT and determine best practices.

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