



Review Article

Fabrication, Transportation, and Installation of Fixed and Floating Offshore Wind Turbines: A State of the Art Review

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Abstract: The rapid growth of offshore wind energy has increased the size and complexity of Offshore Wind Turbines (OWTs), making fabrication, transportation, and installation critical to project cost and schedule. However, previous studies have mostly examined these phases separately. This study presents a PRISMA-based Systematic Literature Review (SLR) of 49 peer-reviewed studies to identify key trends, challenges, and optimization opportunities in OWT construction. The review covers fixed and floating foundations, specialized installation vessels, and turbine pre-assembly strategies. Key quantitative findings reveal that weather windows vary significantly across foundation types: Tension Leg Platforms (TLPs) are limited to only 30–50% operational availability due to their high sensitivity ($H_s < 0.8$ m), while semi-submersibles achieve 70–85% availability with tolerance up to $H_s < 2.0$ m. Additionally, WTIVs capable of handling 15–20 MW turbines are projected to number only 8–10 vessels globally in 2025, creating a severe supply-demand gap that could drive day rates up by 50–100% by 2028. The findings demonstrate that construction efficiency depends on selecting methods suited to site conditions, vessel availability, technological limits, and logistical requirements. This review supports the development of safer, more efficient, and sustainable offshore wind construction practices.

Keywords: offshore wind turbines; construction methodology; fabrication and installation; installation vessels; floating foundations.

1. Introduction

Over the past decade, offshore wind energy has become a key component of the global energy transition. By March 2025, more than 48 GW of offshore wind capacity was under construction, with an additional 350 GW expected to be installed between 2025 and 2034 [1]. This expansion reflects not only the increasing demand for renewable energy but also the growing complexity of Offshore Wind Turbine (OWT) construction.

The effectiveness of fabrication, transportation, and installation methods is critical to project success. Construction

challenges have intensified due to larger turbine capacities, diverse foundation systems, limited installation vessel availability, and complex logistics[2][3]. Inefficiencies in any construction stage can significantly impact project costs and schedules. While previous studies have addressed specific aspects of OWT construction, integrated analyses covering all construction phases remain limited. Furthermore, the emergence of 15–20 MW turbines require construction approaches that are better suited to modern offshore wind developments.

As shown in Table 1, previous reviews mainly focus on installation, while fabrication

and transportation remain less explored. Fixed and floating foundations are also often discussed separately, limiting comparative understanding of construction constraints. To address these gaps, this review examines OWT fabrication, transportation, and installation

within a unified framework for both fixed and floating foundations. It highlights key trends, challenges, and optimization opportunities related to turbine scaling, foundation geometry, water depth, and vessel limitations.

Table 1. Summary of Existing Review Studies on Offshore Wind Turbine Construction Methods

Review Paper	Year	Foundation Type	Construction Phase	Focus
[2]	2021	Fixed & Floating	Installation	Installation strategies and vessels
[4]	2022	Fixed	Installation	Integrated installation technologies
[5]	2022	Fixed	Installation	Construction risk and reliability
[6]	2022	Floating	Transportation & Installation	Numerical modelling and installation effects
[7]	2024	Floating	Transportation & Installation	Floating wind farm installation challenges
[8]	2024	Floating	Installation	Installation, O&M integration
[9]	2024	Monopile	Installation	Decommissioning and installation constraints
[10]	2025	Fixed & Floating	Fabrication, Transportation, Installation	Construction technology evolution

2. Methods

This study employs a Systematic Literature Review (SLR) following PRISMA guidelines to ensure a transparent and reproducible review process. The PRISMA methodology is shown in Figure 1. The review procedure consists of four sequential stages [11]. Identification of relevant publications through systematic searches of major scientific databases including ScienceDirect, Web of Science, Google Scholar, ResearchGate, and technical reports focusing on fabrication, transportation, and installation phases. Application of selection and inclusion criteria, where retrieved records were screened based on titles and abstracts after duplicate removal to ensure relevance. Analysis and classification of selected studies according to their focus on fabrication, transportation, or installation phases, A including the relationships among them. Synthesis of key findings to identify major trends, patterns, and best practices across all construction phases. The literature search utilized keywords such as offshore wind turbine construction method, fabrication strategy, transportation

logistics, installation method, foundation installation, and offshore construction. The keyword co-occurrence is mapped in Figure 2 using VOSViewer.

Construction methods were classified into three phases: fabrication (evaluated based on manufacturing location, assembly strategy, and facility requirements), transportation (based on logistics and cargo constraints), and installation (based on vessel selection, installation sequence, and environmental conditions). Furthermore, reviewed studies were categorized by their research objectives into three groups: construction method optimization (improving efficiency), technical and operational feasibility (addressing constraints, equipment, and risks), and impact-oriented analysis (examining effects on project duration, resource utilization, and overall efficiency).

Literature was collected from Web of Science, ScienceDirect, ResearchGate, published technical reports, and Google Scholar. The initial search identified 664 records, which were reduced to 317 unique articles after duplicate removal. Title and abstract screening resulted in 137 and 134 articles, respectively. Following full-

text quality assessment, 76 articles met the eligibility criteria, and 49 articles were ultimately selected for detailed analysis, synthesis, and discussion as shown in Table 2.

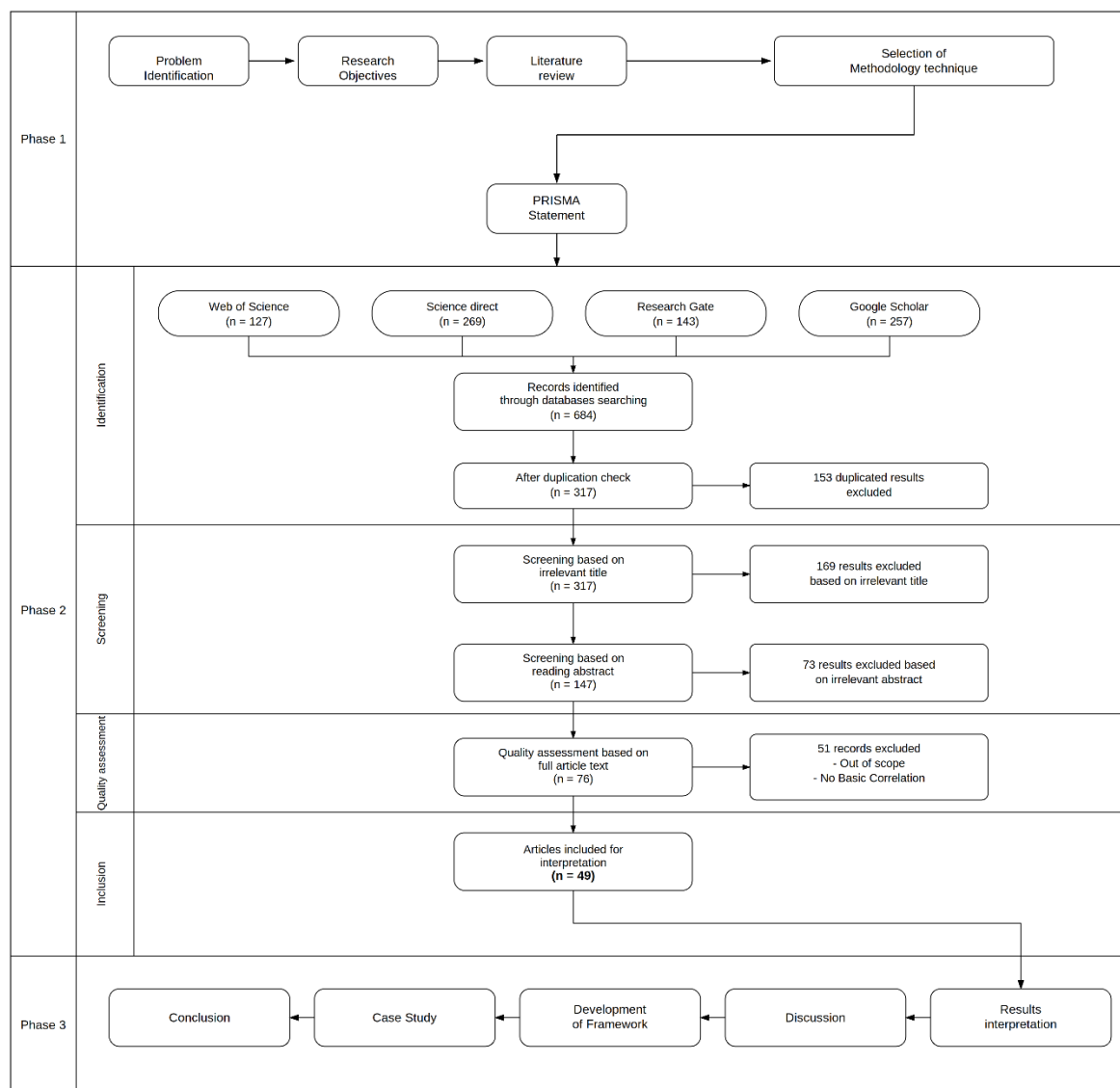


Figure 1. Methodology Flowchart

Table 2 Studies Included Distribution by Publication Year

No	Year Range	Number of Studies	Percentage
1	2010–2014	8	16%
2	2015–2017	5	10%
3	2018–2020	7	14%
4	2021–2022	9	28%
5	2023–2024	10	21%
6	2025	10	21%
Total		49	100%

3. Results

3.1 Offshore Wind Turbine Transportation

3.1.1 Installation

Offshore turbine installation is commonly performed using self-propelled installation vessels or jack-up barges. Due to the need to lift heavy components at significant heights, vessel motions can affect lifting accuracy and safety. Therefore, jack-up systems are used to elevate the vessel hull above the sea surface, providing a stable platform for installation operations [12].

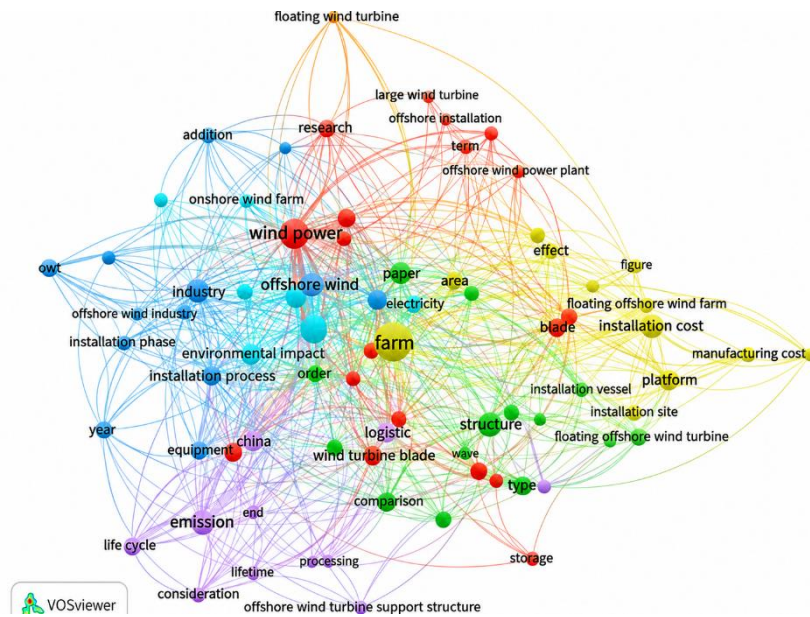


Figure 2. Keyword Co-Occurrence Mapping

Wind turbine installation vessels are self-propelled units specifically engineered to meet offshore industry requirements. These purpose-built vessels are equipped with jack-up legs and

high-capacity cranes to support offshore wind turbine installation operations, as seen in Figure 3.

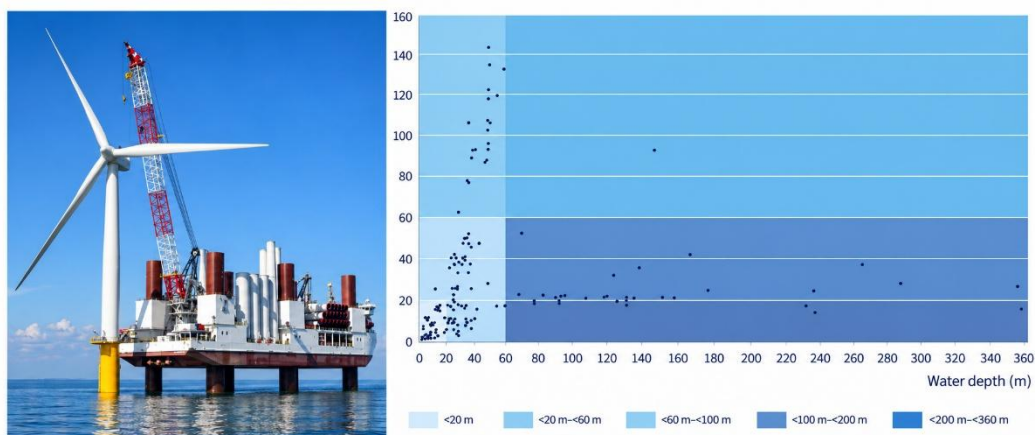


Figure 3. MPI Resolution custom-built jack-up vessel and offshore wind industry development [12].

WTIVs generally provide cargo capacities of 1,300–8,000 t, deck areas of 900–3,750 m², operational water depths of 24–45 m, and jack-up leg lengths of 32–85 m. Their service speed ranges from 7.8–12.5 knots, with jacking speeds of approximately 0.35–0.8 m/min, while accommodation capacity ranges from 16–112

berths. Modern WTIVs have been developed to meet the demands of larger offshore wind turbines and deeper sites, offering deck areas of 2,000–4,300 m², cargo capacities of 2,850–8,400 t, and operational water depths of 45–75 m. Efficient purpose-built WTIVs typically require a payload capacity of about 4,000 t, deck

exceeding 3,000 m², high-cycle jacking systems, dynamic positioning capability, and cranes with safe working loads of around 700 t.

WTIV designs evolved rapidly between 2002 and 2013, as seen in Figure 4. The latest generation of vessels, such as the Pacific Orca and Pacific Osprey (2012–2013), have deck areas of up to 4,300 m², a carrying capacity of 8,400 t, a speed of 13.5 kn, and can operate at depths of 75 m with jacking speeds of 1.2–2.4 m/min. In contrast, earlier vessels, such as the Sea Energy (2002), had a deck area of only 1,020 m² and a capacity of 2,386 t. This development represents a significant increase in the ability to install larger, more efficient turbines in deeper waters [12].

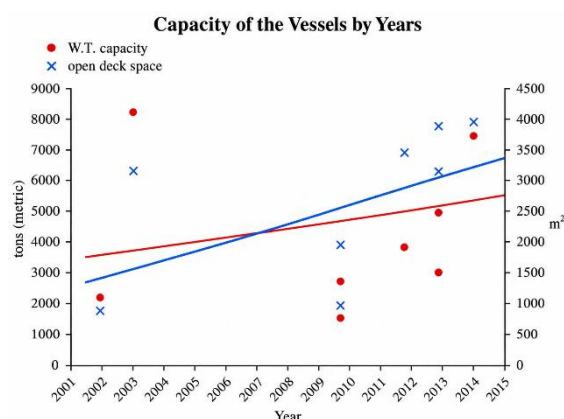


Figure 4. WTIV cargo capacity and operational water depth by year [12]

Both Wind Turbine Installation Vessels (WTIVs) and jack-up barges (JUBs) are equipped with onboard cranes for offshore turbine installation. Heavy components such as nacelles, which may weigh up to 400 t, together with hubs, must be lifted and assembled at heights

typically ranging from 70 to 100 m above sea level. For example, the hub height of the RePower 5 MW turbine at the Thornton Bank offshore wind farm is approximately 94 m [12].

The safe working load (SWL) of a crane depends on its operating radius and generally decreases as the radius increases. Cranes with similar designs exhibit comparable SWL–radius relationships, including telescopic boom cranes with different boom lengths.

A jack-up barge (JUB) is a non-self-propelled elevating platform widely used for offshore wind turbine installation. Unlike WTIVs, JUBs must be towed to the construction site, typically at speeds of around 5 knots, and are not equipped with dynamic positioning systems (DPS). Their cargo capacities generally range from 900 to 2,000 t, with available deck areas of 400–2,500 m², limiting the number of turbines that can be transported per voyage.

JUBs typically operate in water depths of 18–50 m, supported by leg lengths of 40–82 m. Their jacking speeds range from 0.15 to 0.8 m/min, while onboard accommodation capacities vary between 10 and 160 berths. Technical characteristics of JUB operating in the world can be seen in Table 3.

3.1.2 Turbine Pre-Assembly Strategies and Deck Configurations

Offshore wind farms are typically located in high-wind areas, where installation activities are constrained by limited weather windows. Consequently, pre-assembly strategies are widely adopted to reduce offshore installation time and improve operational efficiency.

Table 3. Technical Characteristics of Jack-Up [12].

Name	Year	Space (m ²)	Capacity (t)	Leg Length (m)	Water Depth(m)	Jacking speed (m/min)
LISA A	1977	1000	1600	52.35	27	0.2
Buzzard	1982	600	1300	65	40	0.2
MEB JB 2	1998	510	1200	40	18	0.15
Vagant	2002	400	1000	66	30	N/A
Pauline	2002	450	900	57.5	30	N/A
Sea Jack	2003	2500	2000	50.4	30	0.8 - 1
ODIN	2004	660	1200	60	45	N/A
SeaFox 7	2008	700	1120	73.15	40	0.25
Sea Worker	2008	750	1100	78.85	40	0.3

Name	Year	Space (m ²)	Capacity (t)	Leg Length (m)	Water Depth (m)	Jacking speed (m/min)
JB 114	2009	700	1250	78.85	40	0.65
JB 115	2009	700	1250	73.15	40	0.65
Goliath	2009	1080	1600	73.15	40	0.5
JB 116	2010	1700	1750	80	45	0.5
Thor	2010	1850	3300	82	50	N/A
JB 117	2011	2000	2250	80	45	0.25
Excalibur	N/A	768	1267	75	40	N/A

A wind turbine consists of six main components, or seven when the tower is divided into two sections, enabling various pre-assembly configurations. Despite these variations, turbine installation is generally performed using five principal methods, as illustrated in Figure 5 [12].

1. Separate Pieces (SP6)
2. Five Separate Pieces (SP5)
3. Pre-Assembled Rotor (R2T)
4. “Bunny Ears” with a One-Section Tower (BE1T)
5. “Bunny Ears” with a Two-Section Tower Six (BE2T)

The deck space required per turbine for a given pre-assembly configuration can be estimated by dividing the vessel's available deck area by the number of turbines transported per voyage. For 2–3.6 MW class turbines, the estimated deck-area requirement on WTIVs is approximately 510 m² for BE1T, 255–510 m² for R2T, 350–355 m² for SP5, and 450–533 m² for SP6. Using a vessel with 4,300 m² deck area, the SP5 configuration requires approximately 358 m² per turbine, which closely aligns with the 355 m² and 350 m² reported for the Thanet and Belwind 1 projects, confirming that deck-space

requirements for SP5 remain consistent across the referenced projects.

3.2 Fabrication and Installation

3.2.1 Fixed Foundation

A comparative assessment of fabrication processes shows that each foundation type is characterized by specific manufacturing priorities and constraints arising from its material characteristics and structural form. Jacket structures require a high level of geometric accuracy and meticulous welding of tubular joints to achieve adequate fatigue performance, making dimensional control during assembly particularly critical. Monopiles, which are produced from very thick steel plates, depend heavily on automated welding systems to enable efficient fabrication, yet they still encounter challenges related to plate thickness and long welding durations, especially in large-scale production. In contrast, Gravity-Based Structures (GBS) emphasize modular concrete casting and buoyancy control, as their substantial concrete volumes demand extended curing times and precise fabrication management.

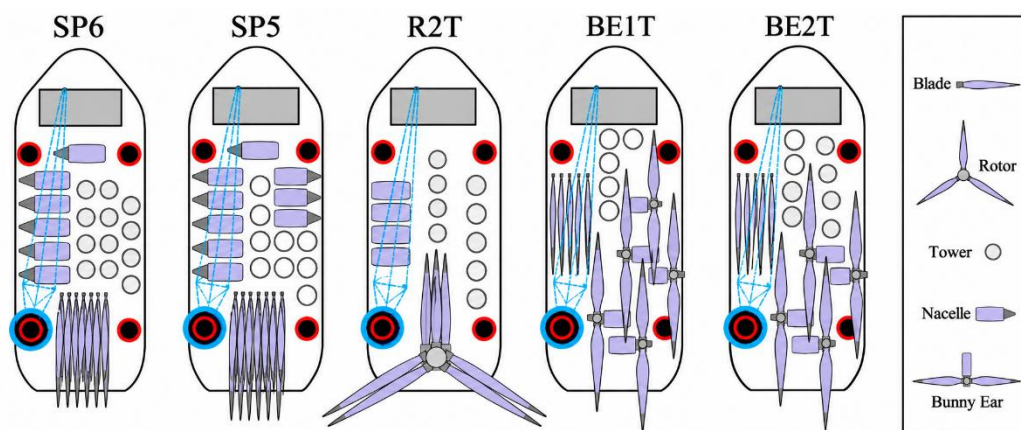


Figure 5. Different Deck Load Configurations on WTIVs [12].

Overall, as can be seen in Table 4, the comparison shows that jacket fabrication is primarily driven by geometric precision, monopile fabrication is limited by the efficiency of thick-plate welding, and GBS fabrication is governed by concrete curing requirements and

buoyancy management. These distinctions highlight the need for tailored fabrication strategies to ensure reliable production and optimal structural performance for each of the foundation types.

Table 4. Fabrication Overview of Offshore Wind Turbine Foundations

No	Foundation	Primary Material	Fabrication Focus	Welding / Casting Method	Assembly Process	Key Production Issues	Final Fabrication Stage
1	Jacket	Steel tubular members with tight dimensional tolerances [13]	Stiffness, fatigue resistance, geometric precision [14]	Welding legs, braces, and TP joints; fatigue grade D & F3 (DNVGL-RP-C203) [15]	Assembly on jigs; geometric control for pile & TP [13]	Stress concentration occurs if the geometry is not precise [14]	Load-out to barge via skidding or lifting [13]
2	Monopile	Extra-thick steel plates (50–80 mm) [16]	Welding of thick plates for large diameters [16]	SESLA (automated ESW for vertical seams) + narrow groove SAW (circumferential seams) [16]	Rolling & welding plates into a single large pipe [17]	Challenges in welding plates >50 mm; long joining time for mass production [17]	Final welding & inspection before mass-production rollout [17]
3	Gravity-Based Structure (GBS)	Reinforced concrete = 720 t (35 m) [18]	Formation of base slab, hollow cells, skirts, and central shaft [18]	Segmental concrete casting using specialized formwork (cellular structure) [17]	Modular fabrication; multi-stage assembly [17]	Large concrete volume → long curing time; buoyancy control [18]	Ready for towing using the float-to-fixed (F2F) method [18]

3.2.2 Floating Foundation

Conventional steel spar buoy foundations present significant fabrication and logistical challenges due to their large dimensions (approximately 15 m in diameter, 90 m in length, and 8,000 t in weight), requiring specialized fabrication facilities, heavy-lift vessels, and complex installation procedures. These requirements increase costs and limit scalability [19], [20]. In contrast, concrete spar buoy concepts can be fabricated in dry docks using modular formwork systems, improving constructability and reducing dependence on specialized infrastructure. The adoption of geopolymer concrete and basalt fiber reinforced polymer (BFRP) rebars further enhances durability, corrosion resistance, and environmental performance while reducing the carbon footprint of construction materials. From a production perspective, a concrete polygonal spar buoy can be fabricated in approximately 102 days, or 68 days when two units are produced simultaneously, demonstrating improved efficiency and

scalability compared to conventional steel concepts [20].

Steel semi-submersible foundations are designed to be fabricated using conventional shipyard construction practices. Their modular configuration, consisting of a central column, offset columns, and connecting pontoons, allows components to be manufactured separately and assembled during final integration, improving fabrication efficiency and quality control [21]. The total structural steel mass, typically ranging from 3,000 to 5,000 t for 5–10 MW turbines, is a key factor affecting fabrication costs, welding requirements, material consumption, and crane capacity demands [22].

As most of the structural weight is concentrated in the main and offset columns, fabrication can be carried out in stages before final assembly and dock float-out (Figure 8), enabling construction in medium-capacity shipyards and reducing dependence on specialized facilities. For a 6 MW offshore wind turbine, Jędrzej Żywicki proposed a steel tension

leg platform (TLP) consisting of an underwater truss-type hull and a central column supporting the turbine tower [23].

The structure has an underwater volume of approximately $5,500 \text{ m}^3$, a draft of 20 m, and an initial steel weight of about 1,430 t. As illustrated in Figure 6, the platform adopts a modular prefabrication approach in which

individual components are fabricated and assembled prior to installation. This strategy improves fabrication quality, simplifies offshore construction, and enables staged assembly in medium-capacity shipyards, reducing dependence on specialized large-scale fabrication facilities.

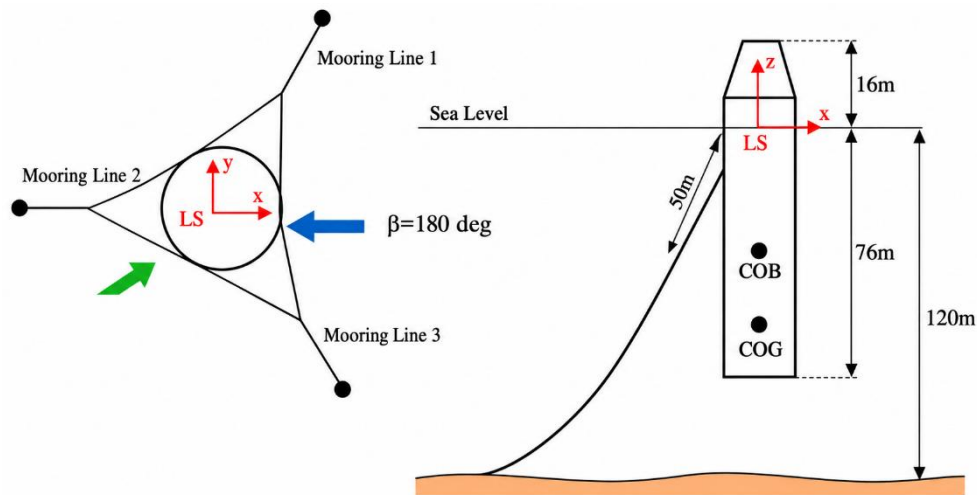


Figure 6. Spar Buoy Mooring System Layout [20].

Conventional Spar installation methods generally rely on offshore heavy-lift operations, making them highly sensitive to weather conditions and vessel availability. To address these limitations, the Nordic Wind concept proposed in [20] adopts a float-over installation approach that transfers a larger proportion of assembly activities to onshore facilities. Compared with conventional installation methods, this strategy reduces offshore lifting requirements, shortens installation duration, and lowers exposure to weather-related risks. The concept further enhances operational efficiency using a dedicated installation vessel capable of transporting multiple fully assembled turbines in a single voyage. Motion-compensation systems are employed to minimize relative vessel–foundation movements during turbine transfer, improving installation reliability under offshore operating conditions. However, the approach requires specialized vessel infrastructure and advanced motion-control technology, which may increase initial capital investment despite the potential

reduction in offshore construction costs. Weather and vessel-motion monitoring systems, such as Octopus, are therefore essential to support safe and efficient execution of installation operations [24].

The mooring system comprises three individual lines attached to the substructure through a bridle. The pretensioning scheme and bridle design provide sufficient yaw stiffness, ensuring that the mooring lines remain taut under normal operating conditions. Consequently, the stability and operational performance of the Spar structure are preserved.

Semi-submersible foundations are among the most widely adopted floating wind turbine concepts due to their favorable stability and towing characteristics. Unlike Spar foundations, which often require complex installation and upending operations, semi-submersible units can be fully assembled in dry docks, including the hull, tower, and turbine, before being towed directly to the installation site and connected to the mooring system, as seen in Figure 7 [25][26].

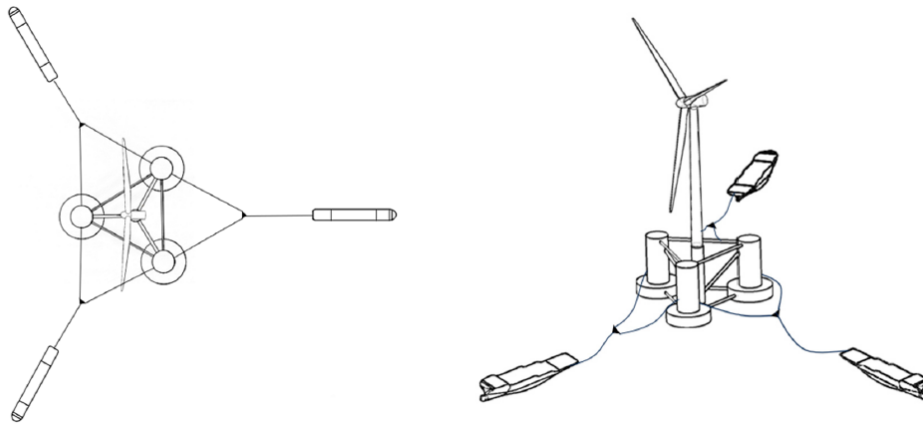


Figure 7. Transport and mooring connection of WindFloat semi-submersible FWT [26].

This approach minimizes offshore assembly activities, reduces dependence on heavy-lift operations, and improves installation efficiency. These constructability advantages have contributed to the widespread adoption and continued technological development of semi-submersible foundations, as reflected by the projects summarized in Table 5.

Compared with other floating foundation concepts, Tension Leg Platforms (TLPs) present greater installation complexity due to their reliance on tendon systems, which require precise positioning, connection, and pretensioning under offshore environmental conditions [27][28]. Although the platform can be fully assembled onshore, installation remains highly sensitive to stability control during towing, ballasting, and tendon connection operations. Consequently, monitoring and decision-support systems play a critical role in ensuring safe installation and maintaining the required lock-off draft before tendon pretensioning [2]. To improve constructability

and reduce operational risks, several innovative installation approaches have been proposed, including the GICON concept, which utilizes a floating slab to facilitate dry towing and controlled deployment of the platform (Figure 8) [29].

Foundation selection for offshore wind turbines is largely governed by water depth, constructability, and installation complexity, as resumed in Table 6. Fixed foundations are generally preferred in shallow to intermediate waters due to their established installation methods, whereas floating foundations are more suitable for deepwater applications. Among floating concepts, semi-submersibles offer favorable constructability and towing performance, while TLPs provide higher structural stiffness at the cost of greater installation complexity. These trade-offs emphasize the need to balance structural performance, logistical requirements, and operational risks when selecting a foundation system.

Table 5. Examples of offshore wind turbine projects utilizing semi-submersible foundations.

No	Project Name	Country	Water Depth	Capacity	Commission	Decommission
1	WindFloat [30]	Portugal	45 m	1 × 2 MW	2011	2016
2	WindFloat Atlantic [30]	Portugal	85–100 m	3 × 8.4 MW	2019	N/A
3	Kincardine [31]	UK	60–80 m	5 × 9.5 MW	2021	N/A
4	Les Éoliennes Flottantes du Golfe du Lion [31]	France	70–100 m	3 × 10 MW	2024	N/A
5	Erebus [31]	UK	70 m	N/A	2027	N/A
6	Korea Floating Wind [31]	S Korea	250 m	N/A	2028	N/A
7	EOLINK demonstrator [32]	France	N/A	1 × 5 MW	2024	N/A
8	BLOW project [33]	Bulgaria	N/A	1 × 5 MW	2025	N/A
9	Fukushima Mirai [34]	Japan	120 m	1 × 2 MW	2013	2021
10	Fukushima Shimpuu [34]	Japan	32 m	1 × 7 MW	2015	2020
11	Yangxi Shapa III Demo [35]	China	30 m	1 × 5.5 MW	2021	N/A
12	FuYao prototype [36]	China	50–70 m	1 × 6.2 MW	2022	N/A

No	Project Name	Country	Water Depth	Capacity	Commission	Decommission
13	Haiyou Guanlan [37]	China	100+ m	1 × 7.25 MW	2023	N/A
14	New England Aqua Ventus [38]	US	60–110 m	2 × 6 MW	2024	N/A
15	Pentland FOWF [39]	UK	60–102 m	7 × 15 MW	2026	N/A
16	TwinHub demo [40]	UK	50–60 m	2 × 16 MW	2026	N/A

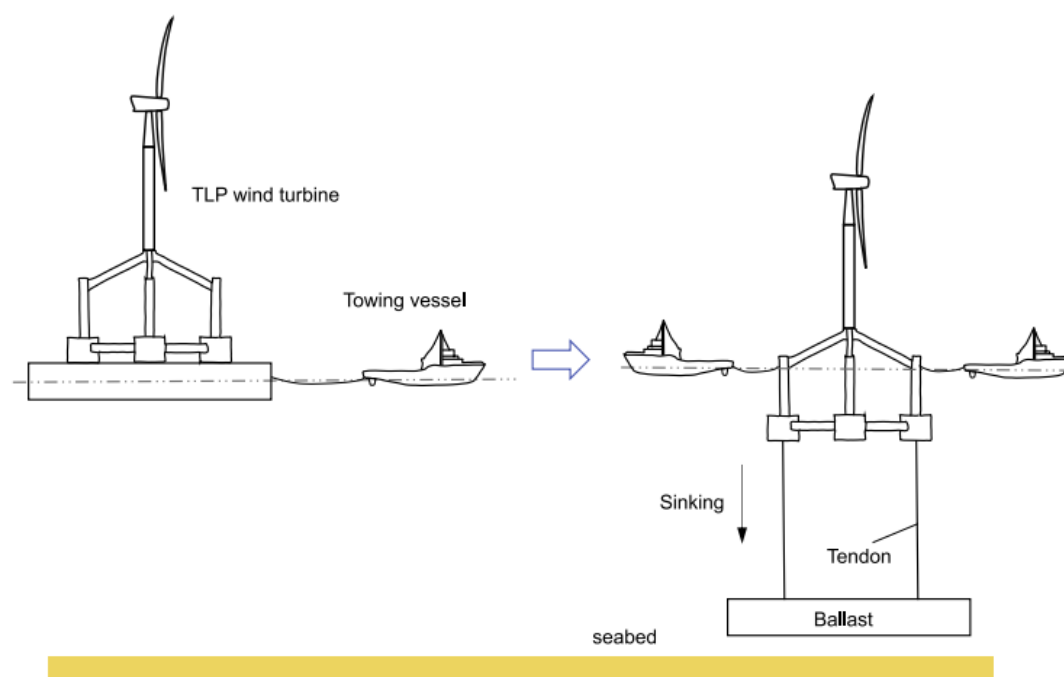


Figure 8. GICON TLP installation concept (adapted from [2]).

Table 6. Comparison of Offshore Wind Turbine Foundation Types and Their Installation Features

Foundation Type	Water Depth	Transportation	Main Installation Phases	Key Equipment	Advantages	Disadvantages
Monopile	10 - 30 m	Dynamic ally positioned crane vessels [41]	Upending → Pile driving → Grouting [42]	Hydraulic hammer, upending frame, gripper devices [16]	Simple installation; efficient with DP/crane vessels. [43]	Weather-sensitive; jack-up time-consuming; uneconomical >30 m [16].
Jacket	30-50 m	Barge/crane vessel [13]	1) Stabbing pile installation frame → 2) Pile driving → 3) Upending → 4) Mating → Grouting [2]	Installation frame, locating cones, subsea guides [1]	Stable structure; suitable for deeper waters [13].	Complex multi-phase work requires many specialized tools [13].
Gravity Based (GBS – F2F)	35 - 50 m	Towed with a tugboat [18]	Float-out → Towing → Submerging → Permanent ballasting [44]	Ballasting system [44]	No heavy-lift vessel; low logistics cost; low weather risk [18]	Needs a large fabrication area; heavy permanent ballast [18].
Spar Buoy (Nordic Wind)	Deep waters (>100 m)	Specialized installation vessel; towing spar buoy [20]	Full preassembly onshore → Loading to vessel → Transport → Approach to site → Gripper connection → Turbine transfer → Mating → Skidding [24]	Motion compensation system, gripper, and lifting system [24]	Minimal offshore lifting; safer deep-water installation [19].	Needs a specialized vessel; docking is still sensitive [24].

Foundation Type	Water Depth	Transportation	Main Installation Phases	Key Equipment	Advantages	Disadvantages
Semi-Submersible	Deep waters (100 – 250 m)	Wet Towed [25]	Preassembly in dry dock → Towing → Mooring hook-up [22]	Mooring chain/catenary system, dry dock facilities [25]	Highly towable; extensive onshore preassembly reduces offshore work [25].	Complex mooring; large fabrication area; more complex in deep water [21].
Tension Leg Platform (TLP)	80 –150 m	Design-dependent dry- or wet-tow transport [29]	1) Tendon installation at site → 2) Onshore upright assembly of TLP → 3) Towing with temporary buoyancy support → 4) Controlled ballasting to lock-off draft → 5) Tendon connection → 6) Pretensioning [45]	Tendons & mechanical connectors, crane vessel, buoyancy modules, ballasting system, tendon porch, monitoring/decision-support system [28]	High stiffness; good for deeper waters; quality-controlled onshore assembly [28].	Sensitive to environment; complex ballasting & tendon handling [45].

3.2.3 Wind Turbine Component Structures

The fabrication of offshore wind turbine towers is a mature, standardized process using modular construction, precision welding, and strict quality control to ensure accuracy, structural integrity, and height flexibility with phased inspections. However, many welded joints increase complexity, inspection needs, and production time, while extensive corrosion protection reflects long-term durability challenges in marine environments. Industrially proven, the method is resource-intensive and relies on specialized facilities, limiting scalability and cost efficiency for large-scale deployment.

The nacelle is a critical offshore wind turbine component that must house complex mechanical systems in a confined space while ensuring durability [46]. Made from fiberglass composites for light weight, formability, and corrosion resistance, it still faces significant bending and torsional stresses during emergency braking, which can cause structural deflection and drivetrain misalignment, leading to bearing wear and higher maintenance demands. To improve installation efficiency, the nacelle is often pre-assembled with the rotor hub and lifted as a single unit, reducing offshore work but requiring high-capacity cranes and precise lifting control during tower mating [47].

Nacelle installation requires precise lifting and alignment to ensure successful tower mating. Lifting stability is maintained through crane-assisted control systems, and accurate

positioning is critical to minimize risks and delays. Installation is influenced by weather, vessel capability, lifting capacity, and sequencing. Studies also show that nacelle motions are smaller than tower vibrations, and tuned mass dampers can effectively improve structural stability during mating [2].

Wind turbine blades comprise several structural sections, including the root, chord, midspan, and tip, each serving distinct load-bearing and aerodynamic functions [46]. The root is designed to resist operational loads, while the remaining sections contribute to lift generation and load transfer along the blade. These functional requirements influence blade geometry, material selection, and manufacturing processes.

E-glass fibers are the most common blade reinforcement, improving strength and stiffness with higher content, though exceeding ~65% volume can cause resin starvation and defects that reduce fatigue performance; carbon and basalt fibers are also explored as alternatives. Single-blade installation using jack-up vessels and cranes is highly sensitive to motion between blade root and hub during alignment, with environmental disturbances causing delays that require suspension or lowering of blades, so efficiency relies on weather windows and motion control, making operational planning critical to minimize risk and downtime. [46] Blade installation using a yoke system involves lifting the blade to hub height, aligning the blade

root, and completing the bolted connection using components such as guide pins and T-bolts [48].

The following table provides a comprehensive synthesis of offshore wind turbine construction methods by grouping each stage based on components, advantages, limitations, and most suitable application conditions. This synthesis is intended as a decision-making tool in determining construction strategies that are in line with site characteristics and project constraints.

The conclusions of this comparative analysis confirm that no single construction method is superior for all conditions, as seen in Table 7. Determining the appropriate approach must be based on a thorough evaluation of water depth, soil characteristics, infrastructure availability, meteorological and oceanographic constraints, and budgetary constraints. The table presented serves as an analytical framework for assessing the technical and economic trade-offs between alternatives and identifying the specific conditions under which each method can provide optimal performance.

As a crucial decision-making tool, the following table illustrates the direct relationship between environmental parameters and construction performance. A quantitative understanding of these constraints enables project managers to: (1) determine the type of foundation best suited to the site characteristics, (2) realistically estimate waiting times, and (3) identify operational stages that require specific risk mitigation strategies.

The quantitative data demonstrates fundamental differences in environmental resilience between construction methods, which have a direct impact on project planning. Wave height tolerance limits can differ by up to approximately 2.5 times between the most sensitive and the most tolerant methods (TLP versus semi-submersible), resulting in significant variations in weather window availability (approximately 30–85%) and the level of delay risk, as seen in Table 8. These findings emphasize that the choice of construction method should be preceded by a site-specific, long-term probabilistic metocean analysis, rather than solely based on technical or economic considerations.

3.3 Metocean Constraints and Delay Risks

Table 7. Methods Comparison Used in Fabrication, Transportation and Installation

Stage	Method/ Component	Advantages	Limitations	Suitable Conditions	Reference
Fixed Foundation Fabrication	Jacket	Lightweight structure with high rigidity. Suitable for depths >30 m.	Fabrication requires high geometric precision. Complex welding process (tubular joints).	Waters with a depth of >30 m, soil conditions that support jacket installation.	[13]
	Monopile	Simple design, quick installation. Mature fabrication technology.	Requires thick steel plate (50–80 mm). Welding is time-consuming for mass production.	Shallow waters up to 30 m, suitable subgrade for piling.	[42]
	Gravity-Based Structure (GBS)	No hydraulic hammer or heavy lifting required. Low logistics costs.	Requires a large fabrication area. Long concrete curing time.	Waters up to 35 m, soil with high bearing capacity (dense sand/bedrock).	[44]
	Spar Buoy	The concrete concept allows for modular fabrication. Corrosion resistant (geopolymer). Modular fabrication in standard shipyards.	Conventional steel fabrication requires specialized facilities. Transportation and upending complex.	Deep water, location with access to dry dock and concrete fabrication facilities.	[20]
Floating Foundation Fabrication	Semi-Submersible	Easy to tow.	Requires a complex mooring system. Large steel mass (3,000–5,000 t).	Deep water (45–250 m), location with access to medium capacity shipyards.	[21]

Stage	Method/ Component	Advantages	Limitations	Suitable Conditions	Reference
Transportation	Tension Leg Platform (TLP)	High vertical stiffness. Modular fabrication, quality controlled.	The installation is very sensitive to environmental conditions. Complex tendon management.	Waters 30–150 m, relatively calm sea conditions for tendon installation.	[23]
	WTIV (Wind Turbine Installation Vessel)	Large carrying capacity (1,300–8,000 t). Spacious deck, equipped with crane and jack-up system. Lower costs than WTIV.	Limited availability, high rental costs. Low speed (7.8–12.5 knots). Not self-propelled (needs to be towed).	Large scale projects, locations with operating depths up to 75 m.	[12]
	Jack-Up Barge (JUB)	Can be used for installation. Doesn't require a special ship.	Smaller carrying capacity (900–2,000 t). Low speed (± 5 knots).	Projects with limited budgets, locations with depths up to 50 m.	[12]
	Towing (GBS & Floating)	Suitable for large structures (GBS/Floating).	It really depends on the weather conditions.	Floating structures (GBS, semi-submersible, spar).	[12]
Installation	Monopile	The process is relatively simple: upending $\rightarrow$ piling $\rightarrow$ grouting. Stable at depths >30 m.	Sensitive to weather. Not economical at depths >30 m.	Shallow waters (<30 m), soft to medium soils.	[49]
	Jacket	Can be installed with templates and guide cones.	Multi-stage process requires special tools (frame, cone).	Waters >30 m, soil with sufficient bearing capacity for piles.	[10]
	GBS (Floated-to-Fixed)	Does not require a heavy lift vessel. Low weather risk. Minimal offshore lifting.	Requires permanent ballasting. Large fabrication area.	Waters up to 35 m, soil with high bearing capacity.	[44]
	Spar Buoy (Nordic Wind)	Safe for deep sea installation.	Requires a special vessel with a motion compensation system.	Deep water, location with access to onshore pre-assembly facilities.	[24]
	Semi-Submersible	Pre-assembly in dry dock, reducing offshore work. High stiffness, suitable for deep sea.	Complex mooring system. Large fabrication area. The ballasting process and tendon connection are very sensitive to the environment.	Deep water (45–250 m), location with dry dock and towing access.	[25]
	TLP	Onshore assembly quality is maintained.		Waters 30–150 m, calm sea conditions during installation.	[28]
Turbine Configuration	SP5 (Five Separate Pieces)	Reduce offshore installation time.	Requires a fairly large ship deck (± 350 m ² /turbine).	Projects with WTIV decks are sufficiently wide, the weather is relatively stable.	[12]
	R2T (Pre-Assembled Rotor)	Reduce the number of offshore lifts.	Requires careful logistical planning.	Weather conditions with limited windows, the ship's lifting capacity is adequate.	[12]
	BE1T/BE2T (Bunny Ears)	Deck space efficiency (510 m ² /turbine). Quick installation.	Special configuration requires additional equipment.	Projects with limited ship carrying capacity but require time efficiency.	[12]

Table 8. Comparative Weather Windows and Installation Risks for Offshore Foundations

Foundation Type	Max Allowable Hs (m)	Max Wind Speed (m/s)	Current Limit (kn)	Weather Window	Typical Delay Risk Factor	Key Sensitive Operations	Reference
Monopile	1.0 - 1.2	10 - 12	1.5	40-60%	High (1.3-1.5)	Upending, Hammering	[49]

Foundation Type	Max Allowable Hs (m)	Max Wind Speed (m/s)	Current Limit (kn)	Weather Window	Typical Delay Risk Factor	Key Sensitive Operations Template	Reference
Jacket	1.5 - 2.0	12 - 15	2.0	50-70%	Medium-High (1.2-1.4)	positioning, Grouting	[10]
GBS	1.2 - 1.5	12 - 14	1.8	60-80%	Medium (1.1-1.3)	Ballasting, Positioning	[44]
Spar	1.0 - 1.5 (upending)	10 - 14	1.5	50-70%	Medium-High (1.2-1.4)	Upending, Turbine transfer	[24]
Semi-submersible	1.5 - 2.0 (mooring)	14 - 16	2.0	70-85%	Medium (1.1-1.3)	Mooring connection	[25]
TLP	0.8 - 1.0 (tendon)	8 - 10	1.2	30-50%	Very High (1.5-1.8)	Tendon tensioning	[28]

4. Discussion

4.1 Comparative Synthesis of Fixed Versus Floating Foundation

The comparison between fixed and floating foundations highlights key differences in five areas: water depth, material needs, fabrication complexity, installation sensitivity, and supply chain dependence, as summarized in Table 9. This finding underscores that foundation selection is not solely determined by water depth, but also by the level of marine environmental difficulty as quantified through the Ocean Severity Index, as well as the availability of fleet capabilities and delivery methods. This matrix represents a visual framework that can serve as a supporting tool in the technical-logistical planning of offshore projects, particularly in balancing risk considerations and operational feasibility in a dynamic maritime environment.

Three cross-cutting observations emerge from Table 9 that no single row reveals. First, an inverse relationship exists between technology readiness and depth capability: TRL declines monotonically from 9 (monopile) to 5 (TLP) as accessible depth increases, meaning the industry's deepest-water options are precisely its least proven. Second, steel mass does not scale with depth capability the TLP (1,500–2,500 t) requires less than half the steel of a semi-submersible (3,000–5,000 t) for overlapping depth ranges, suggesting that if TLP installation risks can be managed, it offers the more material-efficient deepwater pathway. Third, weather sensitivity is decoupled from structural type: the jacket and semi-submersible share the highest Hs tolerance (2.0 m) despite belonging to opposite foundation families, indicating that installation-phase robustness is a function of installation method, not of whether the foundation is fixed or floating.

Table 9. A Multi-Dimensional Framework for Comparing Offshore Wind Turbine Foundations.

No	Parameter	Monopile	Jacket	GBS	Semi-Submersible	Spar	TLP
1	Water depth (m)	10–30	30–50	25–35	45–250	100–300	80–150
2	Steel mass (t)	600–1,000	800–1,500	N/A	3,000–5,000	5,000–8,000	1,500–2,500
3	Plate thickness (mm)	50–80	30–50	N/A	20–40	30–60	25–45
4	Fabrication complexity (1–5)	2	4	3	3	4	4
5	Weather sensitivity Hs (m)	1.2	2	1.5	2	1.5	0.8
6	Installation time (days/turbine)	1–2	3–5	2–3	2–4	3–5	4–6
7	Vessel dependency	Low	Medium	Low	Medium	High	High
8	Technology readiness level (1–9)	9	8	7	7	6	5

Foundation selection for offshore wind turbines involves trade-offs among material cost, water depth capability, weather sensitivity, fabrication complexity, and installation time. Monopiles offer low steel usage and fast installation but are limited to shallow waters, while semi-submersibles support deeper sites with higher material demand and mooring complexity. TLPs provide strong vertical stability

but are highly sensitive to weather windows, whereas jackets require more complex fabrication with moderate installation duration. Overall, foundation selection depends on fabrication capacity, vessel availability, water depth, and site-specific metocean constraints. Figure 9 presents a decision matrix linking foundation and transport method selection to water depth and ocean severity.

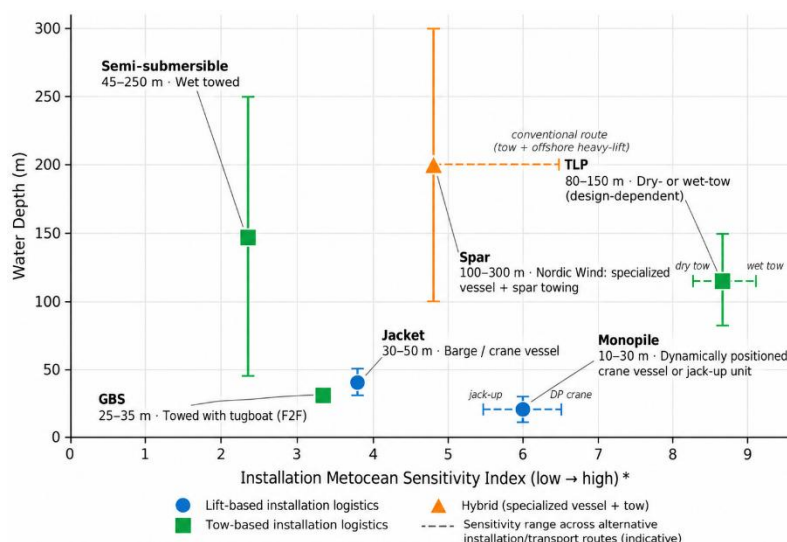


Figure 9. Decision-Support Matrix for Offshore Foundation and Transport Method Selection Based on Water Depth and Ocean Severity Index.

Figure 9 reveals that depth capability and installation robustness are independent attributes rather than a single trade-off. The deepwater options span nearly the full sensitivity range: the semi-submersible combines the greatest depth capability (~175 m and beyond) with the lowest installation sensitivity, reflecting its fully towed, dry-dock-assembled delivery, while the TLP occupies the opposite corner comparable depth capability but the highest sensitivity in the matrix, driven by its tendon connection and pretensioning operations. This diagonal contrast explains the deployment pattern documented in Table 5, in which semi-submersibles account for essentially all commissioned floating capacity while TLP projects remain at concept or demonstrator stage. Among fixed foundations, a parallel contrast appears at smaller scale: the jacket and GBS cluster at moderate sensitivity owing to their barge- and tug-based logistics, whereas the monopile despite being the most mature

technology carries higher installation sensitivity because its dynamically positioned lifting operations are directly exposed to sea-state limits. For a project planner, the practical reading is that the vertical axis screens options by site depth, after which the horizontal axis indicates how much schedule contingency each surviving option demands: pathways toward the left of the figure suit sites or seasons with poor weather windows, while pathways toward the right require either benign conditions or generous weather contingency in the installation schedule.

4.2 Integrated Synthesis

While Sections 3.2–3.3 evaluated each phase in isolation, construction decisions are made jointly: a foundation choice constrains vessel options, which in turn constrain pre-assembly configurations. Table 10 therefore consolidates the phase-level findings into a single trade-off structure, with the final column

expressing each option's cost consequence relative to the monopile baseline.

Table 10. *Comprehensive comparative synthesis of offshore wind turbine construction methods.*

No	Phase	Method	Advantage	Limitation	Optimal Condition	LCOE Impact
1	Fabrication	Monopile	Simple, low cost	Depth limited	≤30 m	Baseline
		Jacket	Stiff, stable	High precision, complex welding	30–50 m	+10–20%
		GBS	No heavy vessel	Large area, long curing	≤35 m, dense soil	+5–15%
		Semi-sub	Modular fabrication	Large steel mass	>50 m	+30–50%
2	Transportation	WTIV	High capacity	Scarce, expensive	Large projects	Premium +20–40%
		JUB	Economical	Slow, small capacity	Budget-limited	Baseline
		Towing	Flexible	Weather sensitive	GBS/floating	+0–10%
3	Installation	Monopile	Fast (1–2 days)	Weather sensitive	≤30 m	Baseline
		Jacket	Stable	Multi-stage	30–50 m	+15–25%
		Semi-sub	Weather resilient	Complex mooring	>50 m	+30–50%
		TLP	High stiffness	Very sensitive	Calm sea	+40–60%

Offshore wind construction depends on weather resilience, installation complexity, and vessel availability. Weather tolerance varies by foundation: TLPs need calm conditions ($H_s < 0.8$ m; 30–50% window), while semi-submersibles operate in higher seas ($H_s < 2.0$ m; 70–85% window). Complexity rises with water depth, shifting risks from monopile lifting to floating integration, particularly TLP tendon connection and pretensioning. Pre-assembly cuts offshore lift by ~40% and weather-dependent time by 30–50% versus piece-by-piece. Vessel availability remains the primary bottleneck to offshore wind expansion. The LCOE impact column should be read as indicative ranges synthesized from the reviewed cost studies rather than as project-grade estimates; actual premiums depend on region, contracting strategy, and market conditions at the time of procurement.

4.3 Strategic Implications

The transition from 6–10 MW to 15–20 MW turbines are reshaping construction practice across all three phases reviewed here. Next-generation designs involve rotor diameters beyond 220 m and nacelle masses well above the ~400 t handled in current practice, while monopile plate thicknesses approach the

welding and fatigue-qualification limits identified before. Three consequences follow. First, foundation selection shifts earlier from monopiles toward jackets and floating concepts as turbine ratings grow, compressing the economically viable depth range of the most mature technology. Second, only the newest generation of WTIVs—an estimated 8–10 vessels globally in 2025—can install 15–20 MW machines, so vessel capability rather than turbine technology increasingly sets the pace of deployment. Third, the industry is shifting assembly onshore: pre-assembly configurations such as R2T, which reduce offshore lifts by approximately 40%, become progressively more attractive as component dimensions increase.

Port infrastructure imposes a parallel and often underappreciated constraint. Marshalling and pre-assembly of 15–20 MW components demand deeper berths, higher quayside load-bearing capacity, larger staging areas for towers and blades, and heavy-lift cranes matched to component masses than most existing ports provide; outside Northern Europe, few ports currently combine all these capabilities. Because pre-assembly strategies transfer work from the offshore site to the quayside, their documented reduction in offshore weather exposure can only be realized where port depth, load capacity, and

staging area are adequate. Port capability assessment should therefore be treated as an integral input to construction-method selection rather than as a downstream logistics detail.

These constraints carry direct strategic implications. For developers, securing installation-vessel commitments several years ahead of construction and screening port capability during site selection become as decisive as foundation choice itself, given day rates projected to rise by 50–100% by 2028. For planners and policymakers, the findings support a portfolio approach: since no foundation type dominates all depths and metocean regimes (Table 9, Figure 9), deployment targets are more robust when fabrication capacity, vessel access, and port upgrades are planned jointly with the project pipeline. For designers, maximizing onshore pre-assembly and modular interfaces offers the most direct mitigation of both the vessel bottleneck and the weather-window risk quantified in Table 8.

4.4 Research Gaps and Future Directions

Two gaps follow directly from this review's findings. First, the weather-window differentials quantified in Table 8 (30–85% availability) are synthesized from heterogeneous studies; site-specific probabilistic metocean models coupled to installation simulation via Monte Carlo or stochastic weather generation are needed to convert these ranges into project-grade schedule risk estimates. Second, the vessel dependency rankings in Table 9 point to WTIV scarcity as the binding constraint, yet no published model couples fleet supply-demand dynamics to installation scheduling; mixed-integer programming and agent-based approaches are the natural candidates.

The quantitative thresholds compiled in this review limiting sea states, weather-window availabilities, and their associated delay factors (Table 8) are synthesized from studies that differ in vessel specifications, site conditions, and underlying assumptions. No standardized framework currently exists in the literature for deriving installation thresholds that are comparable across foundation types and sites. Future research should therefore prioritize the development of harmonized threshold-

derivation methods, coupling site-specific long-term metocean hindcast data with vessel- and operation-specific response criteria, so that the indicative ranges reported here can be replaced by probabilistic, project-grade limits. Until such validation studies are available, the thresholds in this review should be treated as screening-level values for comparing construction methods rather than as design inputs for any project.

5. Conclusions

This systematic review examined 55 peer-reviewed studies on offshore wind turbine construction methods across three integrated phases: fabrication, transportation, and installation. Four key conclusions emerge. First, water depth and metocean conditions jointly determine foundation feasibility: monopiles remain viable to ≤ 30 m, jackets at 30–50 m, GBS to ≤ 35 m, semi-submersibles at 45–250 m, and TLPs at 80–150 m, with installation-limiting sea states ranging from $H_s < 0.8$ m (TLP tendon operations) to $H_s < 2.0$ m (jacket and semi-submersible), producing weather-window availabilities of 30–85% (Tables 8–9). Second, WTIV scarcity is the binding near-term constraint: only 8–10 vessels capable of installing 15–20 MW turbines are projected globally in 2025, with day rates expected to rise 50–100% by 2028, so vessel capability increasingly dictates deployment schedules. Third, onshore pre-assembly is the most effective risk mitigation currently available, cutting offshore lifts by approximately 40% and weather-dependent installation time by 30–50% relative to piece-by-piece methods. Fourth, construction strategy materially affects project economics: relative to the monopile baseline, foundation choice carries an LCOE premium of up to +40–60% (TLP) and vessel selection of +20–40% (Table 10), so construction decisions should enter LCOE targets at the concept stage rather than after site selection.

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