



Installation of offshore wind turbines: A technical review

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ABSTRACT

The installation phase is a critical stage during the lifecycle of an offshore wind turbine. This paper presents a state-of-the-art review of the technical aspects of offshore wind turbine installation. An overview is first presented introducing the classification of offshore wind turbines, installation vessels, rules and regulations, and numerical modelling tools. Then, various installation methods and concepts for bottom-fixed and floating wind turbines are critically discussed, following the order of wind turbine foundations and components. Applications and challenges of the methods are identified. Finally, future developments in four technical areas are envisioned. This review aims to guide research and development activities on offshore wind turbine installation.

1. Introduction

The offshore wind energy community has undergone an evident expansion over the past three decades. In 1991, the world's first ever offshore wind farm (OWF), Vindeby [1], was constructed in Denmark. That wind farm has already been decommissioned, and interest in floating wind farms in deep waters has since increased. For example, the 30-MW (MW) Hywind Scotland pilot park was commissioned in October 2017. This park consists of five spar floating wind turbines (FWTs) and demonstrates the feasibility of future commercial floating wind farms [2].

Today, many offshore wind turbine (OWT) technologies have reached a high technology readiness level, and a substantial decline of 20% in the levelised cost of energy (LCOE) of offshore wind projects has been observed between 2010 and 2018. Such a decline is due to factors including larger rotor diameter, OWF clustering effect, and improved wind turbine technology and installation technology. Still, compared with onshore wind energy and other renewable energy sources like solar photovoltaics, offshore wind energy has a significantly higher LCOE, with a global weighted average of \$ 0.127/kWh [3]. To boost the competitiveness of offshore wind energy, it is important to identify the major cost drivers during the lifecycle of an OWF. Then, research-based innovations should be carried out to advance existing technologies. Because different phases of a lifecycle are interconnected, a holistic view is preferred when considering a technology. For example, a novel foundation may be used as fish habitat, replacing the need for decommissioning.

The lifecycle of an OWF consists of a few stages. Although several

definitions exist for the stages [4–6], five representative stages can be considered for an OWF, as illustrated in Fig. 1. Here, Stage 1 involves site selection and preparation of a formal consent application. Wind speed, water depth and seabed conditions are considered during a site assessment. The application includes details of the wind turbines, environmental impact assessment along with other considerations. Stage 2 refers to the manufacturing and production of turbines, moorings, and cables. The turbine costs have been significant traditionally. Stage 3 involves installation of multiple components of OWTs including cables, foundations, tower, nacelle, and blades. At this stage, installation vessels and handling equipment are needed, depending on the installation methods chosen. To guarantee the efficient operation of an OWF after commissioning, inspection and maintenance activities are called for during its lifespan. In a broad sense, this stage includes various marine operation activities like transportation from port to site, lift-off of wind turbine components at the site and assembly of the components. Strictly speaking, transportation and installation are separate activities, but this paper discusses both. Stage 4 includes online condition monitoring, collection of SCADA data as well as routine inspections and repairs of wind turbine components like blades and gearboxes. Finally, after an OWF reaches the end of its lifespan, the developer will decide whether the OWF is to be decommissioned or repowered (Stage 5). While decommissioning indicates the complete removal of an OWF, repowering accomplishes the updating of wind turbines at an existing OWF by either replacing older turbines with new ones or swapping out the parts in the original turbines with new, more efficient technologies.

Because of the complexities involved, offshore installations are nonstandard operations. Depending on factors like rotor size, foundation

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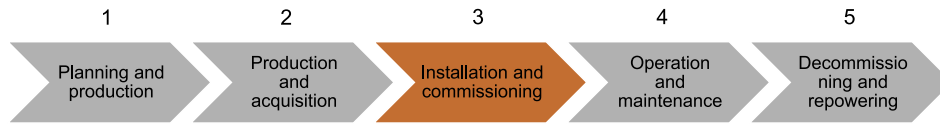


Fig. 1. Five stages typical of an offshore wind farm.

type, technology development, and site conditions, each OWF has unique requirements for offshore installation. The associated costs can also be high. The capital expenditures (Capex) and the operational expenditures (Opex) are two ubiquitous contributors that influence the LCOE of many power generating systems including OWTs. Stehly et al. [7] estimated the LCOE for representative bottom-fixed and floating wind turbine projects. In Stehly's work, the monopile foundation was considered for the bottom-fixed project and the semi-submersible foundation for the floating project, respectively. It was reported that the installation (Stage 3) accounts for 6.3% and 2.4% of the Capex for the bottom-fixed and floating projects, respectively, albeit the installation methods assumed are not specified. Despite the relatively small contribution for the floating project, selecting a suitable installation method for an OWF strongly depends on the foundation types, site conditions, and equipment availability. Thus, it is an important and practical consideration for OWF development.

Along with wind turbine technologies, installation technologies have witnessed development since the inception of the offshore wind industry. For installed OWTs, there have been heated research activities spanning aerodynamics, hydrodynamics, structural loads, dynamics and control, operation and maintenance, drivetrain, and foundation and moorings. In contrast, the research field of OWT installation is relatively new and only receives late attention. A comprehensive overview of the installation methods is lacking so far. What are the installation methods for different types of OWTs? What are the challenges? What are the development trends? This review aims to address these questions by summarising the state of the art of the field. The article is structured into the following sections. Section 2 classifies the OWTs based on the foundation or substructure types. Section 3 lays a foundation for the following discussions and presents the installation vessels and equipment, classification rules, and numerical modelling tools. Section 4 reviews the installation methods for various bottom-fixed and floating foundations with a focus on most common foundation types. Section 5

discusses the research frontiers of wind turbine component installation. Section 6 discusses the future prospects of OWT installations. A final conclusion is drawn in Section 7.

2. Classification of offshore wind turbines

2.1. General

Wind turbines can be classified on the basis of different criteria. A wind turbine can either be vertical- or horizontal-axis if the criterion is the direction of the rotating axis. If the criterion becomes the power transmission method, then direct drive and gearbox transmissions are two main categories. For an OWT, the foundation type is also an important criterion that governs the installation method. Bottom-fixed and floating OWTs are two main categories; a brief overview is provided here.

2.2. Bottom-fixed offshore wind turbines

The current offshore wind energy market is dominated by bottom-fixed OWTs [3]. Fig. 2 illustrates three common types. Among them, the monopile foundation has the simplest form as it consists of one single steel tube pile. Typical monopile OWTs have a diameter of 3–8 m and are considered economic for water depths of 20–40 m, and the development of monopiles of larger diameters and lengths is ongoing [8]. Gravity base foundations (GBFs) are usually made of concrete. They use their self weights to resist overturning moments and are appropriate for the clay, sandy soil and rock seabed conditions [9]. GBFs used to be situated in water depths less than 10 m. Jacket foundations are space frame structures welded from steel tubular members. Despite storage and logistics challenges [10], jacket-supported OWTs are competitive for intermediate water depths (50–70 m) [11].

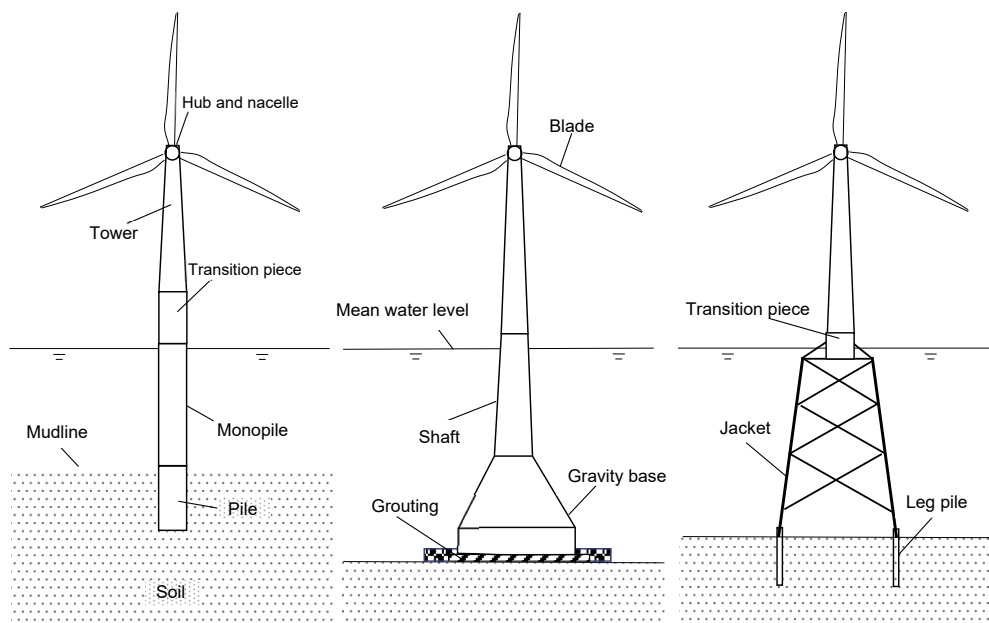


Fig. 2. Schematic of monopile, gravity-based and jacket offshore wind turbines.

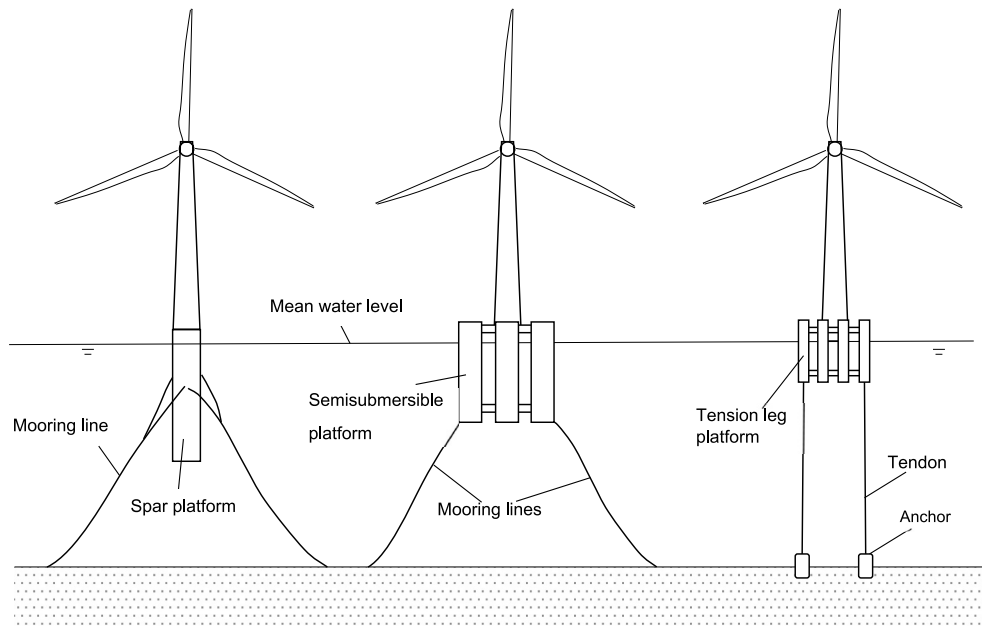


Fig. 3. Schematic of spar, semisubmersible and tension leg platform floating wind turbines.

2.3. Floating wind turbines

Like floating oil and gas platforms, FWTs rely on mooring and anchoring systems to fulfill their station-keeping purposes in deep water. Although the idea of FWTs can be traced back to the 1970s [12], intense commercial and academic interests did not emerge until the early 2000s. Fig. 3 illustrates three typical FWT concepts with mooring systems. Based on the restoring mechanisms for achieving a hydrostatic equilibrium, FWTs can either be regarded as ballast-, buoyancy- or mooring-stabilised during operation. In reality, most FWTs rely on a combination of these mechanisms, and Fig. 4 shows the relative position of selected commercial concepts in the restoring mechanism triangle. Some floating foundations, e.g., spar [2] and tension leg platform (TLP) [5], exhibit quite different restoring characteristics during transportation and installation than during operation. In addition, disparities among FWTs are also large, leading to customised installation methods for individual concepts.

3. Overview of offshore wind turbine installation

3.1. General

An OWT installation is an activity during which multiple parts of a wind turbine are assembled and finally connected to the grid. As this activity occurs offshore, it is deemed a marine operation that faces challenges including marginal installation equipment on the market [10], weather window [13], and safety risks in lifting operations [14], to name a few. In this section, common installation vessels and equipment, relevant international standards, and numerical modelling tools are reviewed.

3.2. Installation vessels and equipment

Installation vessels are involved for any OWT installations. Vessels are selected based on reasons including market availability, budget for installation tasks, and wind turbine technologies, e.g., size and number of components. As illustrated in Fig. 5, different types of installation

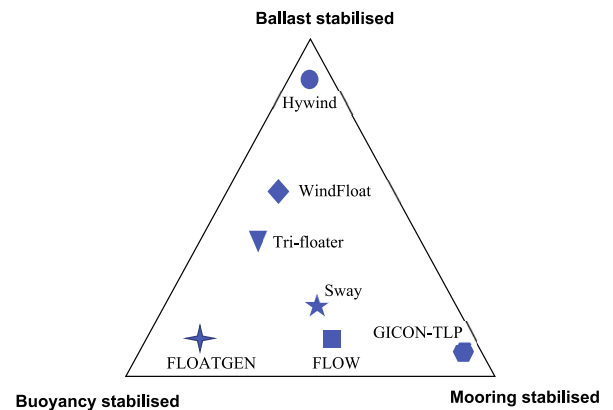


Fig. 4. Categorisation of floating wind turbine concepts based on their restoring mechanisms (Hywind [148], WindFloat [149], Dutch Tri-floater [150], Sway [151], FLOATGEN [101], FLOW [152], GICON-TLP [106]).

vessels can be used in an OWF development, and Table 1 lists a brief description of representative vessels. Among them, tugboats are the most economical and are often used for towing non-self-propelled barges or floating foundations. A tugboat maneuvers other vessels by pushing or pulling them either by direct contact or by means of a tow line.

Heavy lift cargo vessels feature large cargo areas which ensure the vessels to carry heavy modular components to suit specific project requirements. As shown in Fig. 5c), a vessel with a tandem crane arrangement will have a greater lifting capacity. An application example is found in the Veja Mate OWF project [15], where a heavy lift cargo vessel was engaged to transport 67 transition pieces from the construction site in Denmark to the wind farm in the Netherlands.

As lifting operations require cranes with good capacities, crane barges and jackup barges are widely used to lift pre-assembled wind turbines or support structures during installations. Examples are Alpha Ventus and Beatrices OWFs. Originally used in the offshore oil and gas industry, a medium-sized jackup barge may have a hull length of 60–80



Fig. 5. Common vessels used in OWT installation [153–156] (photo courtesy of Damen Shipyards Group, Spanopoulos Group and Fred Olsen ASA).

Table 1
OWT installation vessels and day rates (in US\$), sources [21–23].

Type	Specifications	Day rate ^a
Tugboat	Diesel engines; large power-tonnage ratio (2.2–9.5)	\$ 1000–5000
Crane barge	Sheerleg or rotating crane; large crane capacity (1000–4000 tonnes)	\$ 80,000–100,000
Heavy lift cargo vessel	Loading and discharging of heavy objects; spacious main deck area.	\$ 30,000–50,000
Jackup barge	Non-self-propelled; medium to large crane capacity (200–1300 tonnes); dynamic positioning or mooring system;	\$ 100,000–180,000
Purpose-built jackup vessel	Self-propelled; jacking system; dynamic positioning; large working deck; large crane capacity (800–1500 tonnes)	\$ 150,000–250,000
Semi-submersible crane vessel	Self-propelled; large lifting height and crane capacity (3000–20,000 tonnes).	\$ 280,000–500,000

^a Not necessarily representative of the present market rates.

m. Jackup barges of old generations have mooring systems, and it is necessary to have forecasts of wind and wave directions prior to installations in order to moor the vessel in a safe position relative to the OWT [16]. Another downside of these vessels is that the crane height and crane capacity are inadequate for MW-sized OWTs. To meet this end, purpose-built jackup vessels were constructed in the past decade; see Fig. 5e) for an example. Compared to the older counterparts, these vessels are often in excess of 100 m in hull length, less susceptible to weather conditions, and are equipped with dynamic positioning systems [17]. The large deck spaces make it possible for them to transport and install several OWTs in one trip. Although the day rate is higher, the offshore wind energy sector sees a huge demand for such specialised vessels.

The semi-submersible crane vessels have the largest displacements in the list. Because the lifting capacity of such vessels can reach up to 20,000 tonnes, they are well-suited to lift heavy wind turbine assemblies in demanding installation scenarios. Nevertheless, due to the high day

rate, renting such vessels has economic restrictions.

An offshore installation task cannot be fulfilled without involving specialised equipment. Such equipment can be installation vessel- or OWT-related and is under continuous development. Fig. 6 lists the two categories and several examples under each category. The vessel-related equipment, e.g., motion compensation devices [18], has been integrated into installation vessels and increases the operational efficiency and safety in offshore environments. The OWT-related equipment has been designed in tandem with the OWT technologies. Based on the functionality, the OWT-related equipment can be applied in transport or installation scenarios. In transport, excessive accelerations or vibrations of wind turbine components should be limited due to vessel motions, and sea fastening equipment like transport frames and racks are currently in use [19]. In installation scenarios, various solutions have been proposed to address complex lifting operations [20]. This paper will discuss the equipment for OWT components in Sec. 5.

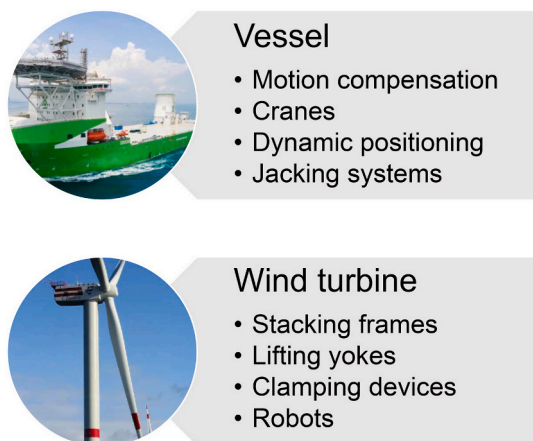


Fig. 6. Category of specialised equipment involved in OWT installations.

3.3. Standards and guidelines

The OWT installation activities, like any other offshore activities, must follow guidelines of regulatory authorities to ensure safety. The planning and execution of OWT installations should address various aspects including risk management, operation criteria, weather forecast, and structural integrity, as required by the offshore oil and gas industry [24].

Table 2 lists a few standards pertinent to OWT installations. Among them, DNVGL-ST-N001 [25] is a unified standard that replaces the legacy DNV-OS-H series standards [26,27]. In this standard, guidance is provided on marine operations of various types of offshore structures, and chapter 8 provides general requirements for installation of OWTs. ISO 29400:2015 [28] is another comprehensive standard with a similar scope. This standard is applicable to port and marine operations for offshore structures including subsea templates, foundations, and OWTs. DNVGL-RP-H103 [29] provides simplified formulas for establishing design loads useful for planning and execution of marine operations. This guideline covers towing operations, weather criteria as well as lifting operations but does not address OWTs in particular. The DNVGL-ST-0378 [30] standard provides requirements for offshore cranes and platform cranes. DNVGL-ST-0054 [31] is a recent standard that provides safety principles and guidance for transport and installation of onshore and OWTs. This standard is applicable to different wind turbine components, bottom-fixed support structures, substations, meteorological masts and power cables, but does not cover installation vessels or lifting equipment. DNVGL-ST-0437 [32] provides guidance for loads and site conditions of wind turbines. As the design situation of transport, installation, maintenance and repair is a design load case, this standard should be used with reference to design standards of OWTs [33, 34].

Although these standards and guidelines reflect the best practices of the day, improvements are always needed. Acero et al. [35] proposed a method for assessing the operational limits and operability of marine operations. As novel marine operation activities are not covered by standards and guidelines either, industry knowledge, experience, and technical know-how should be exercised for evaluating new installation

Table 2
Standards and guidelines for offshore wind turbine installation.

Standards	Title
DNVGL-ST-N001 [25]	Marine operations and marine warranty
ISO 29400:2015 [28]	Ships and marine technology – Offshore wind energy – Port and marine operations
DNV-RP-H103 [29]	Modelling and analysis of marine operations
DNVGL-ST-0378 [30]	Standard for offshore and platform lifting appliances
DNVGL-ST-0054 [31]	Transportation and installation of wind power plants
DNVGL-ST-0437 [32]	Loads and site conditions for wind turbines

concepts.

3.4. Numerical modelling tools

Numerical modelling provides an economical means for design, testing, and verification of novel installation methods. Numerical tools are also important for identifying potential risks during the planning phase and hence for improving safety of marine operations during execution. Here, the focus is on physics-based simulation tools rather than the financial model-based tools [36,37]. To simulate an OWT installation typically involves modelling of mechanical systems under complex load effects, several disciplines are covered including aerodynamics (Aero) [38], hydrodynamics (Hydro) [39], structural dynamics (StrD) [40], and automatic control (AutoC) [41].

The numerical tools applied to OWT installation are collected from literature and summarised in Table 3. As shown, “Y” and “N” respectively denote yes and no, and not all tools can handle the described disciplines in abbreviations. ABAQUS [42] and ANSYS [43] are general-purpose finite element codes. Both can be used to address structural problems that occur during OWT installations. AQWA and Fluent are ANSYS modules that extend the modelling capability to hydrodynamics. Bladed [44] and HAWC2 [45] are aeroelastic programs for fully coupled calculations of OWTs and rotor aerodynamics. Both programs allow for user-specified controllers limited to blade pitch or generator torque control. Because of the multibody formulation and the bearing functionalities, HAWC2 can be applied to calculate the dynamic response of individual wind turbine components in lifting scenarios. EllipSys [46] is an incompressible Navier-Stokes flow solver that can be regarded as a high-fidelity numerical tool. It can be used to derive 2-dimensional airfoil data or to resolve the unsteady vortex shedding on wind turbine blades during installations. The MarIn toolbox [47] is an open-source modularised blade installation simulation toolbox developed in MATLAB/Simulink. MarIn is suitable for design and testing of controller, e.g., tugger line force control, for installation-related problems. Reflex [48] and SIMO [49] are two numerical codes widely used by the offshore industry. Reflex can be applied to simulate the dynamic behaviour of slender structures, while SIMO was originally developed to simulate marine operations of offshore structures. Through external Dynamic Link Libraries, Zhao et al. [50] enhanced the functionality of SIMO by including the aerodynamic load calculation for a nonrotating blade.

There exist other numerical tools that can handle certain aspects of OWT installations. To make proper use of these numerical tools, the users should not only have modelling skills but also show understandings of the underlying physical problems and relevant theories. The numerical modelling theories, e.g., the multibody dynamics [40] and the finite element method [67], are well-established and thus not covered in this paper.

4. Foundation installation

4.1. Bottom-fixed foundations

4.1.1. Monopile

A monopile is typically used in hard to semi-hard seabed conditions.

Table 3
List of physics-based numerical tools for modelling OWT installation.

Codes	Aero	Hydro	StrD	AutoC	Applications
ABAQUS [42]	N	N	Y	N	[51–54]
ANSYS [43]	N	Y	Y	N	[55,56]
Bladed [44]	Y	Y	Y	N	[57]
EllipSys [46]	Y	N	N	N	[58,59]
HAWC2 [45]	Y	Y	Y	N	[60,61]
MarIn [47]	Y	N	Y	Y	[62,63]
Riflex [48]	N	N	Y	N	[64]
SIMO [49]	Y	Y	Y	Y	[50,65,66]

It is necessary to employ a transportation barge to transport the monopiles to the site. Then, either a jackup vessel or a heavy lift crane vessel can be used. As a jackup needs time to elevate itself out of water, a heavy lift vessel with dynamic positioning is a more efficient choice. As illustrated in Fig. 7, the monopile should be upended from the transportation barge by use of an upending frame. As a monopile must stand upright on the seabed because of the friction on the sides, a large hydraulic hammer (Fig. 7(c)) is used to drive the monopile into the seabed. Before and during the pile-driving process, pile-handling tools like gripper devices (red circle in Fig. 7(b)) are also considered for holding and positioning the monopile vertically [10]. Afterwards, grouting equipment will be used to cast the monopile and transition piece together (Fig. 7(d)). For innovative monopile foundations without transition pieces, the last step is skipped [68].

For monopiles, the construction noise that occurs during the pile driving has become a special challenge. Kikuchi [69] reported that the pile-driving noise is broadband and a sound exposure level can reach 210 underwater dB. Such a high noise level causes reactions from marine mammals such as porpoises and seals [70]. To mitigate the noise during installation, various methods have been proposed and Table 4 lists a few measures. Except for the pile-in-pipe piling, these measures have been tested and applied to OWF developments. The physical

principles for noise reduction include shielding, absorption, and scattering. Details can be found in Ref. [71].

As a large monopile can weigh one to two thousand tonnes, handling of monopiles offshore can be a challenging task. Should an installation task proceed if the forecasted wind speed or significant wave height increase? To answer such a question, onboard decision making is critical because it is often the dynamic responses due to an environmental condition that affect the safety. To determine the allowable sea states for the initial hammering process Fig. 8(a), Acero et al. [35] identified failure of the hydraulic system or excessive monopile inclination as two critical events from the procedure shown in Fig. 8(b) and derived the operational limits in terms of sea state parameters using numerical simulations of the vessel-monopile system. In another work, Li et al. [72] focused on the monopile lowering process and compared the allowable sea states using five numerical modelling methods. To the author's knowledge, only numerical works on this aspect can be found. In reality, the numerically derived allowable sea states can primarily serve as references for operations due to the differences between the physical systems and the simplified numerical models. As demonstrated by Tygesen et al. [73], the true digital twin technology can perform system identification and model updating using the offshore measured data. This technology shows promises to facilitate accurate allowable sea states during marine operations.

4.1.2. Jacket

A common jacket foundation is a lightweight lattice structure with three or four legs, and the structural members are fitted into the corner tubes. Most jackets stand on anchor piles –one at each corner of the foundations. The installation of a jacket is illustrated in Fig. 9. First, all piles are stabbed into an installation frame, which is a template structure allowing tight tolerance. Then, the hammering procedure starts. This procedure drives the piles into the seabed and is analogous to that of a monopile installation. Then, the jacket is lifted from a barge or a crane vessel. Upon arrival at the location, if the jacket is transported in a

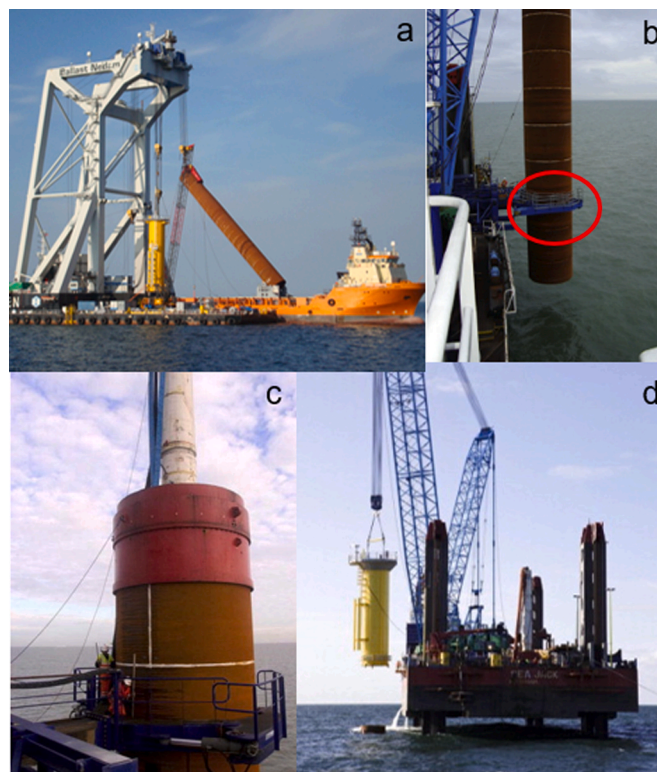


Fig. 7. Processes of an offshore monopile installation (photo courtesy of Seaway Heavy Lifting [157]).

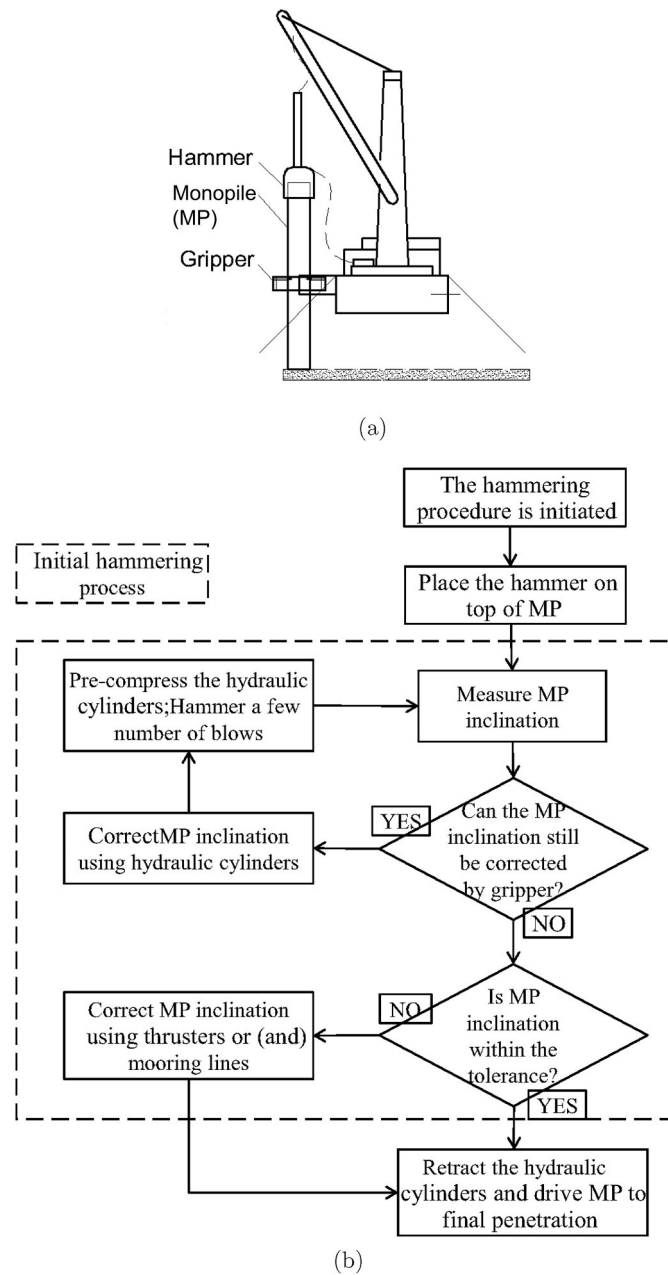


Fig. 8. Installation of monopile foundations. (a) Schematic of main components. (b) Procedure of the initial hammering process [158].

horizontal position (unlike the figure), it must be upended first. Afterwards, the jackets are lowered and mated with the pre-installed piles. The locating cones help to expedite the mating process. To control a successful mating, the inclination, position, and heading of the piles are of importance, and underwater sensors are usually used to provide real-time decision support. Next, the annulus between the pile and the pile

sleeve in the jacket is filled with concrete and left to cure before erecting the wind turbine .

There are relatively few research works in the public domain that address challenges of the jacket OWT installation. Thompson et al. [75] used acoustic monitoring to examine coastal cetaceans response to the jacket pile-driving noise during the installation of two OWTs. They concluded that a short-term response by porpoises could occur within 1–2 km of the site. This noise issue is similar to those of monopile installations. Zhang and Wang [76] considered the pile jacking method as a low-noise alternative to pile driving and conducted field study to compare the stress conditions caused by the installation processes.

In comparison with the installation of monopiles, the jacket installation involves more steps and is of a longer duration. So, the installation efficiency can be regarded as another challenge. To address this, Ruijgrok [77] designed alternative installation frames for pile installation based on an ultimate limit state check of the static internal loads. In this work, the frames were named “Pre-Piling Templates” and were used to

Table 4 Selected noise mitigation measures for pile driving, adapted from [71,74].

Category	Mitigation measure	Application	Noise reduction
Bubble curtains	Big bubble curtain	Trianel Wind park	11–21 dB
Bubble curtains	Little bubble curtain	OWF Alpha Ventus	11–15 dB
Isolation castings	IHC Noise mitigation system	OWF Riffat	5–17 dB
Isolation castings	BEKA shells	ESRa project	6–8 dB
Cofferdam	Cofferdam	Aarhus Bight	17–23 dB
Cofferdam	Pile-in-pipe piling	Model testing	27 dB

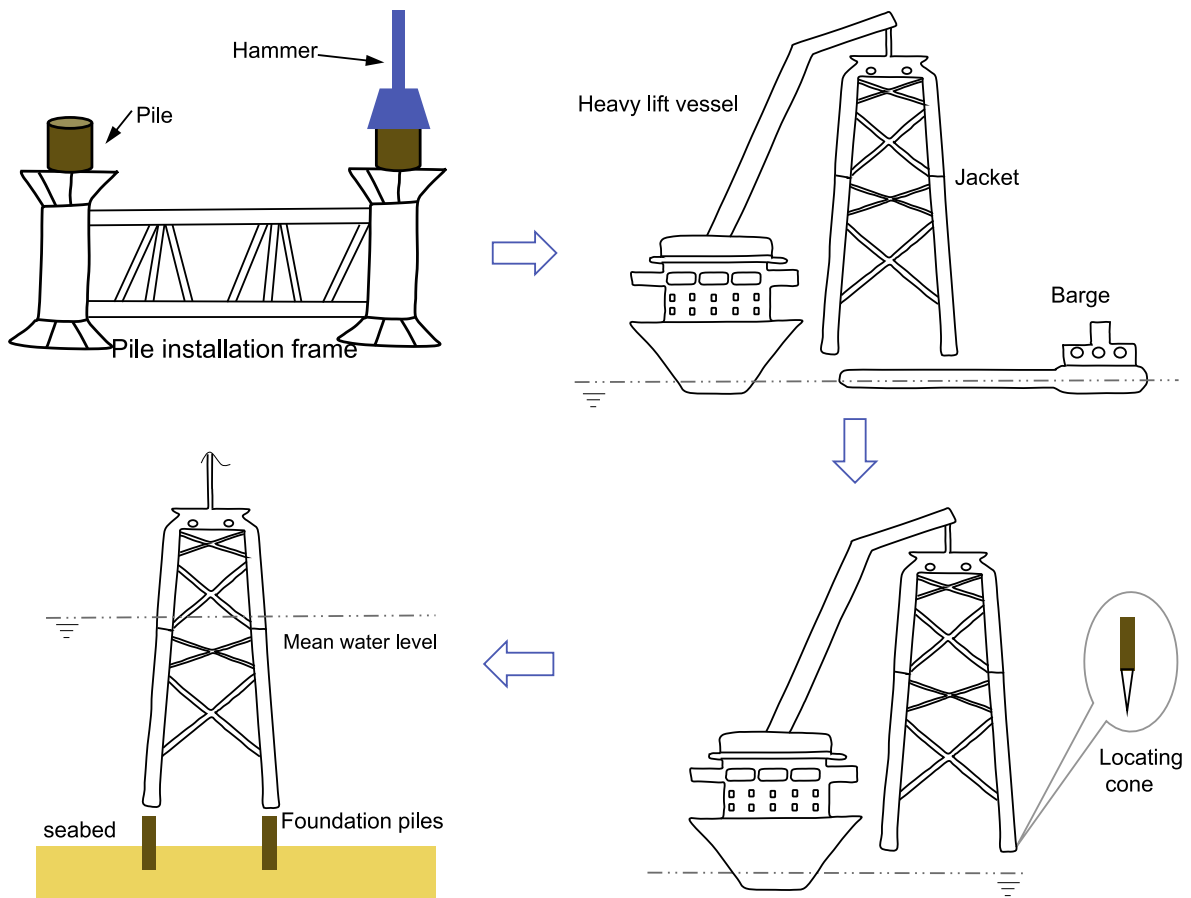


Fig. 9. Key steps of a jacket foundation installation.

speed up the installation process for three- and four-legged configurations of jackets. Actually, the design of installation frames should consider dynamic loads because such frame structures may experience large hydrodynamic loads when being lowered across the splash zone [78].

Apart from the pile-supported jackets, suction bucket jacket foundations have also been tested at the Borkum Riffgrund OWF [79]. The cup foundations can be installed in a single lifting and assembly process, reducing both the construction time as well as the associated costs. An additional advantage is that the installation noise is very low.

4.1.3. Gravity-based foundation

GBFs stand on the seabed by their heavy weights, ranging from 1500 to 4500 tonnes [10]. GBFs have been put into use since the inception of the offshore wind industry in the 1990s. A review of European OWFs with GBFs and three generations of the foundation types can be found in Refs. [80]. Despite the differences in existing concepts, Esteban et al. [81] identified common phases in the installation procedure of GBFs: seabed preparation, support structure manufacturing, support structure installation, and ballasting and anti-scour protection.

Seabed preparation is a unique step for GBFs that is not required for monopiles or jackets. This step appears because the weight of the GBFs will require huge ground-bearing capacity of the seabed, and soils with low bearing capacity must be removed. As mentioned by Ruiz De Termino Alonso [82], during the seabed preparation, the removable layer thickness varies from 0.5 to 10 m and dredgers and offshore tools are involved.

As GBFs are cast in steel-reinforced concrete using molds, manufacturing of these foundations is time-consuming. There are three different types of facility for manufacturing GBFs: dry dock, floating pontoons and onshore [82]. Details of the manufacturing processes are

beyond the scope of this paper.

The size and weight of the foundations make the load-out, transport, and installation cumbersome. As illustrated in Fig. 10(a), an offshore installation is traditionally carried out using a large barge, a floating crane vessel, and tugboats in the absence of self-propulsion systems for the vessels. The barge can possibly transport a number of foundations onboard and the crane vessel must be equipped with a large lifting capacity in order to lift and place the foundation onto the seabed.

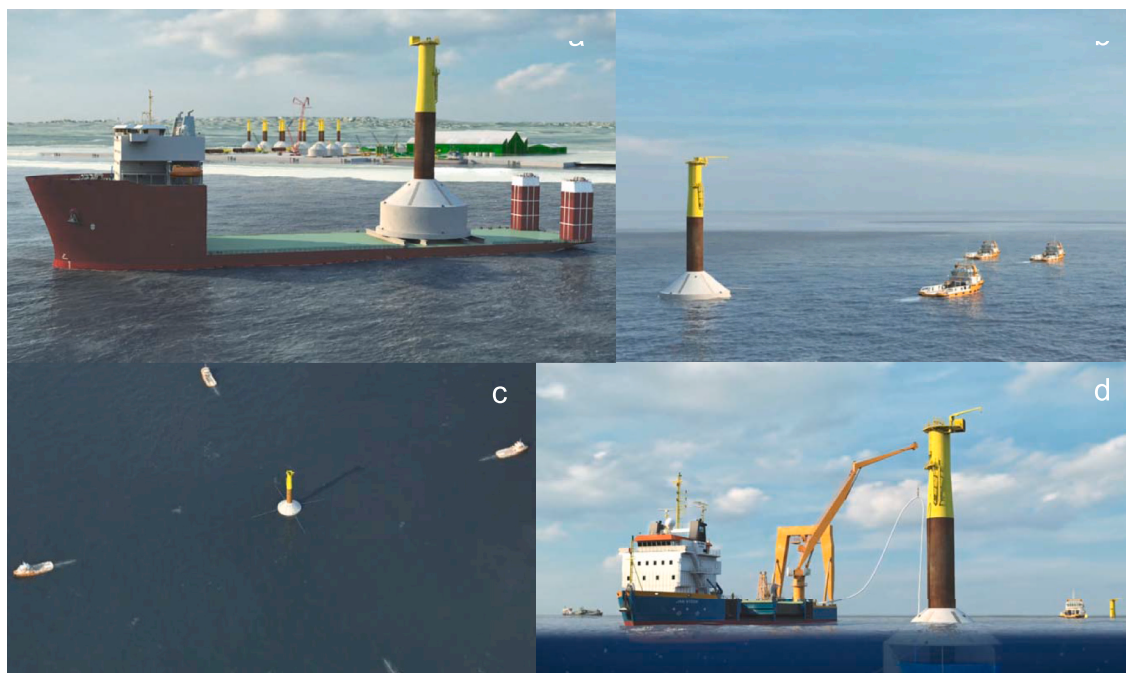
The traditional method faces the challenges of offshore heavy lifts and utilising expensive heavy-lift crane vessels. To resolve these challenges, the “float and submerge” installation method has been applied to the Blyth OWF recently. Fig. 10(b) demonstrates the procedures of this installation method. First, a GBF is produced on land, in a dry dock. Then, the self-floating GBF is wet-towed to its destination using tugboats. Afterwards, the GBF is progressively submerged to the seabed by ballasting it with water and sand. During ballasting, sensor and control technologies are involved to ensure a proper weight distribution of the foundation. Similar to the installation process of the oil and gas gravity platforms [83], this method has good potential to be further adapted to achieve cost reduction and standardisation for large-scale deployment of GBF-supported OWTs.

4.1.4. Other foundation types

There exist other alternative foundation types for bottom-fixed OWTs, including tripod [84] and suction bucket [84,85]. A tripod has a single steel tube above water and a three-legged foundation fitted with anchor piles, and the installation is difficult primarily due to the large footprint. In contrast, the suction bucket foundations could have easier installations. Zhang et al. [86] described an integrated transportation and installation technique that erects wind turbine assemblies like “tree planting”. Due to content limitations, these alternative foundation types



(a)



(b)

Fig. 10. Installations of gravity-based foundations (a) Traditional method for installing gravity base foundations; Left: transport of gravity-based foundations using a barge; Right: Lowering of gravity base foundations using a heavy lift crane vessel [81]. (b) "Float and submerge" method for installing gravity-based foundations [159].

are only succinctly described.

4.2. Floating foundations

4.2.1. Spar

A spar FWT is supported by a simple cylindrical spar foundation. With good hydrostatic stabilities and small waterplane areas, spar FWTs are well-suited for operation in deep water and harsh environmental conditions typical of the North Sea.

In 2009, Hywind Demo, the world's first spar FWT, was installed. The installation procedure included wet towing of the spar foundation from Finland to Norway, upending of the spar, solid ballasting, offshore assembly of tower and rotor assembly, towing to field, followed by mooring system connection and final ballast adjustment [87]. Eight years after the Hywind success, the Hywind pilot park was constructed off the coast of Scotland, and key installation steps are illustrated in Fig. 11. Among the four steps, towing was assisted by tugboats and

upending is achieved by pumping water into the spar foundation. During ballasting, a rock installation vessel with loading arm was used to load solid ballast (magnetite) into the substructure, and simultaneous de-ballasting of water was performed in order to maintain draft. The installation procedure of the Hywind Scotland FWTs is comparable to that of Hywind Demo, except that a large semi-submersible crane vessel was employed to lift a wind turbine assembly during the tower mating process.

A challenge arises because of the wave-induced motions of the spar floater during installation. To reduce the risks, it is preferred to upend the spar foundation and assemble the wind turbine components in sheltered areas. For OWFs far from coastlines, alternative installation methods are desired. Table 5 lists a few installation methods proposed in the past. Among them, the first four methods were the finalists in the Hywind installation challenge [94]. The barge with flipping capability [88] promotes the use of a specialised barge which can load and transport a fully assembled wind turbine horizontally. When towed to the

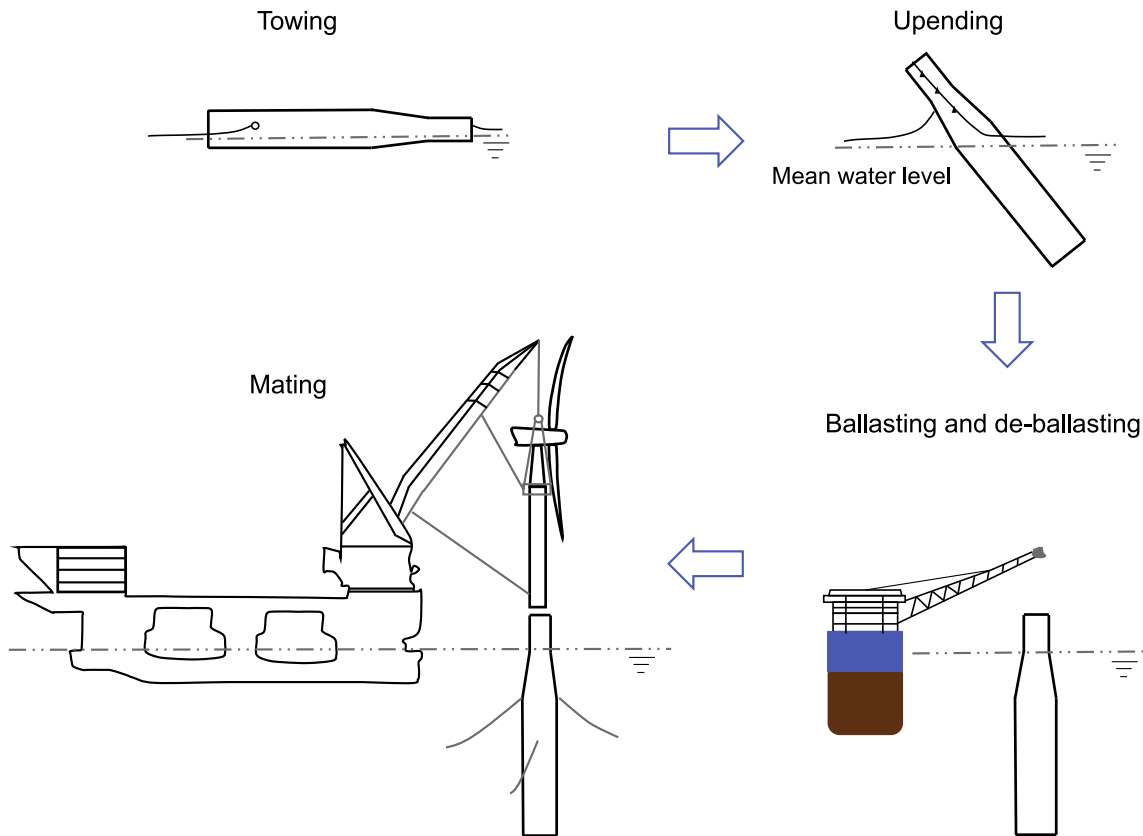


Fig. 11. Key steps of the Hywind Scotland spar FWT installation; adapted from Ref. [2,160].

Table 5
Selected installation methods for spar FWTs.

Method description	Originator	Year	Country
Barge with flipping capability [88]	Windflip AS	2009	Norway
Reusable transport frame [89]	Atkins	2015	UK
Fork-on and float-off [90]	MODEC Inc	2015	Japan
Vessel with a handling system [91]	Ulstein Group ASA	2015	Norway
Wind turbine shuttle [92]	Huisman Equipment BV	2015	The Netherlands
Catamaran installation vessel [66]	SFI MOVE	2018	Norway
Floating dock [93]	Equinor ASA	2020	Norway

location, the ballast tanks of the barge are filled with water until the barge and the attached wind turbine are flipped 90°. The turbine is then released from the barge and towed to its final position for mooring connection. The reusable transport frame [89] can be used to attach multiple turbines and allows towing of the turbines at reduced draughts. Inspired by this concept, Lande-Sudall et al. [95] experimentally investigated the collision loads between a towing barge and an FWT and evaluated the feasibility of the installation method. The fork-on and float-off method [90] utilises a connective system that enables a connection of the wind turbine assembly from the spar at the offshore site. A transportation vessel with twin forks will be used to pick up the assembly, transport it to the site, and connect the assembly onto a pre-installed spar foundation. The vessel with a handling system [91], wind turbine shuttle [92] and catamaran installation [66,96] share the idea of using specialised vessels to transport and install wind turbine assemblies and do not address the installation of spar foundations. As shown in Fig. 12, the catamaran vessel is equipped with sliding and lifting

grippers. During installation, the sliding grippers constrain the relative planar motions between the spar and the catamaran, whereas the lifting grippers play a key role by moving the wind turbine assemblies. An active heave compensator was developed in Ref. [97] to cancel the relative motion between the spar top and the assembly. Lately, a large floating dock [93] was proposed to facilitate mating of spar foundation and wind turbine components in open seas. As presented in Fig. 13, the initial design of the dock has a cylindrical shape and can shield one spar foundation from the external wave excitations. Despite the good intentions, the dock may be subjected to challenges like the piston-mode resonance and the sloshing effects [98].

4.2.2. Semi-submersible

A semi-submersible foundation is principally composed of three or four columns that are at a distance from and connected to each other. Compared to a single-column spar, a semi-submersible has increased waterplane area which provides more hydrodynamic stability and more structural stiffness to resist wave loads.

Liu et al. [99] provided a review of popular semi-submersible FWT designs and identified advantages and challenges of different concepts. One particular feature of semi-submersible FWTs is their superior towability,¹ and hence simpler installation and decommissioning than other FWT concepts. Take WindFloat [100] for example. This 2-MW turbine was commissioned off the Portuguese coast in 2011 and operated for five years. The assembly of WindFloat composed of hull, tower and turbine took place onshore in a dry dock. The entire foundation was then towed to the site and tied to a pre-installed mooring system. Fig. 14 illustrates the installation process. As shown, only three tugboats were used during the transport. When on site, the mooring hook-up was assisted by an

¹ a factor that describes how easily a concept may be transported at sea [5].

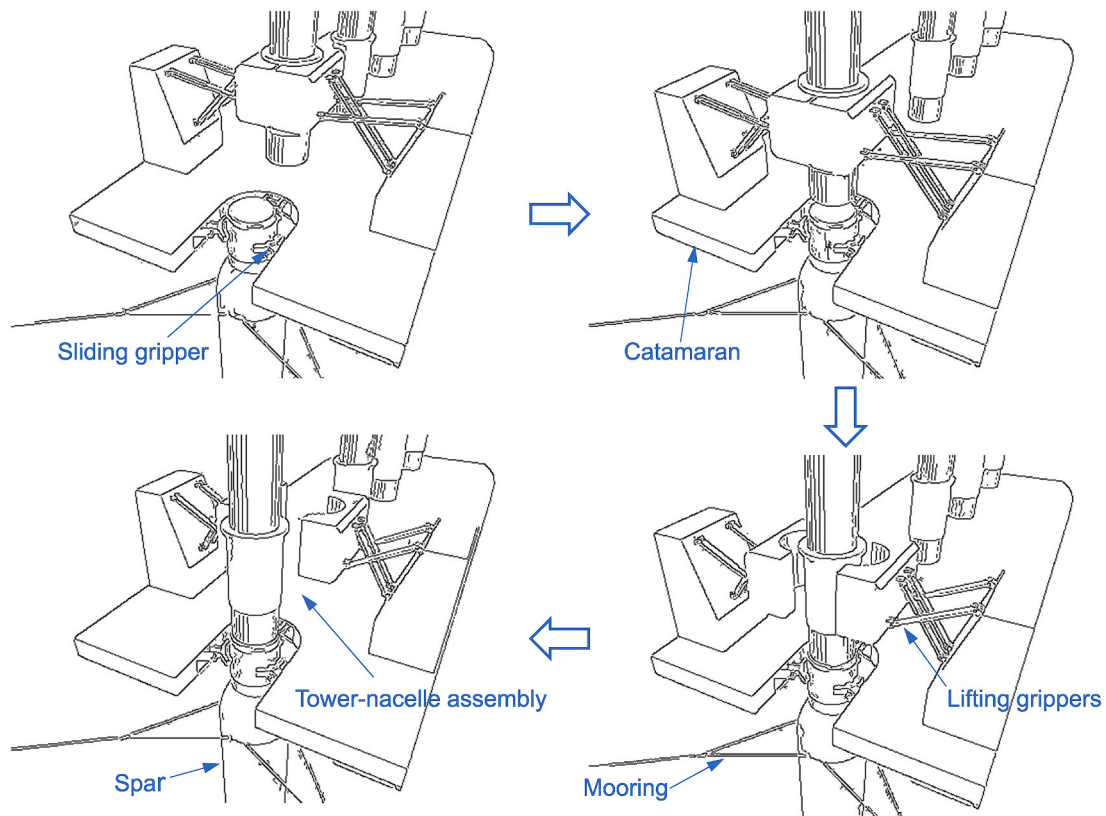


Fig. 12. Illustration of installation steps using a catamaran installation vessel, adapted from Ref. [66].

anchor handling vessel. This convenient installation procedure makes it possible to carry out repair or maintenance of the FWT in a dry dock as well.

To date, many alternative semi-submersible concepts have been developed, e.g., the Ideol platform with a damping pool [101] and the braceless V-shaped floating foundation [102]. Regardless of their individual differences, the installation superiority remains the same.

4.2.3. Tension leg platform

A TLP is a vertically moored compliant platform with excess buoyancy. Many TLP FWT concepts have been proposed in the past; see Refs. [103–107]. Although these designs vary in platform displacement and stability, number of tendons, hull shapes, and number of columns, common features include taught tendons, compact mooring footprint, and limited platform motions. Compared to spar and semi-submersible FWTs, TLP FWTs are less commercialised primarily due to the complexities in anchoring systems and of installations.

In spite of small-scale prototypes, e.g., the Blue H [108], installations of the utility-scale TLP FWTs have rarely been reported and experiences can be drawn from the offshore industry [109–111]. The tendons are usually installed before the platform. If a mechanical connector is used to join together the tendon sections, then the tendons can be dry-towed by a cargo barge to the site, where they are lifted and upended by a crane vessel. Alternatively, the individual tendon sections can be welded together and subsequently wet-towed to the site with buoyancy modules. Once on site, the buoyancy modules are removed; winches or cranes of a crane vessel are used to upend the tendons.

Depending on the design, the free-floating stability of TLPs during transit and installation can be an issue. A TLP FWT system may be fully

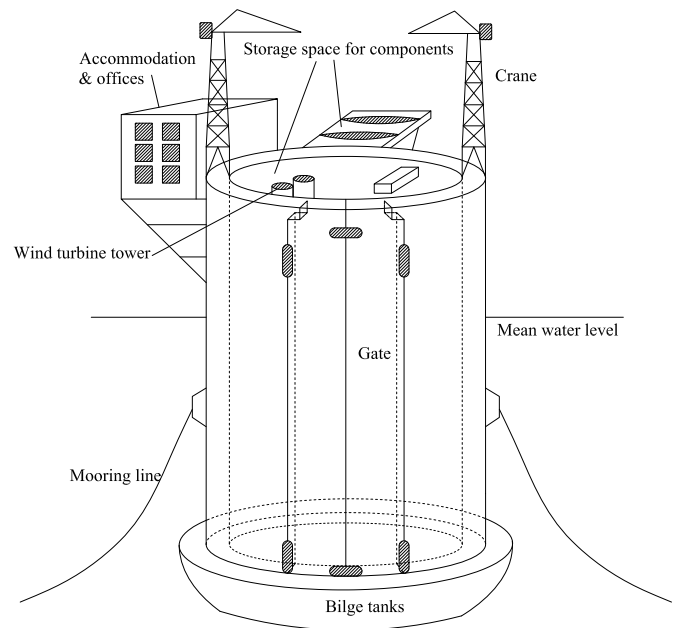


Fig. 13. Schematic of the floating dock concept, adapted from Ref. [93].

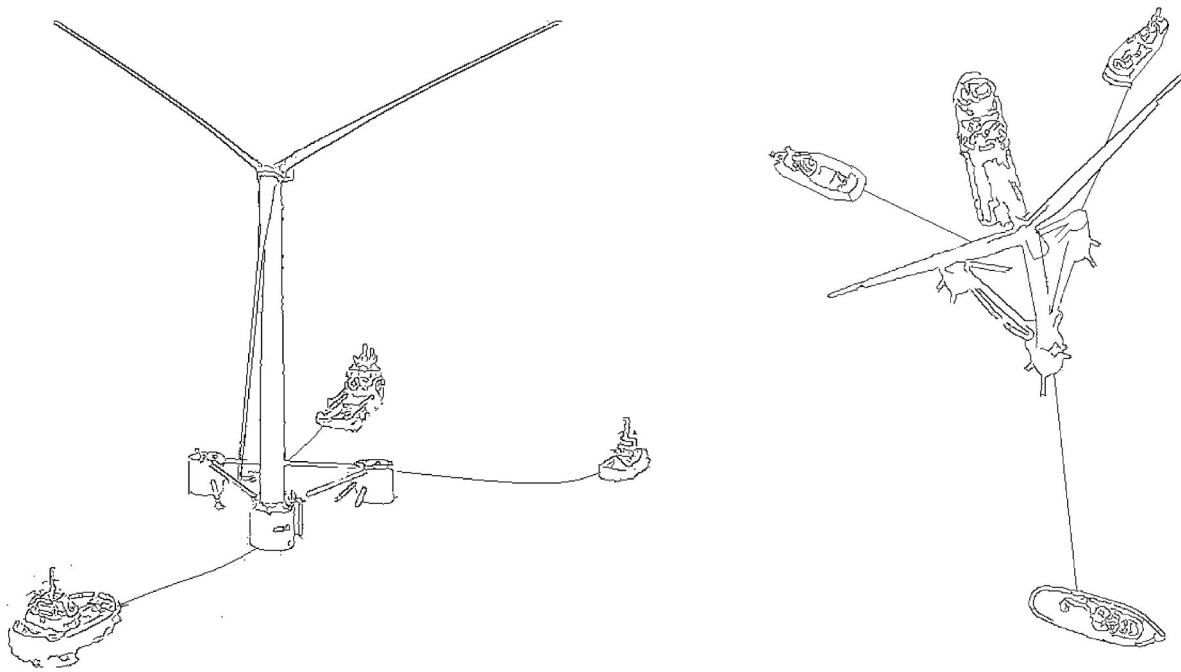


Fig. 14. Transport and mooring connection of the WindFloat semi-submersible FWT.

assembled in its upright position at a coastal facility using a crane [103]. With the assistance of a tugboat, the assembly is towed to the offshore site. Then, the TLP is ballasted between the initial free-floating draft and the lock-off draft at which the TLP is secured to the pre-installed tendons. Finally, the tethers are pre-tensioned by removing water ballast from the platform. Fig. 15(a) illustrates the main components involved in this method. In the figure, the cylindrical buoys act as temporary buoyancy modules, and together with a steel frame, they provide stability in pitch for the floater. For the platform, the reduced free-floating draft is achieved either by the water ballast or by pulling the lifting lines with winches.

As the traditional installation procedure of TLPs is complex and the TLP hulls may experience instability during submergence, there have been attempts to improve the installation method. Wybro et al. [112] suggested using a tensioning device with pull-down lines to complement the time-consuming de-ballasting process. A novel installation procedure has also been demonstrated by the GICON TLP [113]. As shown in Fig. 15(b), the TLP is placed on a floating slab and dry-towed by a tugboat during transit. When on site, the slab will be ballasted, submerging the TLP to its final draft. To realise a full commercialisation of the TLP FWTs, cost-effective installation methods must be developed.

4.2.4. Other types

Due to content limitation, installation methods of the three most studied floating foundations are emphasised. There are other interesting floater concepts worthy of note. For example, the TetraSpar floater [114] combines benefits from known floater concepts and can be installed at water depths between 10 and 1000 m. This floater features a simple tetrahedral structure with a keel. As illustrated in Fig. 16, the keel has ballast tanks that can be air-filled during towing, making the floater's stability resemble that of a semi-submersible. When on site, mooring hook-up is carried out, and the keel is ballasted and lowered to a certain depth. The ballasted keel is connected to the floater via

suspension lines, reducing the centre of gravity and making the system act like a spar.

5. Summary

Table 6 provides a summary of the predominant installation methods for common foundations. Such a comparison should be made with caution as the installation techniques for floating foundations have not converged yet. The tradeoffs are listed in terms of the installation simplicity, technical maturity of the installation methods, and challenges and potential of offshore installations. The range of water depth is drawn from literature and is approximate. Among the presented foundation types, monopiles and semi-submersibles are positively evaluated with regards to the installation simplicity as a reduced number of onsite operations are involved. A streamlined installation lowers cost. All bottom-fixed foundations are deemed technically mature because of the OWF projects worldwide. The technical maturity of spar installation is subjectively rated as medium here because of the multitude of proposed alternatives; see Table 5. In comparison, semi-submersibles and TLPs are respectively judged with high and low technical maturity based on their latest development. To enable time-efficient and cost-effective foundation installations, novel concepts from technological innovations should be underscored.

6. Wind turbine component installation

6.1. Installation methods

Except for the semi-submersible and TLP FWTs mentioned above, most OWTs require an offshore assembly of wind turbine components after being transported to the site. The number of offshore lifts depend on factors like wind turbine design, lifting equipment, sea conditions, and capacities of transport and installation vessels. For example,

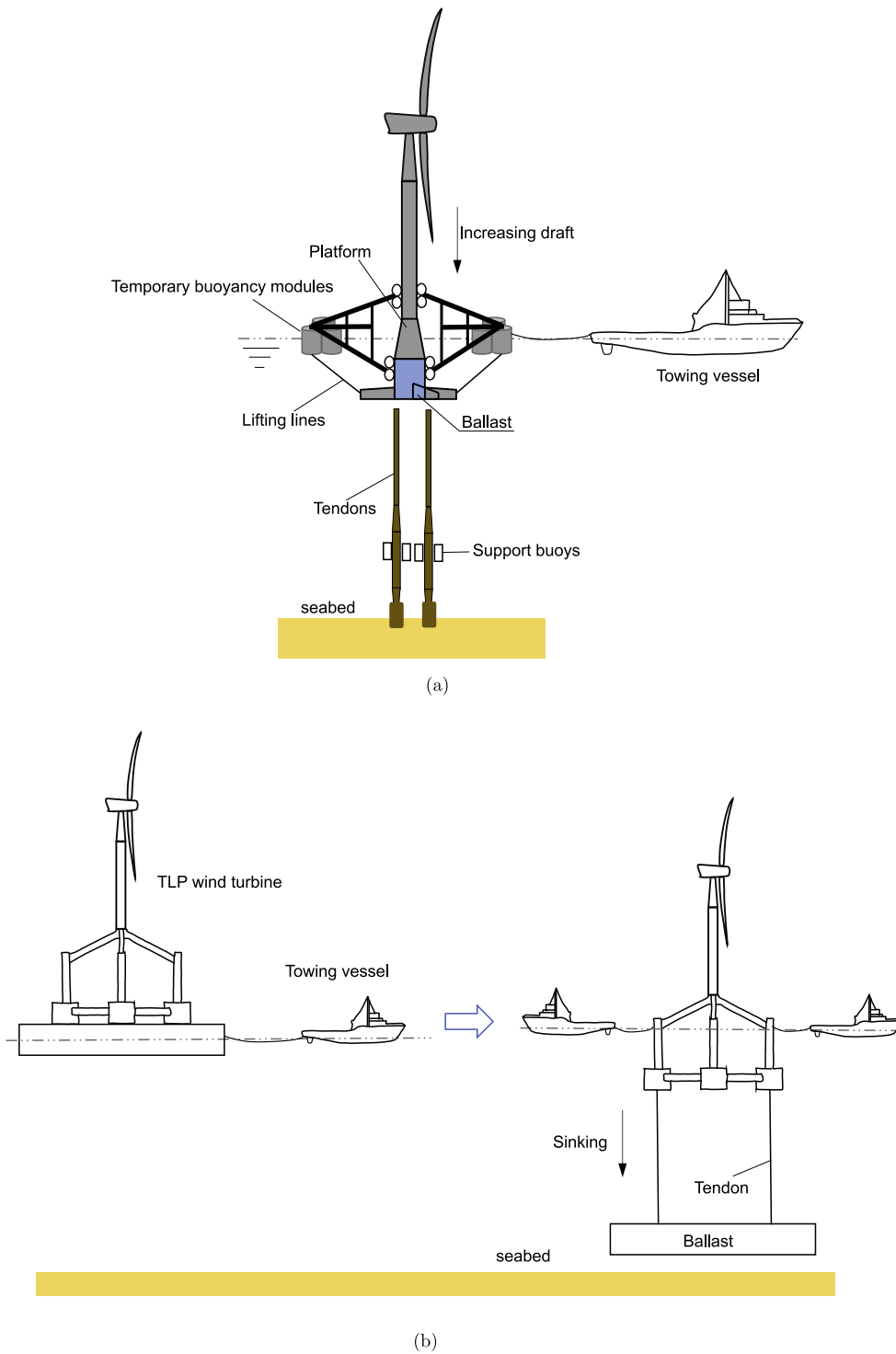


Fig. 15. Installations of TLP FWTs.(a) Installation method for the MIT/Enel TLP, adapted from Ref. [103]. (b) Installation concept for the GICON TLP [113].

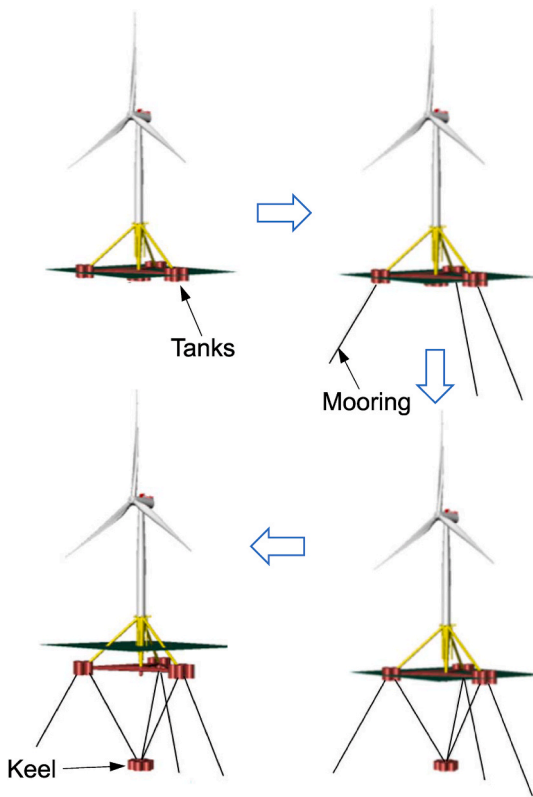


Fig. 16. Installation of TetraSpar FWT (picture courtesy of Henrik Stiesdal).

although an increased number of pre-assembled pieces reduces the number of offshore lifts, an efficient use of the deck space of the transport vessel may be prevented, and large-capacity cranes may be required during the offshore construction consequently. Fig. 17 lists the six installation methods summarised by Ahn et al. [22] and Kaiser et al. [4]. These methods differ because of the number of pre-assembled components. All methods have been applied to installing OWFs in Europe and pertinent works can be found. Uraz [115] distinguished these methods considering site-specific factors and installation vessels. Wang and Bai [116] defined “overall installation” and “split installation” as the two main categories. This definition indiscriminately places most methods listed in Fig. 17 under the “split installation” category. The trend is that more OWTs are assembled in a “split” manner because of the growing wind turbine sizes.

6.2. Blade installation

Blades are airfoils made of composite or reinforced plastics. Table 7 lists the weight and length information of blades of representative commercial and academic OWTs, and the latest announced wind turbine models have power capacities above 10 MW. Even for the largest blades, the low weights (< 100 tonnes) are well within the capacity of offshore cranes. However, given the large lengths (> 100 m) and blades’ sensitivity to wind loads, lifting operations are not without challenges.

In an early work, Wang et al. [57] considered the full rotor of a 1.5-MW wind turbine and calculated the hoisting forces for several rotor configurations and wind conditions using an aeroelastic tool. The analysis was simplified as only steady wind conditions were considered and the rotor was fixed during the simulations. Following the work, the authors applied computational fluid dynamics (CFD) methods to

Table 6 Tradeoffs of mainstream installation methods for various foundation types.

Tradeoffs/types	Monopile	Jacket	GBF	Spar	Semi-sub	TLP
Key installation steps	Pile driving and grouting	Pre-piling, lifting, and lowering	Seabed preparation, lowering, and scour protection	Upending, deballasting, and mooring hook-up	Mooring hook-up	Tendon upending and platform connection
Installation simplicity	Relative advantage	Neutral	Neutral	Neutral	Relative advantage	Relative disadvantage
Technical maturity	High	High	High	Medium	High	Low
Main challenge	Noise issue	Noise issue and efficiency	Heavy lifts	Foundation motions	N/A	Hull instability
Potential Water depth	Noise mitigation 0-40 m	Suction buckets 30-70 m	Self-floating foundations 0-30 m	Specialised vessels > 100 m	N/A >50 m	Novel platform > 80 m

Installation method	1	2	3 to 4	3 to 4	5	6
Number of lifts	1	2	3 to 4	3 to 4	5	6
References	[66, 96]	[4,115]	[57, 116]	[4, 115]	[59-61]	[59-61]

Fig. 17. Installation methods for component installation of OWTs (selected literature is included).

Table 7

List of blade specifications of offshore wind turbines.

Wind turbine model	Weight (tonnes)	Length (m)	Year	Country
IEA 15 MW [117]	65.3	117	2020	USA
GE Haliade-X 12 MW [118]	55	100	N/A	N/A
MHI Vestas V164 10 MW [119]	35	80	2022	France
DTU 10 MW [120]	41.7	86.4	2013	Denmark
LEANWIND 8 MW [121]	80	35	2016	Ireland
Simens SWT 6 MW [122]	N/A	75	2013	Germany
Sevion 5 MW [123]	20.8	61.5	2010	Germany
NREL 5 MW [124]	17.3	61.5	2009	USA
Simens SWT 3.6 MW [125]	15.8	52	2007	UK
Bonus B76 2 MW [126]	6.5	36.5	2000	Denmark

calculate the hoisting forces for steady wind conditions [127].

Recently, single-blade installation has aroused substantial interests. As the name indicates, this installation method involves separate lifts for

each blade, with a total number of five to six lifts for an entire OWT (Fig. 17). For this method, a challenge arises when a lifted blade experiences large vibrations in high wind. When an OWT foundation is subjected to wave-induced motions, the blade mating process can also encounter difficulties. To deal with these challenges, research activities have taken place within the disciplines of aerodynamics, dynamics and control, and structural safety.

In 2014, Gaunaa et al. [128] presented a first-order engineering model for predicting the quasi-steady aerodynamic forces and moments on a nonrotating blade and verified the model against HAWC2 [129]. In another work, Gaunaa et al. [59] used 3-dimensional CFD calculations to examine the validity of the cross-flow principle in calculating the aerodynamic forces. As a results, a correction model was proposed to improve the agreements with CFD results.

Aerodynamics describes the key loading aspect of a blade. For practical single-blade installations, dynamic analysis of the installation systems can provide additional insights. Kuijken [60] established a

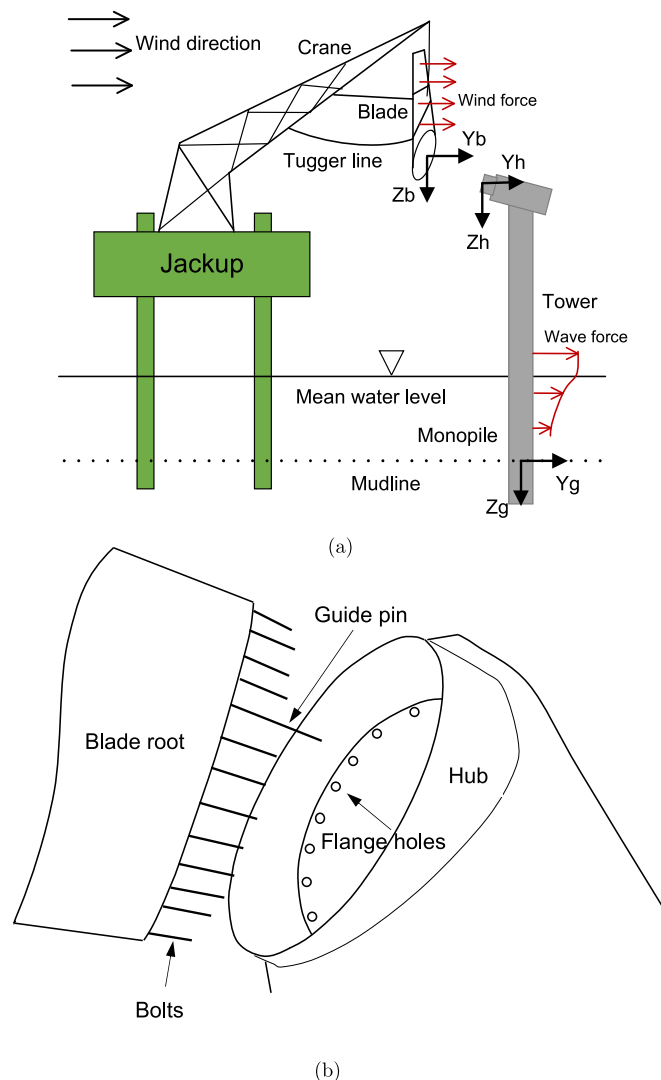
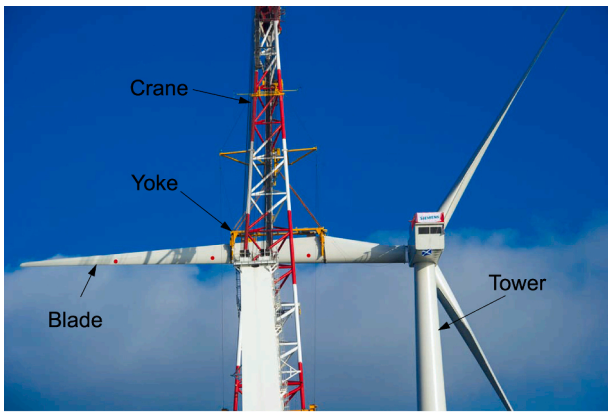
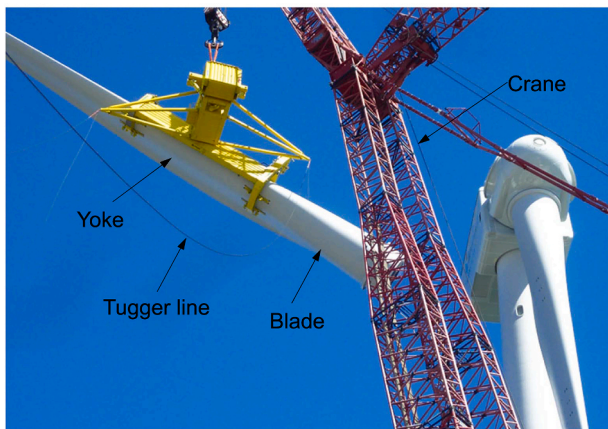


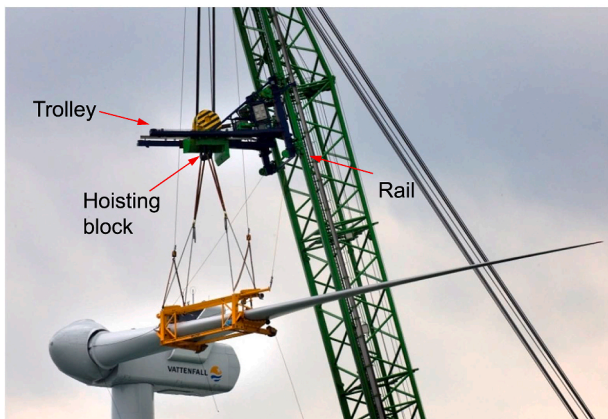
Fig. 18. Scenarios of single-blade installation offshore (a) Scenario of single blade installation for a monopile-supported OWT [131]. (b) Sketch of the final mating phase of an OWT blade.



(a)



(b)



(c)

Fig. 19. Industrial equipment for blade installation (a) Horizontal blade mounting with a lifting yoke; source: Siemens Wind Power GmbH. (b) Inclined blade mounting with a lifting yoke; source: Liftra ApS. (c) Blade mounting using the BoomLock technology; source: High Wind NV.

multibody model of the DTU 10-MW wind turbine blade with two tugger lines and a yoke and analysed the dynamic behaviour of the blade in different wind conditions. Ren et al. [47] conducted code-to-code comparison for a simplified blade lifting system composed of a blade, a hook and lifting wires. Zhao et al. [50] developed a numerical model and identified characteristics of a blade installation system. These works only address the installation systems. When a single blade is mated with a hub of an OWT, motions of the foundations can be very important.

Fig. 18(a) illustrates the blade mating scenario for a monopile-supported OWT. This scenario bears a similarity to the floatover installation of offshore platforms [130]. As shown, the relative motions in the yz -plane should be a critical factor for the mating during which the long guide pin will enter a flange hole before other bolts (Fig. 18(b)). According to a numerical study [131] where both the monopile and blade motions are analysed, the monopile resonant motions can be dominant for sea states with low spectral wave periods. Such large relative motions may cause unwanted consequences. Verma et al. [53, 54] performed impact analysis of blade root and found that the blade-root impact can lead to damaged guide pins and delayed offshore operations in the worst case, which is confirmed by offshore experiences [132].

To address this issue, various means have been proposed. Jiang [61] suggested using passive tuned mass dampers to mitigate the resonant monopile motions during the blade mating phase. Following that, Sander et al. [133] reported the results of a monitoring campaign during an offshore installation in the North Sea and confirmed the effectiveness of a tuned mass damper system. The downside of the passive mass dampers is due to their heavy mass and narrow effective frequency range. Ren et al. [62] focused on the blade installation system and designed an active control scheme to reduce the blade motions by controlling the tugger line forces. The scenario of using three tugger lines was also addressed in another work [134]. These approaches, if combined with motion tracking techniques [63,135], have potential to be applied in other OWT component installations.

A variety of industrial equipment has been developed to facilitate blade installations. These are typically tailor-made mechatronic devices with remote control. Fig. 19(a)(b) show two representative products, the Blade Dragon technology [136] and the Boom Lock technology [137], respectively. The Blade Dragon is a lifting yoke that can grip a blade and install it at different inclined angles without the need to turn the rotor. The Boom Lock is an intelligence system that locks the lateral motion of the crane hook and significantly reduces the blade motion. Using these devices, it is possible to increase the wind speed threshold, to reduce human actions, and eventually to reduce risks during blade installations. More descriptions of industrial equipment can be found in Ref. [20]. Some novel concepts, e.g., Ref. [138], still have a low technology readiness level.

6.3. Installation of transition piece and tower

For many conventional bottom-fixed foundations, a transition piece is placed on top of the foundation to levelise the horizontal inaccuracies after the foundation is installed. Transition pieces pass through the majority of the water column but do not rest on the seabed. For monopile foundations, the gap between the pile and the transition piece is normally filled with cement grout. For jacket foundations and GBFs, transition pieces are installed in port and would not require a separate offshore lift.

Following a lift-off operation very similar to that of a monopile foundation (see Fig. 7(a)), a transition piece will be lifted by an offshore crane and mated onto a pre-installed monopile foundation. Images of transition pieces during and after an installation for two European OWFs are presented in Fig. 20. In the left figure, a transition piece is being mated. This process can be deemed a docking operation. Acero et al. [55] carried out nonstationary and nonlinear time-domain simulations and identified the structural damage of the transition piece's bracket

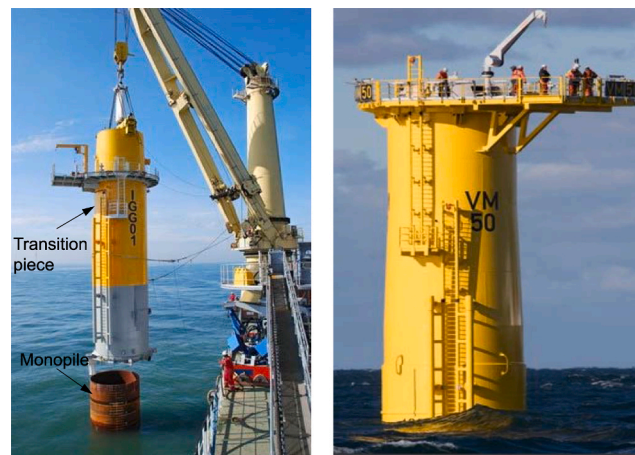


Fig. 20. Installation of transition piece for monopiles left: Anholt OWF [161] right: Veja Mate OWF [162].

Table 8

List of nacelle specifications of offshore wind turbines.

Wind turbine model	Weight (tonnes)	Dimension (m)	Year	Country
IEA 15 MW [117]	821	N/A	2020	USA
GE Haliade-X 12 MW [118]	600	20.6 × 10.4 × 8	N/A	N/A
MHI Vestas V164 10 MW [119]	390	20 × 8 × 8	2022	France
DTU 10 MW [120]	446	21.7 × 8.7 × 8.7 ^a	2013	Denmark
LEANWIND 8 MW [121]	285	20 × 7.5 × 7.5	2016	Ireland
Simens SWT-6-154 6 MW [142]	200	N/A	2013	Germany
Sevion 5 MW [123]	290	N/A	2010	Germany
NREL 5 MW [124]	240	N/A	2009	USA
Simens SWT 3.6 MW [125]	125	N/A	2007	UK
Bonus B76 2 MW [126]	82.5	N/A	2000	Denmark

^a Values derived based on description.

supports as a critical event and large horizontal motions of the transition piece bottom as a restricting event. Such mating operations are also analogous to the floatover operations [139] and active motion compensation systems can be used to improve the success rate [140].

For installation of a single OWT tower, the lifting and mating procedures do not vary much from those of a transition piece. To the author's knowledge, there is little relevant literature. Nevertheless, a few concepts have been proposed to address the installation of a tower and rotor nacelle assembly. Sarkar and Gudmestad [64] presented the idea of a floatable subsea structure fitted with a hull on the top for installing tower assembly. Although the authors claimed that this concept is more environmentally robust than existing methods and can be performed at a significant wave height of 2.5 m, an uncommon telescopic wind turbine tower is assumed which hinders the application potential. In a separate work, Acero et al. [56] proposed a novel procedure for installing the tower assembly onto bottom-fixed foundations. The procedure is based on the inverted pendulum principle and requires a medium-sized heavy lift vessel together with a special upending frame. The feasibility of this concept has only been shown by numerical analysis so far. Beyond the numerical studies, model testing and prototypes are needed to elevate the technology readiness level.

6.4. Nacelle installation

The nacelle is a “box-shaped” structure composed of a main frame and a cover. A nacelle houses the generator, drivetrain (with or without), and monitoring, communications, control and environmental maintenance equipment [141].

Selected weights and dimensions of large OWTs are summarised in

Table 8. Most wind turbine models presented use gearboxes, but the latest IEA 15-MW reference turbine and the GE Haliade-X 12-MW turbine use direct drive generators. The nacelle dimensions of the 10-MW OWTs are quite close. During transportation and installation, it is common to have pre-assembled nacelle and rotor hub units, and a transport frame has been suggested to facilitate the transportation of the heavy units [143]. As the nacelles are much heavier than the blades, the nacelle lifting operations require offshore cranes with greater capacities.

A typical installation involves lifting of the nacelle unit from the transportation vessel and mating with the tower. As shown in Fig. 21(b), the mating phase is similar to that of a blade, and a nacelle is connected to lift wires, a crane hook, and tugger lines. Before mating, the nacelle and the tower must be aligned first, often with the assistance of the installation crew. Among the few works that specifically addressed nacelle installation, Søvik et al. [144] investigated the final mating phase of a nacelle for a monopile-supported 10-MW OWT and found that the nacelle motions are small compared to the tower oscillations, and a tuned mass damper can be used to improve the mating process. Their analysis used constant drag coefficients to calculate the aerodynamic forces on the nacelle. As a nacelle has sharp edges and may experience vortex shedding in the wind, advanced computational methods [145] or experimental methods [146] are needed for accurate representations of the unsteady aerodynamics.

7. Future outlook

The prospects of the OWT installation market look promising as many novel solutions exist. Yet, no consensus has been reached on how a wind turbine should be assembled offshore. Based on the previous

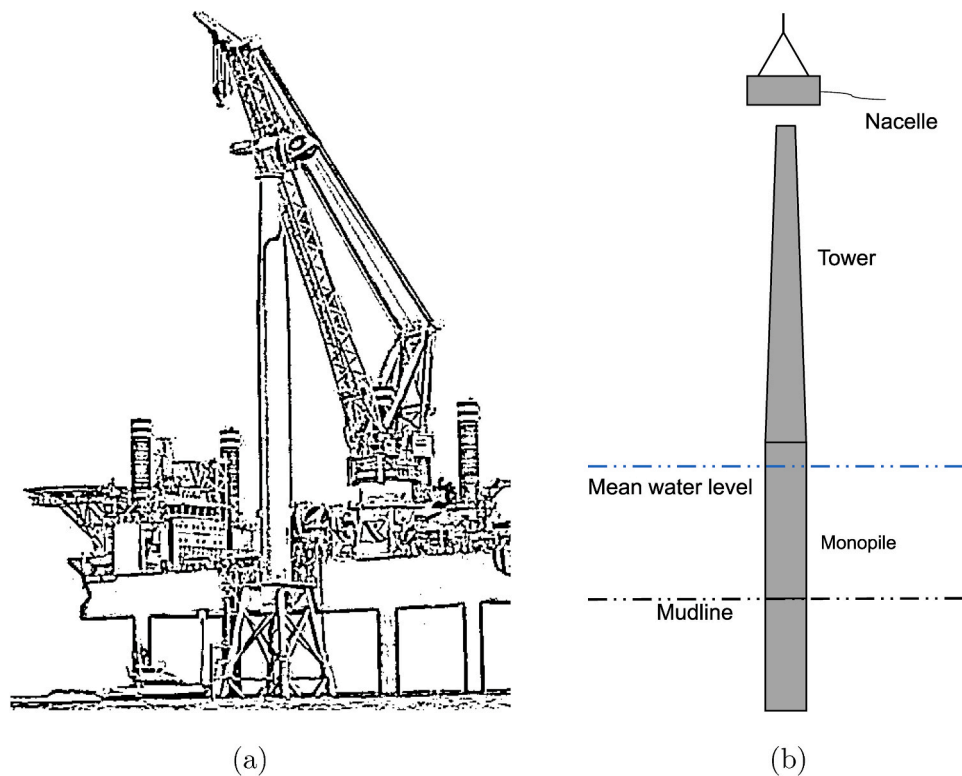


Fig. 21. Illustration of nacelle installation of offshore wind turbines (a) Main components involved in an offshore installation. (b) Mating phase.

sections, the following technical areas related to OWT installation are envisaged to experience rapid advancement in the near future:

- Wind turbine installation vessels. Given the development trend of OWTs, larger wind turbines steadily appear on the market. To keep up with the size growth of OWTs, next-generation installation vessels with large deckspace, heavy lifting capacity, and wide operational window should be built. The market may have a special demand for versatile floating vessels that can handle installations of OWTs with several support structures, e.g., monopile and spar.
- Specialised equipment. Although various lifting and mating equipment can be found, there is a growing need to conduct research and development on passive, semi-active, and active mechatronic devices for the offshore industry which used to be labour-intensive. Advanced automatic control strategies like the centralised control scheme can help achieve the goal of using less expensive equipment. Robotics, remote sensing, and artificial intelligence also have broad application potential for the most challenging activities. Successful standardisation of the off-the-shelf industrial products can lead to marine operations under all seasons, less human intervention, and lowered risks for the offshore wind industry.
- Numerical tools. Conventional aeroelastic programs are most suitable for simulating normal operations of OWTs, whereas general-purpose finite element codes require substantial extension in order to model installation systems. There is still a need to develop multiphysics simulation tools for testing, design, and of installation methods and concepts. A desirable numerical tool for such purposes should be modularised, user-friendly, and preferably open-source.
- Foundation technology. The installation methods and costs are closely related to the OWT technologies and especially the foundation concepts. Hence, the foundation technologies are expected to further evolve with an “installation-friendly” mindset. For new floating

foundations, good towability together with the “drop keel” concept [147] could be viable solutions that reflect the design principles.

8. Concluding remarks

This paper provides a comprehensive review of the installation technologies for offshore wind turbines. The first part of the paper presents the background including installation vessels and equipment, pertinent international standards and guidelines, and available numerical simulation tools. The review follows the order of bottom-fixed foundations, floating foundations, and wind turbine components. Various existing technologies and academic works are critically reviewed, and challenges along with opportunities of each installation method are discussed. Finally, the prospects of four technical areas within this emerging research field are highlighted. The main conclusions are as follows:

- The installation methods for bottom-fixed foundations have reached a degree of maturity. For monopile and jacket foundations with piles, the noise during the pile-driving process poses a major challenge despite the current mitigation measures. For jacket foundations, the installation efficiency is another challenge. Compared to the piles, the suction bucket foundations can streamline the assembly process. For gravity-based foundations, the traditional installation method encounters the challenge of offshore heavy lifts and the “float and submerge” method is at an early phase.
- The installation solutions for floating foundations are still open. The spar floating wind turbines can be regarded as the most technically mature, and a known challenge relates to the cost-effective assembly in open seas. A plethora of interesting concepts have been proposed because of active industrial participation. The semi-submersible floating wind turbines have a relatively converged installation

solution because of their good towability. Tension leg platform floating wind turbines are the least commercialised, and many concepts face installation challenges because of the platform stability issue and the complex anchoring systems, and the installation method is expected to evolve with the foundation technology.

- For installation of offshore wind turbine components, significant interests have been shown in the single-blade installation method. To facilitate the installation in higher wind speeds and with less human intervention, a trend has been observed of utilising specialised lifting, mating and damping devices. Meanwhile, a few novel concepts have also been suggested for offshore installations of the tower assemblies, but most concepts still have low technology readiness levels.
- Numerical modelling and analysis has proved to be a useful means for design and verification of novel installation concepts, and for determination of operational limits at the planning phase of a marine operation. To deal with practical installation tasks, numerical simulations can complement, but not replace model testing, prototyping, or real-time measurements during actual operations.

The scope of this paper is limited. The author does not consider hydraulic wind turbines, vertical-axis wind turbines or airborne wind turbines because these are less mature wind turbine technologies with few installation examples. The paper does not establish any financial models [36] or carry out any economical analysis for the installation methods, either. It is believed that a comparison of the installation costs of the preliminary concepts can lead to biased conclusions [5].

Credit author statement

Zhiyu Jiang: Conceptualization, Methodology, Investigation, Writing, Reviewing and Editing, Resources.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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