Review

Research Progress on Offshore Wind Turbine Foundation Structures and Installation Technologies

Xiangchuan Meng [1], Jijian Lian [1], Haijun Wang [1], Hui Zhao [2] and Run Liu [1,*]

[1] State Key Laboratory of Hydraulic Engineering Intelligent Construction and Operation, Tianjin University, Tianjin 300072, China; xcmeng@tju.edu.cn (X.M.); jjlian@tju.edu.cn (J.L.); bookwhj@163.com (H.W.)

[2] Huadian Heavy Industries Co., Ltd., Beijing 100000, China; 1433097954@qq.com (H.Z.)

* Corresponding author. E-mail: liurun@tju.edu.cn (R.L.)

Received: 15 March 2025; Accepted: 11 April 2025; Available online: 23 April 2025

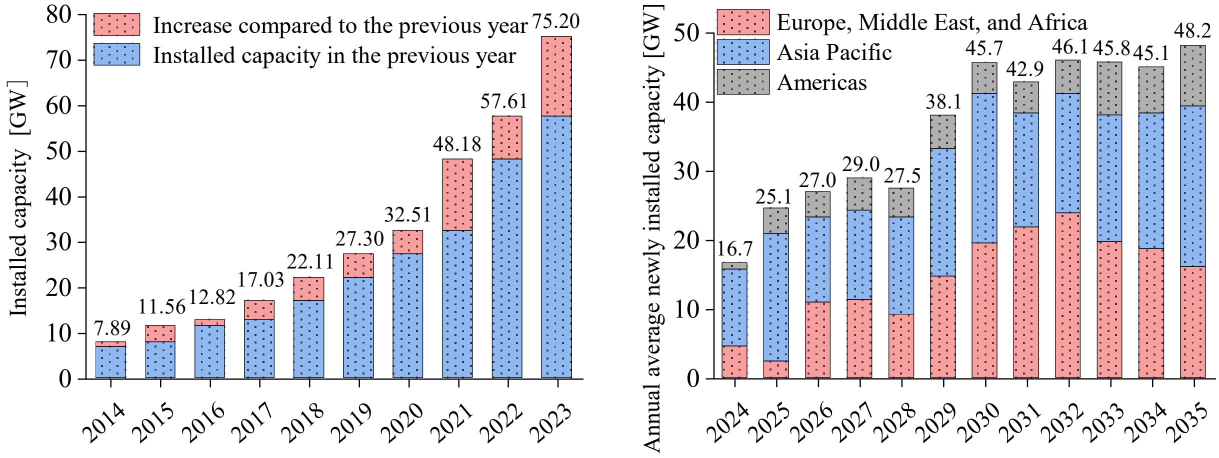
ABSTRACT: Offshore wind power, as an important component of renewable energy, has gradually become one of the key technologies in global energy transition. The development of offshore wind power faces complex technical challenges, including strong wind, waves, currents, foundation bearing capacity, and installation technologies for wind turbines, among other issues. In recent years, with technological advancements, significant breakthroughs have been made in the design of offshore wind power foundation structures, installation technologies, and equipment. This paper provides a comprehensive review of the recent progress in offshore wind power technologies, deeply exploring innovative technologies in areas such as the overall development trends, foundation structures, installation technologies, and equipment of offshore wind power. Special attention is given to the design and safety analysis of wind turbine foundation structures under different foundation conditions, as well as installation technologies for wind power in complex sea conditions and deep-water areas. The paper argues that the applicable depth of fixed foundations is expected to extend beyond 50 m. The jacket foundation remains the mainstream choice for future large-scale wind turbines, with the potential to increase its applicable water depth to 100 m. Furthermore, floating foundations have significant potential for cost reduction and efficiency improvements. Developing entirely new foundation structures and installation technologies suitable for deep-water environments is also a key direction for future development.

Keywords: Offshore wind power; Fixed-bottom foundations; Floating foundations; Installation technologies; Wind power equipment

1. Introduction

Offshore wind power, as a clean and renewable energy source, has become one of the key solutions globally for reducing carbon emissions and addressing climate change. With the increasing global demand for energy and heightened awareness of environmental protection, offshore wind power has gradually become one of the main sources of electricity. Compared to onshore wind power, offshore wind power faces more severe natural and technical challenges, such as extreme weather conditions like typhoons, giant waves, and strong winds, as well as complex marine geological environments. To achieve efficient, low-cost, and stable operation of offshore wind power, it is essential to overcome a series of technical bottlenecks, including foundation structure design, wind turbine installation, and transportation technologies, and the construction of offshore wind power in deep-water areas.

Currently, numerous countries worldwide have invested substantial amounts of funding into the development of offshore wind power. Europe has been a pioneer in the development of offshore wind power, particularly in regions such as the North Sea and the Baltic Sea, where a large number of offshore wind farms have been established. By the end of 2023, the global installed offshore wind capacity reached a total of 75.2 GW. According to BloombergNEF's forecast, by 2035, the global offshore wind capacity is expected to increase to 519 GW, approximately seven times its current level, as shown in Figure 1. In recent years, global offshore wind capacity has continued to grow. China has made significant progress in the offshore wind sector, gradually becoming one of the world's largest offshore wind markets. China's cumulative offshore wind capacity has ranked first globally for four consecutive years, and an increasing number of countries view the offshore wind industry as a key component in achieving their long-term climate goals [1].



(**a**) (**b**)

Figure 1. Annual growth and total installed capacity of the world. (**a**) Current global installed capacity (**b**) Annual growth forecast of wind turbines in all regions of the world.

With continuous technological innovation, offshore wind power costs have gradually decreased, while its reliability and safety have significantly improved. Notably, there have been a series of innovative technologies in areas such as foundation design, wind turbine installation, and transportation, which have greatly enhanced construction efficiency and operational stability. In addition, intelligent technologies have progressively improved offshore wind power's operational management, enabling wind farms to generate electricity more efficiently and connect to the grid. Among various new energy industries, offshore wind power is favored by China and other countries worldwide due to its large resource potential, minimal land use, and low environmental noise pollution.

This paper aims to review the development history of offshore wind power technology, analyze the existing technical bottlenecks and innovations, and explore the future trends and challenges of offshore wind power technology. First, an overview of the current development status of offshore wind power will be presented. Then, a detailed analysis of the design of offshore wind power foundations and technological innovations will be provided. Finally, the installation technologies and equipment for offshore wind power will be discussed, offering insights into the industry's future development.

2. Overall Development of Offshore Wind Power

The overall development of offshore wind power has gone through a process from the experimental stage to commercialization. Over the past few decades, offshore wind power has gradually evolved from its initial stage into a technology capable of large-scale power generation. In the early stages, offshore wind power was primarily concentrated in nearshore areas, with relatively small wind turbine capacities and limited electricity output. However, with continuous technological advancements, the development of offshore wind power has gradually expanded into deeper offshore areas, and the individual capacity of wind turbines has also significantly increased.

2.1. Development Trend of Offshore Wind Power in European

In 1990, Sweden installed the first offshore wind turbine at a depth of 6 m and 350 m offshore for experimental purposes, and the worldwide development of wind power technology entered a fast lane [2]. In 1991, Denmark established and commissioned the world's first offshore wind farm, the Vindeby Wind Farm, located off the northwest coast of Lolland Island. The wind farm is situated at an average distance of 2 km from the shore, with a maximum water depth of 4 m. Its total installed capacity is 5 MW, composed of 11 turbines, each with a capacity of 0.45 MW. The annual power output is sufficient to meet the electricity demands of 2000 to 3000 households [3,4]. The wind farm is located in shallow waters, and due to the sufficient bearing capacity of the seabed, the turbine foundations are primarily made of concrete gravity-based structures. This type of foundation resists horizontal loads through the underlying soil's combined bearing capacity and the concrete base's self-weight. In 2000, megawatt-level wind turbines were introduced offshore, and offshore wind power projects began to demonstrate their commercial viability. In 2002, Denmark completed the world's first large-scale offshore wind farm in the North Sea.

The development of offshore wind power in Europe can be divided into three main stages:

(1) Technology Feasibility and Validation Stage (1991–2001): During this period, the construction scale and turbine capacity were relatively small. Denmark, the Netherlands, the UK, and other countries collectively built nine offshore wind projects, five of which had capacities under 10 MW.
(2) Commercial Development Stage (2002–2011): During this phase, offshore wind construction projects gradually increased in scale, technological innovation accelerated, and government support expanded. The average size of wind farms reached 400 MW, with a cumulative installed capacity exceeding 6 GW. Offshore wind power entered the era of large turbines, with average turbine capacities reaching 4 MW.
(3) Large-Scale and Deep-water Development Stage (2012–Present): During this period, Europe began exploring deep-water and far-offshore wind farms. Hywind Scotland, the world's first floating offshore wind farm, was established. The Hywind Demo wind farm, consisting of five turbines, each with a capacity of 6 MW, commenced operation in 2017 after being tested over several years starting in 2009.

2.2. Development Trend of Offshore Wind Power in China

With the introduction of national wind power policies, offshore wind power development in China can generally be divided into four stages: the early exploration stage (1995–2008), the embryonic demonstration stage (2009–2013), the rapid development stage (2014–2016), and the full acceleration stage (2017–present):

(1) In November 2007, the completion and operation of the trial turbine (1.5 MW) at CNOOC's Suizhong 36-1 drilling platform marked the formal initiation of China's offshore wind power policy. Prior to this, offshore wind power in China was still in the early exploration stage, and there were few national policies specifically related to it.
(2) In January 2009, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) officially launched the planning work for offshore wind power in coastal areas. In June 2010, China's first offshore wind farm, and also the first in Asia—the 100 MW Shanghai Donghai Bridge Offshore Wind Farm—along with the Longyuan Rudong Offshore (Intertidal Zone) Test Wind Farm, began to generate electricity and connect to the grid. During this period, China essentially mastered the engineering construction technology for offshore wind power, accumulating valuable experience for large-scale development in the future. This marked China's entry into the demonstration project construction phase. With the strong promotion of related policies, the embryonic demonstration period saw significant breakthroughs in offshore wind farm construction. By the end of 2013, China had completed a total of 17 offshore wind projects.
(3) The year 2014 is regarded as the "first year of offshore wind power" in China, as the industry experienced explosive growth, entering the rapid development stage. Offshore wind power policies became progressively clearer, with a shift from general wind power policies to more specialized offshore wind power policies. After 2016, offshore wind power in China entered the full acceleration stage. During this time, policy issuance became more frequent and detailed. In November 2016, the National Energy Administration officially issued the "13th Five-Year Plan for Wind Power Development", which proposed that, by the end of 2020, China's offshore wind power grid-connected installed capacity would exceed 5 GW.
(4) During the "13th Five-Year Plan" period, thanks to earlier technological advancements, a complete industrial chain, and a more transparent investment and financing environment, China's offshore wind power development entered a rapid growth phase, and nearshore wind power began to scale up. By June 2020, approximately 11 million kW of offshore wind power projects were under construction, primarily in Guangdong, Jiangsu, Liaoning, and Fujian provinces. In 2020, 3.06 million kW of new offshore wind power capacity was added to the grid. By the end of 2020, the total grid-connected offshore wind power capacity reached approximately 9 million kW. In terms of technological innovation, large-capacity turbines suitable for offshore use showed rapid iteration, with 5 MW turbines reaching mass deployment and the era of 10 MW turbines beginning. During this period, the planned and under-construction Fujian Fuzhou Xinghua Bay prototype test wind farm accurately recorded the evolution of offshore wind power technology. This wind farm serves as a leading domestic research and innovation platform for offshore wind turbines and is China's first large-scale offshore wind power test facility. The "14th Five-Year Plan" period is crucial for achieving the "30·60" targets. During this time, the pace of offshore wind power development in China has significantly accelerated, becoming a new engine for the growth of renewable energy installations.

3. Offshore Wind Power Foundation Structures

Offshore wind power structures are among the most complex "high-rise" structures. Their safe operation is subject to long-term influences and threats from strong typhoons, massive waves, ocean currents (and ice), and the dynamic loads generated by large wind turbines. Overcoming the challenges of strong coupling between wind, wave currents, foundation, structure, and turbine requires advancements in analytical theory and design methods. Developing offshore wind power foundation systems that are adaptable to various types of foundations is fundamental and crucial for achieving safe, efficient, high-quality, and low-cost offshore wind power development. Based on the different support technologies for offshore wind turbines, the foundations of offshore wind turbines can currently be classified into two main categories: fixed-bottom and floating.

3.1. Fixed Bottom Foundation Types

The foundation structure of offshore wind power is critical for ensuring the stable and safe operation of wind turbines. Offshore wind power structures must withstand extreme natural conditions such as strong winds, waves, ocean currents, and ice. Therefore, their design must take into account the complex marine environment, foundation-bearing capacity, and the dynamic loads imposed by wind turbines. In recent years, significant progress has been made in the research and technological development of offshore wind power foundation structures. Fixed-bottom foundations, categorized based on the type of base and supporting structure, are primarily divided into the following five types: Gravity-based, Suction bucket, Monopile, Pile cap, and Jacket, as shown in Figure 2.

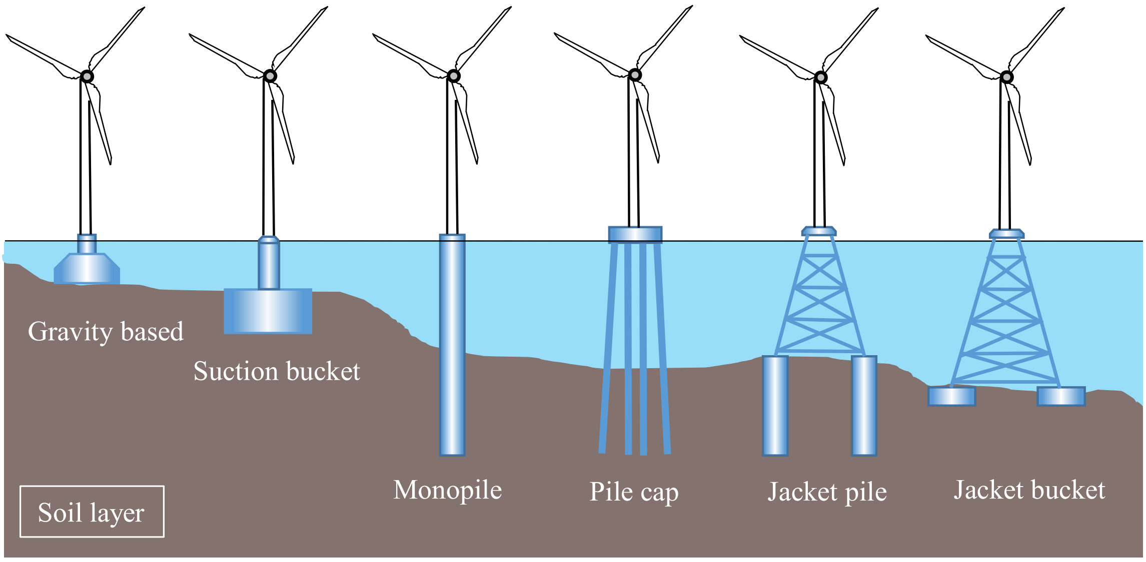


Figure 2. Common types of fixed-bottom offshore wind power foundations.

The gravity-based foundation [5] is the earliest applied offshore wind turbine foundation structure type. It is commonly made of a concrete gravity base structure, which resists the loads from wind turbines and various environmental forces through self-weight. Typically, precast reinforced concrete gravity base structures are used with internal ballast materials such as sand, gravel, slag, or concrete. Due to limitations in construction conditions and economic factors, this type of structure was commonly adopted during the early stages of offshore wind energy development, such as at the world's first offshore wind farm, Vindeby [6]. Gravity-based foundations are generally suitable for shallow waters with depths of up to 10 m. In addition, for shallow water areas where pile foundations are not feasible, gravity-based foundations are recommended, such as at Denmark's Nysted Wind Farm [7].

The bucket foundation [8] has a shape similar to an inverted bucket, with a relatively shallow burial depth and a large diameter. It is typically installed by vacuum-assisted penetration. This foundation type offers advantages such as simple manufacturing, easy transportation, and fast construction. It is generally suitable for water depths ranging from 0 to 25 m. Currently, this type of foundation is used in several offshore wind farms in China, including those in Jiangsu's Qidong, Xiangshui, Dafeng, and Rudong, as well as in Guangdong's Guishan and Yangjiang, Fujian's Changle and Putian, and Dalian's Zhuanghe.

The monopile foundation for offshore wind turbines is similar to that used on land. It is the simplest and most widely applied structure, composed of welded steel pipes made from rolled steel plates. This type of foundation is suitable for non-rocky seabed areas with water depths of up to 30 m. Due to limitations in construction conditions, earlier applications typically used steel pipes with diameters of less than 4 m, such as those used in Denmark's Horns Rev I wind farm [9]. As construction technology has advanced and the capacity of individual wind turbines has increased, monopile foundations are now being developed with larger diameters. In 2012, the Jiangsu Rudong offshore wind farm in China adopted a large-diameter steel monopile with a diameter of 5.2 m, which was the largest steel monopile in Asia at the time [10].

The pile cap foundation [11] is a foundation type and substructure independently developed by China, suitable for soft soil foundations. It consists of several piles and a cap located above the sea level (or above the scour line), forming a pile foundation structure. This type of foundation is commonly used in large bridges and coastal construction projects and is currently being applied to offshore wind turbine foundations. It consists of a base pile at the bottom and a rigid cap at the top. The pile cap foundation has advantages such as high structural stiffness, good collision resistance, ease of construction, and high resistance to overturning loads. It is generally suitable for water depths ranging from 0 to 20 m. Currently, the high-pile cap foundation structure is used in China's Donghai Bridge [12] and the Zhoushan-Putuo offshore wind farm in Zhejiang.

The jacket foundation [13] is commonly used in deep-sea oil drilling platforms. When the water depth exceeds 30 m, the cost of using a monopile foundation increases significantly, and the jacket foundation can be used as an alternative to the monopile foundation. This foundation type is now being promoted for offshore wind turbine structures. The substructure uses a truss structure, which interconnected steel pipes to form a spatial prismatic structure. The leading pipe at the bottom of the foundation is equipped with a sleeve connecting to the pile foundation. The connection between the jacket sleeve and the pile or bucket foundation is achieved through grouting. The foundation consists of 3–4 steel pipe piles or suction buckets, and the jacket foundation is generally suitable for water depths of 20 to 40 m. Currently, this foundation type is used in the UK's Thornton Bank Phase II wind farm, the Thornton Bank Phase II wind farm in Belgium, and the Guishan wind farm in Guangdong, China [14]. The jacket foundation has advantages such as high strength and low installation noise but requires a large amount of steel.

The characteristics of the five types of fixed bottom foundations can be summarized in Table 1, and they have been applied internationally in the wind energy sector, as shown in Figure 3. In China, due to the planning characteristics of the coastline and geographical conditions, most of the completed and under-construction wind projects are concentrated in shallow sea areas, with large-diameter steel pipe piles becoming the dominant foundation type. Flexible piles with diameters between 1.5 m and 2 m mainly appear in the form of high-capacity pile groups. In comparison, semi-rigid or rigid piles larger than 2 m are mainly used as monopile foundations. For example, in June 2010, China's first national-level offshore wind power demonstration project, the Shanghai Donghai Bridge Wind Farm, was completed and successfully connected to the grid [10]. This project used high-capacity steel pipe pile foundations with diameters between 1.5 m and 2.0 m and pile lengths between 60 m and 80 m. From 2015 to the present, the piles used in the Jiangsu Xiangshui Wind Power Project are high-capacity steel pipe piles, with diameters between 1.8 m and 2.0 m and pile lengths between 70 m and 80 m. In June 2010, the construction of the "Rudong 30 MW Tidal Zone Experimental Offshore Wind Farm Project" began, with pile diameters primarily ranging from 5 m to 6.5 m for large-diameter steel pipe piles [10]. In 2011, the "Longyuan Jiangsu Rudong 150 MW Offshore (Tidal Zone) Demonstration Wind Farm" began construction, where the selected steel pipe piles also had diameters ranging from 5 m to 6 m. Between 2014 and 2015, the China General Nuclear Power Group's 150 MW Rudong Offshore Wind Farm successfully used large-diameter steel pipe piles with diameters of 6.6 m and pile lengths of 93 m. By September 2015, 20 ultra-large-diameter monopile foundations had been successfully installed for this project. From 2015 to the present, the China Power Investment Corporation's Binhai North H1#100MW Offshore Wind Project, with water depths ranging from 6 m to 13 m, also used monopile foundations with diameters between 4.6 m and 6.8 m, with average pile lengths of about 67.0 m and embedment depths of about 53 m. Between 2017 and 2019, the Guohua Dongtai Phase IV (H2) 300MW Offshore Wind Project primarily used large-diameter steel pipe piles with diameters ranging from 6 m to 6.5 m and embedment depths of 30 m to 32 m. From 2016 to 2020, Huaneng Wind Power's Phase I and II primarily used large-diameter steel pipe piles with diameters ranging from 6 m to 6.5 m and embedment depths of 30 m to 34 m. In 2024, China Dongfang Electric's largest 26 MW turbine will be supported by a fixed bottom foundation and officially launched in Fuzhou, Fujian. The seawater depth in the above areas is relatively shallow, with seabed foundations consisting of a mixture of silty soils, silty sand, and fine sand, with considerable coverage depth. Using large-diameter steel pipe piles offers significant advantages. Most steel pipe piles have their tips embedded in soil layers with good bearing capacity, which serve as the bearing layer, as they cannot reach bedrock. The tip has free boundary conditions. In the coastal regions of Fujian, due to the shallow burial depth of the bedrock, some piles are embedded in the bedrock at the bottom, where the pile bottom can be considered to have fixed boundary conditions.

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 3. Common types of fixed-bottom offshore wind power foundations. (**a**) Blyth, UK; (**b**) Three gorges Xiangshui, China; (**c**) London Array, UK; (**d**) Donghai Bridge, China; (**e**) Alpha Ventus, Germany.

Table 1. Characteristics of fixed-bottom foundations for offshore wind turbines.

Foundation Type	**Overview**	**Applicable Water Depth**	**Structure**	**Classification**	**Advantages**	**Advantages**
Gravity-based foundation	Earliest application	<10 m	Prefabricated reinforced concrete caisson structure, filled with sand, gravel, slag, or concrete ballast material	Prefabricated concrete caissons and steel structure caissons	Good stability	High foundation requirements; seabed treatment needed during installation; sensitive to seabed scour
Suction bucket foundation	Prefabricated on land, submerged by water suction, and removed by water injection	<25 m	Composed of a cylindrical body and an extending section	Prestressed reinforced concrete structure and steel structure	Low cost, fast construction speed	High precision required during construction
Monopile foundation	Simplest structure, most widely used	<30 m	Composed of welded steel pipes made from rolled steel plates	Monopile with transition section, monopile without transition section	Simple structure, quick construction, relatively low cost	Low stiffness, low natural frequency, significantly affected by seabed scour, high requirements for construction equipment
Pile Cap foundation	Independently developed lower structure and foundation type in China, suitable for soft soil foundations	<20 m	Composed of several piles and a pile cap located above sea level (or above the scoured area)	Conventional pile cap foundation, high pile cap foundation	High structural stiffness, good stability, good collision resistance, mature construction process	Long construction period, unsuitable for deeper waters
Jacket foundation	Based on offshore oil platform technology	20 m~40 m	The lower structure adopts a truss structure, with the bottom connected to piles or bucket foundations	Jacket pile foundation, Jacket bucket foundation	High stiffness, good stability	Complex structural forces, potential fatigue issues, higher construction and maintenance costs

As the capacity and power of offshore wind turbines increase, the foundation’s water immersion depth gradually increases, and the traditional foundations’ anti-tilt ability becomes insufficient. This has led to the emergence of other support structures. Based on different foundation conditions, the wind energy team at Tianjin University proposed the “giant multi-compartment offshore wind turbine bucket foundation structure system”. This structure greatly improves the foundation’s anti-tilt ability through a design with a large diameter and adjustable skirt length, providing strong support for offshore wind turbine installation. The “giant multi-compartment offshore wind turbine bucket foundation structure system” (shown in Figure 4) consists of an upper section as a transition segment connecting the tower bucket, which transfers the wind turbine load to the foundation. The lower part includes a top cover and the compartment skirt structure embedded into the seabed [15]. The foundation diameter ranges from 30 m to 45 m, with skirt lengths between 5 m and 20 m. This “wide and shallow” structure provides significant anti-tilt capacity, which is essential for the “tree-planting” method of installing turbines as a whole [8,16]. In 2010, the single bucket multi-compartment composite bucket foundation prototype for a 2.5 MW wind turbine was successfully installed in the Qidong Sea area of Jiangsu, marking the first application of the multi-compartment bucket in China's wind power industry [16]. In 2017, the Jiangsu Xiangshui offshore wind farm achieved one-step installation of the foundation, tower, and turbine, with a total installation time of only 8 h per turbine, signaling the maturity of the one-step installation technology for the multi-compartment bucket [17,18]. Currently, multi-compartment buckets have been mass-produced, with foundations spread across the South China Sea and Yellow Sea, and the foundation types are gradually developing toward larger sizes and greater diversity.

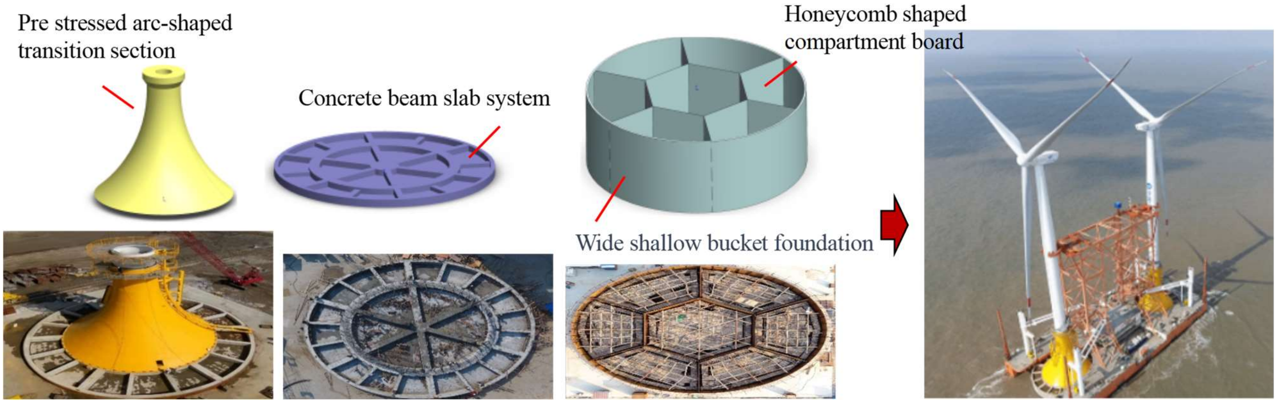


Figure 4. Giant multi-compartment offshore wind turbine monopile foundation type.

3.2. Floating Foundation Types

In recent years, with the frequent occurrence of extreme weather events and the setting of "carbon peak and carbon neutrality" goals, the demand for clean energy has become a major focus. As tidal zones and nearshore areas gradually become saturated, the construction of wind farms moving into deeper seas has become inevitable. The shift from land to sea, from shallow to deep waters, and from fixed bottom foundations to floating platforms will become the development trend of offshore wind power. In shallow sea areas with a water depth of less than 50 m, fixed bottom foundation structures are typically used. However, in deep-sea areas where the water depth exceeds 50 m, the cost of fixed bottom foundations increases sharply, making them difficult to implement [19,20]. Compared with fixed-bottom foundations, floating foundation structures offer advantages such as better operability, ease of removal, and recyclability. As a result, floating structures have become the preferred foundation type for offshore wind farms in deep and remote sea areas.

Unlike nearshore wind turbines, floating wind turbines are not fixed to the seabed with monopiles or jackets but instead float on the sea surface. The supporting system of floating wind turbines mainly consists of the seabed floating foundation structure, mooring system, and anchoring structure [21]. The key design tasks are flotation, mooring, and anchoring. Flotation addresses the issue of the turbine floating on the sea surface. Based on the type of foundation, floating wind power can be divided into four types: Tension Leg Platform (TLP), Barge, Semi-Submersible, and Spar, as shown in Figure 5. Demonstration projects for all four types have been completed or are under construction abroad [22]. Mooring ensures the platform does not tilt under various operating conditions and sea states. The mooring lines are typically of three types: catenary mooring, tension mooring, and mooring line mooring [23–25]. The mooring system primarily comprises winches, cable guides, mooring ropes, and gravity buoyancy attachments. Anchoring addresses the issue of securing the turbine at the design installation site. The seabed anchoring structures typically have four types: drag anchor, pile anchor, suction bucket anchor, and gravity anchor [26–28].

Tension-leg foundations have the advantages of low structural weight, fewer moving parts in the wind turbine, and excellent stability. However, their installation requires a specially designed barge, making it more difficult. Additionally, tension-leg foundations' mooring and anchoring systems are subject to higher loads.

Barge foundations are generally made of concrete and operate similarly to ships. They have a large waterline area, a shallow draft, and excellent stability. The construction, transportation, and installation are convenient. They are typically suitable for installation in waters deeper than 30 m. However, their unique design makes barge-type foundations respond with significant rolling and pitching motion in rough seas, making them more suitable for calm seas.

Semi-submersible foundations are flexible in terms of water depth and can operate in shallow water areas. They have lower transportation costs compared to jacket and tension-leg foundations and can be refurbished in port. This is the most widely used floating foundation type. However, semi-submersible foundations require high structural quality to provide sufficient buoyancy and stability, which increases the foundation cost. Additionally, more welding joints and complex steel structures raise manufacturing difficulties.

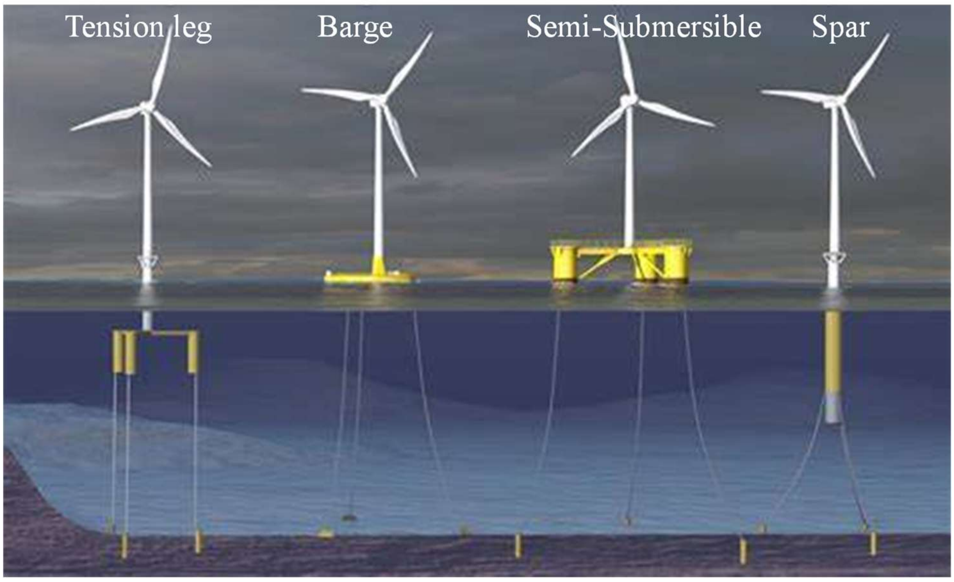


Figure 5. Common floating foundation types for offshore wind turbines.

Spar foundations have advantages such as being lightweight, having a simple structure, good stability, and low cost, making them one of the most mature technologies. However, they have specific water depth requirements (typically used in waters deeper than 100 m). The large draft limits the ability to tow the jacket-type foundation back to port for maintenance, and its large size adds difficulty to installation and transportation.

In 1972, HERONEMUS [29] first proposed the concept of floating offshore wind turbines. Due to the technological and cost limitations at the time, it was not developed for engineering applications. It was not until 2009, when Equinor, a Norwegian oil and gas company, invested in the project, that the world's first floating wind turbine, "Hywind", was completed and put into operation. This turbine had a capacity of 2.3 MW, a rotor diameter of 82.4 m, a hub height of 65 m, and weighed 11,500 t.

Since the commissioning of the first floating wind turbine, floating wind turbines have been developed worldwide, as shown in Table 2. Europe has been at the forefront of developing offshore wind technology. With the gradual increase in single-turbine capacity, the potential for the development of floating offshore wind energy has been proven.

Table 2. Parameters of floating offshore wind power in China [30].

Country	Commissioning Year	Wind Farm Name	Water Depth /m	Single Turbine Capacity/MW	Foundation Type	Turbine Model	Number of Turbines
Norway	2009	Hywind Demo	10	2.3	Spar	2.3MW (SGRE)	1
UK	2017	Hywind Scotland	95~120	6.0	Spar	SWY6.0 MW-154 (SGRE)	5
France	2019	Floatgen	33	2.0	Semi-Submersible	V80-2.0MW (MHI Vestas)	1
Japan	2019	Hibiki Nada	55	3.2	Semi-Submersible	3.2MW(Aerodyn)	1
Portugal	2020	WindFloat AtlanticI	100	8.4	Semi-Submersible	V164-8.4MW (MHI Vestas)	2
UK	2021	Kincardine	60~80	10.0	Semi-Submersible	V164-9.6MW (MHI Vestas)	5
Norway	2022	Hywind Tampen	260~300	8.0	Spar	SWT 8MW-154(SGRE)	11
France	2022	Eollennes Florrantes de Groix	70	9.5	TLP	V164-9.5MW (MHI Vestas)	3
France	2023	Eolmed	60	10.0	Barge	V164-10MW (MHI Vestas)	3
France	2023	Provence Grand Large	100	9.5	TLP	SWT-8.4MW (MHI Vestas)	3
France	2023	EFGL	70~100	10.0	Semi-Submersible	V164-10MW (MHI Vestas)	3

In 2013, China launched the floating wind power project under the National 863 Program. During this period, Xiangdian Wind Energy developed a 3 MW reinforced concrete floating foundation, while Goldwind proposed a 6 MW semi-submersible platform solution. In 2016, as part of the Green Energy demonstration project, Green Energy Company, in collaboration with the Shanghai Institute of Survey and Design, Shanghai Jiao Tong University, and Shanghai Electric, conducted research on two solutions: a 3.6 MW tension leg platform and a 6 MW semi-submersible platform. However, the demonstration project was not realized. The rapid development period of floating technology and patent applications in 2019. The first floating demonstration project at sea in China, the Three Gorges "Leading", was installed in 2021. By 2030, the cumulative installed capacity of global floating offshore wind power will reach 16.5 GW. By 2036, floating offshore wind power will enter the stage of commercialization with new installed capacity reaching GW level.

China's floating offshore wind power technology is largely synchronized with international advancements and is currently in the small-scale demonstration phase, either with single or multiple turbines [29]. As of 2024, China has five floating offshore wind turbines, as shown in Table 3 and Figure 6.

Table 3. Parameters of floating offshore wind power in China.

Project	Commissioning Year	Location (Sea Area)	Water Depth/m	Offshore Distance /km	Single Turbin Capacity /MW	Foundation Type	Steel Consumption per MW/t	Steel Consumption per MW/ (10,000 RMB)
Three Gorges Leading	2021	Yangjiang, Guangdong	30	30	5.5	Semi-Submersible	1.023	5.91
CSSC Fu Yao	2022	Zhanjiang, Guangdong	65	15	6.2	Semi-Submersible	645	5.63
CNOOC Guanlan	2023	Wenchang, Hainan	120	136	7.25	Semi-Submersible	552	4.87
China Energy Gongxiang	2023	Putian, Fujian	35	14	4	Semi-Submersible		
Ming Yang Tiancheng	2024	Yangjiang, Guangdong	45	70	16.6	Semi-Submersible		

Note: CSSC is the abbreviation for China State Shipbuilding Corporation Limited, CNOOC is the abbreviation for China National Offshore Oil Corporation.

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 6. Floating offshore wind power demonstration projects in China. (**a**) Three Gorges Leading; (**b**) CSSC Fu Yao; (**c**) CNOOC Guanlan; (**d**) China Energy Gongxiang; (**e**) Ming Yang Tiancheng.

An analysis of the foundation types for the 43 floating wind turbines surveyed reveals the number of installations for different types of floating foundations, as shown in Figure 7. The characteristics of the floating foundations are presented in Table 4.

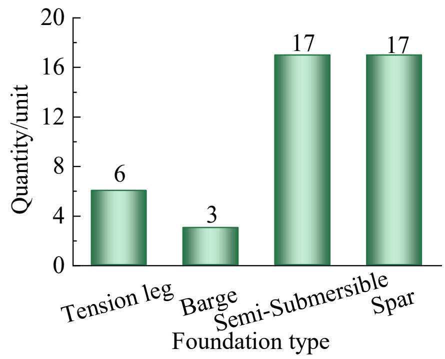


Figure 7. Number of different foundation types.

Table 4. Characteristics of different types of floating foundations.

Foundation Type	Environmental Conditions	Installation	Applicable Water Depth	Suitability for Turbine	Technological Maturity	Potential for Mass Production
Barge	Mild	Simple	Unrestricted	General	High	General
Spar	Harsh	Complex	>100 m	Good	High	General
Semi-submersible	Harsh	Simple	Unrestricted	Good	High	General
TLP	Harsh	Complex	Unrestricted	Good	Low	High

As shown in Figure 7, floating offshore wind power currently mainly relies on Spar and semi-submersible foundations. The Spar is easy to construct but complicated to install, requiring deep waters for stabilization operations and integration of the wind turbine and foundation. It is unsuitable for developing industrial chains, shipping routes, and sea area conditions in China. Due to semi-submersible mature technology, superior hydrodynamic performance, and the fact that the foundation construction, assembly, outfitting, and commissioning, as well as the installation of the wind turbine, can all be completed at the dock before being towed out and deployed, the semi-submersible platform is expected to be the main foundation type for floating wind power. The TLP wind turbine has in-place performance similar to fixed wind turbines, with higher overall power generation. The corresponding mooring line coverage area is smaller, the layout is simpler, and the cables have better fatigue resistance, making arranging the power transmission direction easier. Overall, semi-submersible and TLP wind turbines are China's main development directions for floating wind power.

To better reflect the technological maturity level of offshore wind turbine foundations, the Technology Readiness Level (TRL 1-9) is used to map the maturity of foundation types, as shown in Table 5.

Table 5. Maturity mapping of fixed and floating foundation types.

Maturity Level	Fixed Bottom Foundation Types	Floating Foundation Types
TRL 1 Concept proposed, but no experimental validation yet.		
TRL 2 Preliminary technical concept formed, laboratory validation begins		
TRL 3 Key functions validated in a laboratory environment		
TRL 4 Components or subsystems integrated and validated in a laboratory environment		
TRL 5 Components or subsystems validated in a simulated environment		
TRL 6 System prototype validated in relevant environment	Bucket foundation	TLP, Barge
TRL 7 System prototype validated in an actual environment	Gravity-based foundation, Pile cap foundation	Spar
TRL 8 System completed and tested, ready for commercialization	Jacket foundation	Semi-Submersible
TRL 9 Technology successfully applied in real-world scenarios, commercialization completed	Monopile	

Table 5 shows that the monopile foundation technology is relatively mature and is currently the most widely used foundation in offshore wind power. The other foundations are mainly in the stage between technical development and commercialization. They are insufficient for practical application and require further research for specific environments.

From the perspective of cost, analyzing the foundation types, the high construction cost of floating wind power is the main constraint on its commercialization process. Det Norske Veritas (DNV) used industrial cost estimation to show that floating designs are competitive at water depths exceeding 50 m in terms of the Levelized Cost of Energy (LCOE) compared to fixed-bottom foundations. When project investments exceed 50 million euros, the cost competitiveness index of floating wind increases. However, although floating wind turbines are more competitive than fixed wind turbines at water depths greater than 50 m, the technology is still not commercially competitive compared to other energy sources. Figure 8 shows the cost variation trends of fixed and floating wind turbines [31].

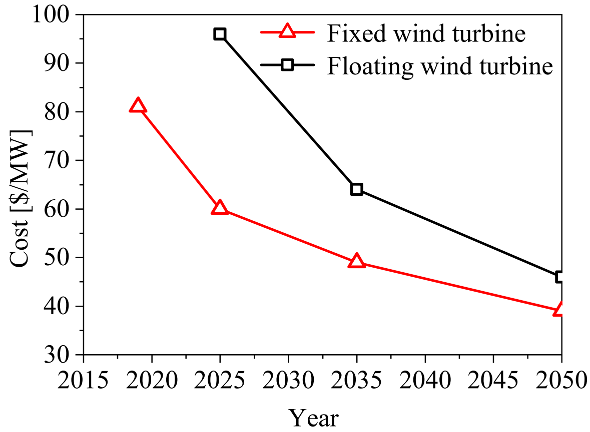


Figure 8. Cost variation of fixed and floating wind turbines.

As shown in Figure 8, with the advancement of technology and resource integration, the construction cost of floating wind turbines is gradually decreasing. However, it will not fall below the cost of fixed-bottom turbines. The cost difference between the two is expected to converge by 2050. The key to reducing the cost of floating wind power is the use of larger turbines, larger wind farms, significant technological development, and the creation of highly cost-competitive supply chains. Among these, the cost of foundations accounts for a significant share of the overall offshore wind farm construction. The cost of fixed-bottom wind turbine foundations accounts for 24%, while the cost of floating wind turbine foundations accounts for 17%. Compared to fixed-bottom foundations, floating wind foundations do not require seabed preparation or piling processes before installation. Therefore, the proportion of foundation costs is relatively smaller for floating wind. However, the anchoring system represents a larger proportion of the floating wind construction cost, offering substantial potential for cost reduction.

4. Offshore Wind Power Installation Technologies and Equipment

Offshore wind construction vessels, as essential carriers for offshore wind farm construction, have become indispensable foundational equipment for marine specialized operations. Early wind power construction equipment was primarily based on the modification of traditional offshore construction vessels, which resulted in low construction efficiency and limited application scenarios. With the development and expansion of the offshore wind industry, more investors have recognized the growth potential of specialized vessels, leading to an increase in the construction of vessels specifically designed for offshore wind farm construction. The development of wind power specialized vessels has rapidly advanced, construction processes have gradually been optimized, and construction efficiency has significantly improved. However, as offshore wind power moves toward deeper waters and the rapid growth of individual turbine capacities, the pace of innovation in vessel performance will limit the rapid development of offshore wind power. The industry is increasingly favoring larger, smarter, and more customized vessels.

The installation technology of offshore wind power is a critical link in ensuring wind turbines' safe and efficient operation. Offshore wind power installation often takes place under complex sea conditions, and traditional installation technologies face significant challenges in deep-water areas or extreme marine conditions. In recent years, with technological advancements, a series of innovative installation techniques and equipment have been proposed and applied. Among these, one of the most important breakthroughs is the introduction of the "tree planting" integrated floating transport and installation technology. This technology involves floating and transporting the bucket foundation, tower, and turbine as a single unit using air-supported flotation transport. The world's first U-type and U-K-type offshore wind turbine monopile foundation-tower-turbine integrated floating transport and installation equipment was developed (Figure 9), which reduces equipment investment by approximately 70% compared to traditional construction equipment. It significantly improves installation efficiency and allows installation in relatively harsh sea conditions. Meanwhile, regarding turbine lifting in complex sea conditions, this technology effectively addresses the challenge of lifting turbines on ultra-soft foundations [8,18,32].

(**a**) (**b**)

Figure 9. Bucket foundation-tower-unit integrated floating transportation and installation technology. (**a**) Traditional dry tow floating transportation; (**b**) New ship-under air-floating op towing technology.

Europe, as one of the earliest regions to enter the offshore wind power industry, has developed specialized wind turbine installation platforms after decades of exploration and research. Other countries have also accelerated the development and manufacturing of jack-up wind turbine installation vessels in an effort to gain control over the offshore wind installation market. As early as the 1950s, a company in the United States developed and manufactured the world's first self-propelled jack-up platform, which was primarily used for offshore drilling and oil extraction services. It was not until 1991, when Denmark built the world's first offshore wind farm, countries worldwide began to develop offshore wind power. By 2019, the countries with the highest cumulative installed offshore wind capacity were the United Kingdom, Germany, China, Denmark, Belgium, and the Netherlands. These countries are also the leaders in the development and construction of wind turbine installation vessels, such as the UK's MPI, Seajacks, Denmark's A2SEA, and the Netherlands' Jack-up Barge companies [33]. As of August 2020, more than 700 vessels had participated in offshore wind power projects globally. Among these, 52 specialized offshore wind installation vessels have both jack-up and self-propulsion capabilities, with 31 vessels having a Safe Working Load (SWL) greater than 800 t. In addition, there are currently 14 self-elevating platforms under construction, with 9 of them having a SWL greater than 800 t [34]. Some of the major third-generation large self-elevating offshore wind power operation platforms abroad are shown in Table 6 and Figure 10.

Table 6. Major third-generation large self-elevating offshore wind farm platforms.

Ship Owner	Ship Name	Technology Type	Main Dimensions /m × m × m	Maximum Operating Water Depth/m	Lifting Capacity /t
JanDeNul	Voltaire	Lifting Capacity	169.3 × 60 × 14.6	80	3000
Shimizu	NG14000X	Lifting Capacity	142 × 50 × 11	65	2500
Seajack	Scylla	Lifting Capacity	139 × 50 × 11	65	1500
GeoSea	Innovation	Self-elevating	147.5 × 42 × 11	50	1500
Swire Pacific Offshore	Pacific Osprey	Self-elevating	155.6 × 49 × 10.4	65	1425
Sea Energy Sea Installer Sea Power	NG9000	Self-elevating	123.55 × 39 × 9	45	1000

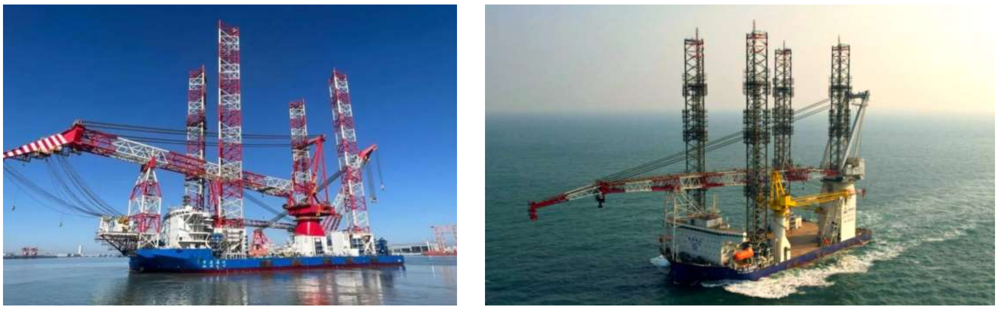
(**a**) (**b**) (**c**) (**d**)

Figure 10. Jack-up offshore installation vessel. (**a**) Voltaire; (**b**) NG14000X; (**c**) Scylla; (**d**) Innovation.

Although China started later in the development and manufacturing of wind turbine installation vessels, it has rapidly advanced with the development of offshore wind power and the support of relevant policies. Chinese shipowners have become an important force in the current offshore wind installation vessel market. According to data, among the top 10 offshore wind installation vessel shipowners globally, six are China shipowners, including Nantong Ocean Water Conservancy Engineering Co., Ltd., Fuzhou, China Communications Haifeng Wind Power Development Co., Ltd., Shanghai Ou Yang Offshore Engineering Group Co., Ltd., and others. Some typical Chinese self-elevating installation vessel models are shown in Table 7 and Figure 11.

Table 7. Typical self-elevating installation vessels in China.

Ship Owner	Ship Name	Technology Type	Main Dimensions /m × m × m	Main Dimensions/m	Lifting Capacity/t
Tianjin Port and Waterway Engineering	Port & Navigation Ping 5	Jack-up	135 × 50 × 11	135	1800
Zhengli Offshore Engineering	Port & Navigation Ping 5	Jack-up	143.8 × 56.6 × 13	136	3500
Hengtong Land	Port & Navigation Ping 5	Jack-up	135 × 50 × 10	135	1600
CRCC Harbour & Channel engineering bureau	CRCC Wind Power 2000	Jack-up	136 × 53 × 10	131	2000
CRCC Harbour & Channel engineering bureau	CRCC Wind Power 01	Jack-up	105 × 42 × 8.5	85	1300
Shanghai Zhenhua Heavy Industries	Longyuan Zhenhua No. 3	Jack-up	100.8 × 43.2 × 8.4	85	2000
Bridge Bureau	Bridge Offshore Wind	Jack-up	138.3 × 53 × 10	131	2000
CCCC Third Harbor Engineering Bureau	Haifeng 1002	Jack-up	133.88 × 50 × 11	130	1800
	Haifeng 1001	Jack-up	133.88 × 50 × 11	120	2500
Hailong Wind Power	Hailong Windcai	Jack-up	128 × 48 × 9.5	130	1200
Jujie Technology	Jujie 1200	Jack-up	110 × 48 × 9	120	1200
	Jujie 1600	Jack-up	123.95 × 48 × 9.5	120	1600
HaiJian New Energy	Haijian 020	Jack-up	123.95 × 48 × 9.5	120	1600
Huaxia Golden Leasing	Huaxia Honghu	Jack-up	106.6 × 44.2 × 8.45	120	1500
Boqiang Offshore Engineering	Boqiang 3060	Jack-up	133 × 53 × 11	120.5	2200
Huaxi Offshore Engineering	Huaxi Wind 01	Jack-up	136 × 50 × 10	125.85	1600
China Merchants Group	China Merchants Chengfeng	Jack-up	125 × 48 × 9.5	120	1600
Three Gorges Corporation	Baihetan	Jack-up	126 × 50 × 10	120	2000
Ouyang Offshore Engineering	Ouyang 005/006	Jack-up	90.2 × 43 × 8	104	800
	Ouyang 007/008	Jack-up	90.2 × 43 × 8	104	800
Baosheng Changfei	Changsheng 1200	Jack-up	105 × 40.8 × 7.5	97.7	1200



(**a**) (**b**)

Figure 11. Jack-up installation vessels in China. (**a**) Longyuan Zhenhua No. 3; (**b**) China Railway Construction Corporation CRCC Wind Power 01.

In 2020 and 2021, with the growth in demand for offshore wind power development, orders for crane vessels were steadily delivered, and the fleet's growth rate rapidly increased. Domestic crane vessels have reached an internationally leading performance level. The lifting capacity of crane vessels used for offshore wind construction has developed from the 1000-ton class to the 12,000-ton class, with lifting heights reaching 130 m. The vessel types have also evolved from catamaran and conventional barge designs to semi-submersible platforms. Notable large crane vessels in China include the Jujie 3600, Chuangli Hao, Guansheng Yihang, and Zhenhua 30, among others. Typical Chinese floating crane vessels are shown in Table 8 and Figure 12.

Table 8. Typical floating crane vessels in China.

Ship Owner	Ship Name	Technology Type	Main Dimensions /m × m × m	Lifting Capacity/t	Lifting Height/m
Zhenhua Offshore	Zhenhua 30	Full Rotation	298 × 58 × 28.8	12,000	123
CNOOC Engineering	Blue Whale	Full Rotation	217 × 50 × 20.4	7500	110
	Blue Frontier	Full Rotation	157.5 × 48 × 12.5	3800	87
Yantai Salvage Bureau	Dehe	Full Rotation	199 × 47.6 × 15	5000	97
Jiangsu Huaxi Village	Huaxi 5000	Full Rotation	178 × 48 × 17	5000	95
Guansheng Shipping	Guansheng One hang	Full Rotation	168.5 × 51.8 × 11.8	2300 × 2	125
Shanghai Salvage Bureau	Chuangli Hao	Full Rotation	198.8 × 46.6 × 14.2	4500	95
	Weili Hao	Full Rotation	141 × 40 × 12.8	3000	85
Baosheng Changfei	Changsheng 5000	Full Rotation	182 × 49 × 15	4000	116.5
Wenzhou Haobo	Haobo 4000	Full Rotation	176 × 52 × 12.5	4000	125
Guangzhou Salvage Bureau	Huatianlong	Full Rotation	174.85 × 48 × 16.5	4000	95
Yuhang Ocean-Land	Yuhang Crane 58	Full Rotation	145 × 44.6 × 10.4	3800	122.8
	Yuhang Crane 3000	Full Rotation	148.4 × 44.6 × 12	3500	103
	Yuhang Crane 32	Full Rotation	150.2 × 42 × 10.8	3500	128
Jujie Technology	Jujie 3600	Full Rotation	171 × 43.8 × 14.2	3600	115
Jiangsu Hengtong	Hengtong 3500	Full Rotation	143 × 55.4 × 10.8	3500	130
Three Gorges Corporation	Wudongde	Full Rotation	181.65 × 46 × 15	3000	130
Three Gorges Corporation	Baihetan	Full Rotation	126 × 50 × 10	2000	160
Nengjian Guanghuo	Nengjian Guanghuo 002	Full Rotation	181.58 × 48 × 13	3000	125
Yongjian Ocean	Yongjian 3000	Full Rotation	171 × 43.8 × 14.2	3000	115

(**a**) (**b**)

Figure 12. Offshore wind power installation platform. (**a**) Wudongde; (**b**) Baihetan.

Based on the above research results, a maturity mapping of offshore wind power equipment is made using the TRL (Technology Readiness Level) maturity scale from Table 5.

Jack-Up Installation Vessel: These are typically at TRL 9, as they are widely used in the offshore wind industry, and the technology is highly mature.

Semi-Submersible Installation Vessel: Likely at TRL 8, as they have been applied in some projects but may still require further testing and validation.

Floating Installation Vessel: These are likely at TRL 6, as they have been validated in laboratory and simulated environments, but they may not yet be mature enough for practical application.

Future development trends in offshore wind power equipment are focused on semi-submersible and floating installation vessels to adapt to deep offshore and large-capacity wind turbine installations.

5. Conclusions and Outlook

Offshore wind power, as a core area of the global low-carbon energy transition, has developed a full-chain technology system, ranging from nearshore fixed bottom foundations to deep-water floating foundations. Over the past three decades, Europe and China have led industry progress through differentiated development paths: Europe, relying on its North Sea projects, was the first to achieve breakthroughs in floating prototype validation and dynamic cable technology; China, through large-scale engineering practices, has driven the capacity of fixed-foundation turbines to 26 MW. The potential for future development is enormous, and with the ongoing global energy transition, offshore wind power will play an increasingly important role in future electricity production.

Technological progress is reflected in the following three aspects:

(1) The diameter of fixed bottom foundations has increased, and structural optimization (e.g., single-pile wall thickness gradient design and multi-tube jacket negative pressure penetration) has continuously broken through the

applicable water depth boundaries. Fixed offshore wind foundations now achieve large-scale applications in water depths of up to 50 m.
(2) Floating wind power has completed the transition from conceptual design to prototype demonstration, with innovative foundation structures gradually allowing it to adapt to waters deeper than 50 m.
(3) The iteration of installation equipment has improved construction efficiency, driving the development of larger, deeper, and more diversified offshore wind turbines.

However, the development of offshore wind power still faces many challenges, such as extreme weather conditions, complex marine geological environments, and high costs. In the future, the development of offshore wind power will increasingly rely on innovative technologies, especially in foundation design, wind turbine installation technologies, and equipment advancements. There are still many technological challenges that need to be overcome. With continuous progress in material science, automation technology, and intelligent technologies, the construction costs of offshore wind power will be expected to decrease. Further, turbine efficiency will improve, and safety and reliability will be effectively ensured. In conclusion, while the development prospects for offshore wind power are vast, continuous innovation and optimization of technologies are required to drive the large-scale and commercial development of offshore wind power, making a greater contribution to achieving global energy transition goals and addressing climate change.

Future technological breakthroughs will focus on four main directions:

(1) With the gradual increase in turbine size, fixed-bottom foundation technologies will undergo iterative development. Under reduced cut-in wind speed conditions, turbines will effectively avoid resonance with the monopile's 1P frequency, thus potentially increasing the applicable water depth for monopile foundations to over 50 m.
(2) Due to the superior cost-effectiveness of fixed bottom foundations and the existing advantages of China's large equipment inventory, monopile and multi-pile jacket foundations will remain the mainstream choice for future large-scale turbines. Previous studies have demonstrated that jacket foundations can be applied at water depths of up to 70 m. The development of new fixed foundation technologies is expected to increase the applicable water depth to 100 m.
(3) The construction costs of floating foundations are significantly higher than those of fixed-bottom foundations, indicating a substantial potential for cost reduction. Lowering construction costs is a key pathway to the commercialization of floating foundations. Research into new structural designs, the adoption of new materials, and improvements in mooring systems will be effective ways to reduce costs and improve efficiency.

Author Contributions

Conceptualization, X.M. and J.L.; Methodology, H.W.; Software, H.Z.; Validation, X.M., H.Z. and R.L.; Formal Analysis, J.L.; Investigation, H.Z.; Resources, R.L.; Data Curation, R.L.; Writing—Original Draft Preparation, X.M.; Writing—Review & Editing, H.W.; Visualization, J.L.; Supervision, R.L.; Project Administration, J.L.; Funding Acquisition, R.L.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data will be made available upon reasonable request.

Funding

This research received no external funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Williams R, Zhao F. *Global Offshore Wind Report 2024*; Global Wind Energy Council: Brussels, Belgium, 2024.
2. Lin Y, Zhang J. Development status and prospect of offshore wind power. *Distrib. Energy* **2023**, *8*, 1–10.
3. Lai Y. Modelling of Lateral Behavior of Large-Diameter Monopoles Supporting Offshore Wind Turbines in Soft Clay. PhD Thesis, Zhejiang University, Hangzhou, China, 2021.
4. Huang H, Hu Z, Dai W, Xin J, Shi W. Development status and trend of offshore wind power. *Energy Energy Conserv.* **2020**, *6*, 51–53.
5. Ye C, Fang X. Gravity foundation design for offshore wind turbines. *Shanxi Archit.* **2016**, *42*, 87–88.
6. Barthelmie RJ, Courtney MS, Højstrup J, Larsen SE. Meteorological aspects of offshore wind energy: Observations from the Vindeby wind farm. *J. Wind. Eng. Ind. Aerodyn.* **1996**, *62*, 191–211.
7. Barthelmie RJ, Jensen LE. Barthelmie—Evaluation of wind farm efficiency and wind turbine wakes at the Nysted offshore wind. *Wind. Energy* **2010**, *13*, 497–586.
8. Meng X, Yang X, Liang C, Lian J, Liu R, Liu Y, et al. Research on the calculation method of penetration resistance of bucket foundation for offshore wind turbines. *Mar. Struct.* **2023**, *91*, 103474.
9. Brandt MJ, Diederichs A, Betke K, Betke K, Nehls G. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Mar. Ecol. Prog. Ser.* **2011**, *421*, 205–216.
10. Yang Q. On the Lateral Bearing Response of Large-Diameter Mono-Piles for Offshore Wind Turbines through Centrifuge Model Test. PhD Thesis, Hohai University, Nanjing, China, 2019.
11. Lin Y, Lu Z, Huang J, Zhou X. Design features and essential mechanical issues of High-Rise cap with multiple pile foundation for offshore wind turbine generators. *J. Ocean. Technol.* **2016**, *35*, 29–36.
12. Li Z, Yang S, Guo Z, Zhou X. Design and construction of steel boxed cofferdams for elevated pile caps at sea. *World Bridges* **2004**, S1, 57-60.
13. Zhao Z, Li D, Zhang F, Qiu Y. Ultimate lateral bearing capacity of tetrapod jacket foundation in clay. *Comput. Geotech.* **2017**, *84*, 164–173.
14. Zhu A, Li S, Zhang M. Jacket foundation design for 200MW offshore demonstration wind farm project of Zhuhai guishan. *Wind. Energy* **2013**, *9*, 94–98.
15. Ma P, Liu R, Lian J, Zhu B. An investigation into the lateral loading response of shallow bucket foundations for offshore wind turbines through centrifuge modeling in sand. *Appl. Ocean. Res.* **2019**, *87*, 192–203.
16. Ding H, Lian J, Li AD, Zhang P. One-Step-Installation of offshore wind turbine on large-scale bucket-top-bearing bucket foundation. *Trans. Tianjin Univ.* **2013**, *19*, 188–194.
17. Wang X, Zhang P, Ding H, Liu R. Experimental study of the accumulative deformation effect on wide-shallow composite bucket foundation for offshore wind turbines. *J. Renew. Sustain. Energy* **2017**, *9*, 1–23.
18. Jia N, Zhang P, Liu Y, Ding H. Bearing capacity of composite bucket foundations for offshore wind turbines in silty sand. *Ocean. Eng.* **2018**, *151*, 1–11.
19. Wang X, Zeng X, Li J, Yang X, Wang H. A review on recent advancements of substructures for offshore wind turbines. *Energy Convers. Manag.* **2018**, *158*, 103–119.
20. Laura CS, Almudena FV, Isabel LG, Luis CC. Methodology to calculate the installation costs of offshore wind farms located in deep waters. *J. Clean. Prod.* **2018**, *170*, 1124–1135.
21. Borisade F, Choisnet T, Cheng PW. Design study and full scale MBS-CFD simulation of the IDEOL floating offshore wind turbine foundation. *J. Phys. Conf. Ser.* **2016**, *753*, 092002.
22. Guo Y, Wang H, Lian J. Review of integrated installation technologies for offshore wind turbines: Current progress and future development trends. *Energy Convers. Manag.* **2022**, *255*, 115319.
23. Hong S, Lee I, Park SH, Lee C, Chun HH, Lim HC. An experimental study of the effect of mooring systems on the dynamics of a SPAR buoy-type floating offshore wind turbine. *Int. J. Nav. Archit. Ocean. Eng.* **2015**, *7*, 559–579.
24. Jeon SH, Cho YU, Seo MW, Cho JR, Jeong W. Dynamic response of floating substructure of spar-type offshore wind turbine with catenary mooring cables. *Ocean. Eng.* **2013**, *72*, 356–364.
25. Kim H, Choung J, Jeon G-Y. Design of Mooring Lines of Floating Offshore Wind Turbine in Jeju Offshore Area. *J. Soc. Nav. Archit. Korea* **2014**, *9*, 1–11.
26. Li J, Bian J, Ma Y, Jiang Y. Impact of Typhoons on Floating Offshore Wind Turbines: A Case Study of Typhoon Mangkhut. *Mar. Sci. Eng.* **2021**, *9*, 1–21.
27. Kanitz M, Hager A, Grabe J, Goniva C. Numerical and experimental analysis of the extraction mechanism of an anchor plate embedded in saturated sand. *Comput. Geotech.* **2019**, *111*, 191–201.
28. Diaz BD, Rasulo M, Aubeny CP, Fontana CM, Arwade SR, Degroot DJ, et al. Multiline anchors for floating offshore wind towers. In Proceedings of the OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, USA, 19–23 September 2016; pp. 1–9.
29. Heronemus WE. Pollution-Free Energy from Offshore Winds. In Proceedings of the 8th Annual Conference and Exposition Marine Technology Society, Washington, DC, USA, 11–13 September 1972; pp. 1–8.

30. Cui S, Qi X. Development status and trend analysis of floating offshore wind power equipment in China. *Straits Sci.* **2024**, *10*, 44–49.
31. Li D, Sun T, Yi C, Gao W. Development of Deep-Sea Floating Wind Power Technology. *Strateg. Study CAE* **2025**, *27*, 1–15.
32. Zhang P, Jia N, Le C, Ding H. Penetrating-levelling tests on bucket foundation with inner compartments for offshore wind turbines in sand. *Mar. Struct.* **2022**, *82*, 103143.
33. Kang S. Technology status and development trend of offshore engineering foundation pile driver. *Ship Eng.* **2021**, *43*, 1–7.
34. Sun Y. "Golden age" of installation ship. *Wind. Energy* **2021**, *2*, 39–43.