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Concrete Support Structures for Offshore Wind Turbines: Current Status, Challenges, and Future Trends

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Abstract: Today's offshore wind turbine support structures market is largely dominated by steel structures, since steel monopiles account for the vast majority of installations in the last decade and new types of multi-leg steel structures have been developed in recent years. However, as wind turbines become bigger, and potential sites for offshore wind farms are located in ever deeper waters and ever further from the shore, the conditions for the design, transport, and installation of support structures are changing. In light of these facts, this paper identifies and categorizes the challenges and future trends related to the use of concrete for support structures of future offshore wind projects. To do so, recent advances and technologies still under development for both bottom-fixed and floating concrete support structures have been reviewed. It was found that these new developments meet the challenges associated with the use of concrete support structures, as they will allow the production costs to be lowered and transport and installation to be facilitated. New technologies for concrete support structures used at medium and great water depths are also being developed and are expected to become more common in future offshore wind installations. Therefore, the new developments identified in this paper show the likelihood of an increase in the use of concrete support structures in future offshore wind farms. These developments also indicate that the complexity of future support structures will increase due to the development of hybrid structures combining steel and concrete. These evolutions call for new knowledge and technical know-how in order to allow reliable structures to be built and risk-free offshore installation to be executed.

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1. Introduction

In the past two decades, offshore wind has emerged as a new source of renewable energy. By the end of 2019, the cumulative capacity installed worldwide had reached 29.1 GW [1] (22.1 GW in Europe [2] and 7.0 GW in Asia, mostly in China [1,3]). The installed offshore wind power capacity is increasing rapidly. This is illustrated in Figure 1, which shows the annual and cumulative offshore wind capacity installed between 2000 and 2019. According to forecasts, this trend is expected to continue in the coming decades, in line with the targets set by many countries to decarbonize their economies. Hence, the cumulative capacity of offshore wind plants in Europe could reach between 45 GW and 100 GW by 2030 [4], and globally as much as 400 GW by 2045 [5]. In line with these forecasts, the European Union strategy for offshore wind recently set the objective of reaching 60 GW by 2030 and 300 GW by 2050, which are estimated to require investments of EUR 800 billion until 2050 and make offshore wind an essential factor or the European Union's

climate neutrality target at the horizon of 2050 [6]. High offshore wind development objectives have also been declared in other regions: e.g., 40 GW in the UK by 2030 [7], 30–45 GW in Japan by 2040 [8], and 86 GW in the US by 2050 [9].

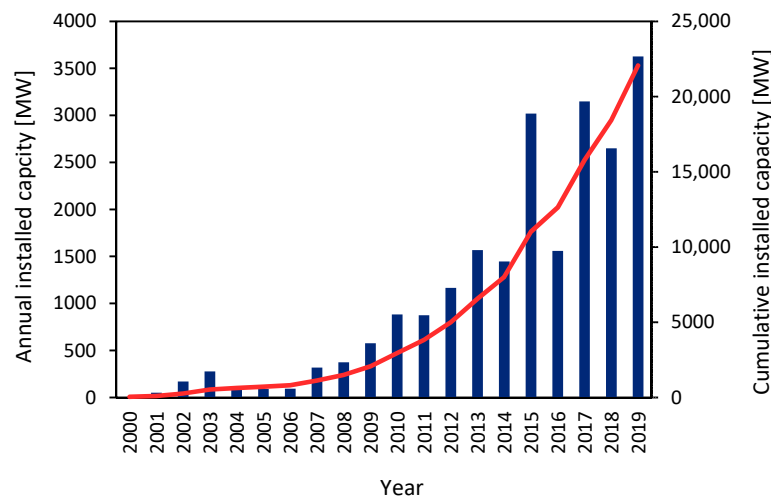


Figure 1. Cumulative and annual installed capacity of European offshore wind farms between 2000 and 2019, elaborated with data from [2,10,11].

The development of offshore wind power has been dependent on government funding [12], due to the higher cost of offshore wind installations compared to that of installations of onshore wind and other sources of electricity. Cost reductions are required for this technology to become more competitive with respect to other energy sources and to contribute to the high targets set by many countries in terms of the reduction of greenhouse gas emissions. Therefore, the choice of support structures and their production, transportation, and installation methods is particularly important. Support structures account for a large part—as much as 20–40%—of the total capital costs of offshore wind farms [13–16]. Indeed, it has been reported that optimization of the support structure presents the largest cost-reduction potential regarding investment costs [17].

Several different types of support structures, consisting of either steel or concrete (reinforced or prestressed) have been used as support structures for offshore wind turbines. Gravity-based foundations made of concrete, similar to those used for onshore wind turbines, were a commonly used solution in the very first offshore wind farms situated in very shallow waters. These foundations have successively been supplanted by steel monopiles, which account for most of the support structures installed over the past two decades.

The rotor diameter and height of the wind turbines increase with their increasing capacity (Figure 2a). In addition, wind farms are nowadays located further from shore and in deeper waters (Figure 2c,d). As the conditions for offshore wind farms change, requirements for support structures also change. Support structures have been scaled up in order to support the larger turbines in these water depths, and monopiles with diameters as large as 8 m are now used [12].

The vast majority of support structures for offshore wind turbines are made of steel, and most of those are monopiles. However, recent studies highlight the potential benefits of using concrete for offshore structures in general [18] and for offshore wind turbines in particular [19–22], since concrete structures have lower production costs, and better durability and fatigue resistance. The cost of concrete structures is also more predictable as steel material prices are very volatile, with price fluctuations that are several times larger those of cement.

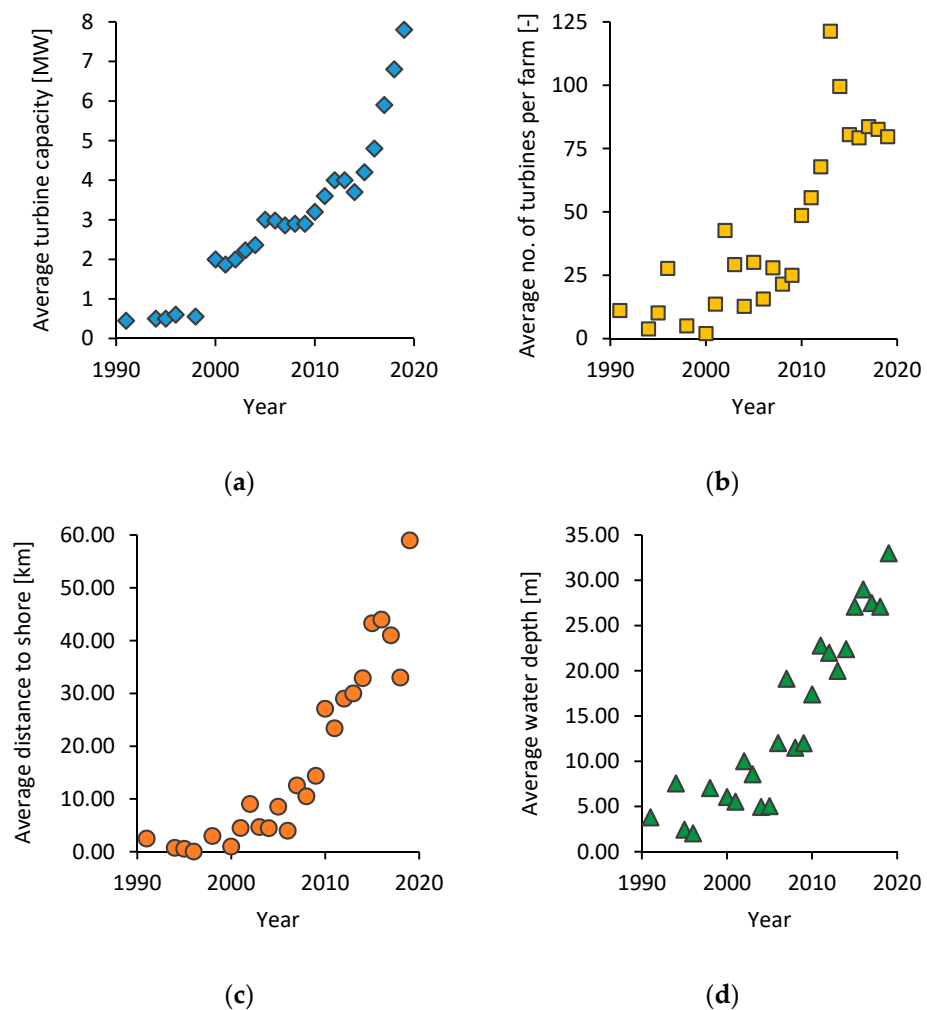


Figure 2. Yearly averages for offshore wind farms installed in Europe between 1991 and 2019: (a) turbine capacity, (b) number of turbines per farm, (c) distance to shore and (d) water depth, elaborated with data from [2,10,11,23–30].

Many new solutions for concrete support structures are currently being developed [31–33]. Consequently, it is necessary to examine these developments with respect to offshore wind turbines, taking into account the conditions under which future offshore wind farms will be constructed and operated. Indeed, as the conditions for offshore wind farms change, it becomes ever more important to monitor alternative options and to identify those that are potentially cheaper and more effective than existing solutions.

The aim of this article is to identify the challenges and future trends related to the use of concrete structures in future offshore wind projects. The paper starts with a brief review of the current status of and challenges for support structures for offshore wind turbines and concrete structures in particular (Section 3). The different types of support structures used in offshore wind farms are described, and a comprehensive list of the worldwide installations of concrete support structures is included. Subsequently, patterns and future trends are identified by scanning new technological developments in the field of concrete structures for offshore wind turbines, and the potential of using concrete substructures in future offshore wind projects is discussed based on the identified challenges and future trends (Section 4).

2. Research Method

Databases of offshore wind farms [3,34] were used to collect the characteristics of offshore wind farms and the solutions used for their support structures. Both operating wind farms and wind farms yet to be built were considered, and those with concrete sub-structures were identified and studied in detail. The review of planned wind farm projects available in these databases was complemented by a review of scientific articles (using the scientific literature databases Scopus and Web of Science and the search engine Google Scholar), technical reports (from international and national wind energy trade associations, e.g., the Global Wind Energy Council (GWEC), WindEurope and the Carbon Trust, and intergovernmental organisations, e.g., IRENA), and industry news and press releases (on the OffshoreWIND news platform [35]). This information permitted the identification of concepts and methods that are being developed. Those at an advanced stage of demonstration or close to commercial implementation, or deemed to represent innovative solutions with a strong potential impact on future offshore wind turbine support structures were selected and studied more thoroughly. The selected concepts were categorized into important developments areas and aspects describing the evolution of the technology were covered with a focus on suitability, experience, structural, buildability, and sustainability aspects.

3. Current Status of and Challenges for Support Structures for Offshore Wind Turbines

The production and installation of support structures represent between 20% and 40% of the total capital costs for a wind farm [13–16]. Therefore, the choice of support structure and of production and installation methods is crucial in an offshore wind farm project. This choice is based on cost estimation and risk analysis considering the multifaceted project's specific conditions such as, offshore site conditions (e.g., water depth, geotechnical and metocean conditions), turbine type and associated loads, market and supply chain, offshore installation process (e.g., installation equipment required, transport distance, weather window), previous experience with the technology.

Some clear trends can be observed in offshore wind farms constructed in the last decade and in projects to be constructed in the next decade. As can be seen in Figure 2, wind farms are becoming bigger, and their locations tend to be further from shore and in deeper waters. The increase in the size of wind farms is a result of the larger number of turbines per farm and, above all, the increase in turbine capacity. Nowadays, turbines between 6 MW and 10 MW are routinely installed, corresponding to rotor diameters of more than 150 m and hub heights of more than 100 m. Turbines of 13 MW to 15 MW, with rotor diameters of about 220 m, have been developed (e.g., the Haliade-X turbine by GE Renewable Energy and the SG 14-222 DD turbine by Siemens Gamesa), and are planned to be installed at a number of offshore wind farms worldwide by 2026 [36–41].

Increasing turbine sizes set higher requirements on support structures, which must ensure the stability and serviceability of the whole wind turbine structures in aggressive marine environments under very high and complex loads generated by wind, waves, currents, tides and sea ice [42,43]. Offshore wind structures have to withstand up to 10^9 load cycles during their relatively short design service life of usually 20 to 25 years [44,45]. Therefore, the loading conditions of offshore wind turbines are different from the ones of oil and gas platforms that are typically designed for more than 100 years and subjected to predominantly vertical loads from the dead weight of the structure and fatigue loads characterised by a small number (in the order of 10^3) of high amplitude cycles from storm events.

3.1. Types of Substructures

3.1.1. Nomenclature and Classification

Figure 3 shows the parts of support structures for offshore wind turbines and the denotations used in this paper, according to the ones defined in [46].

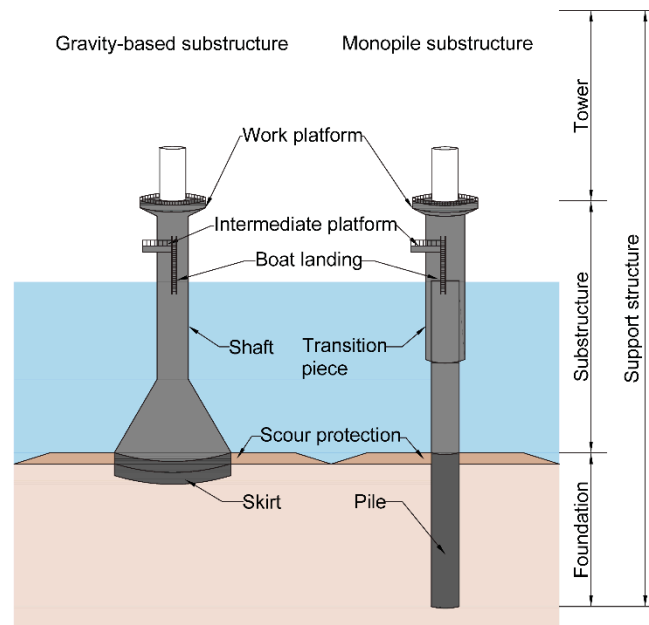


Figure 3. Nomenclature for the components of different types of support structures for offshore wind turbines.

The main types of bottom-fixed substructures and floating substructures for offshore wind turbines are illustrated in Figure 4 and Figure 5, respectively, and are briefly described in Sections 3.1.2–3.1.5.

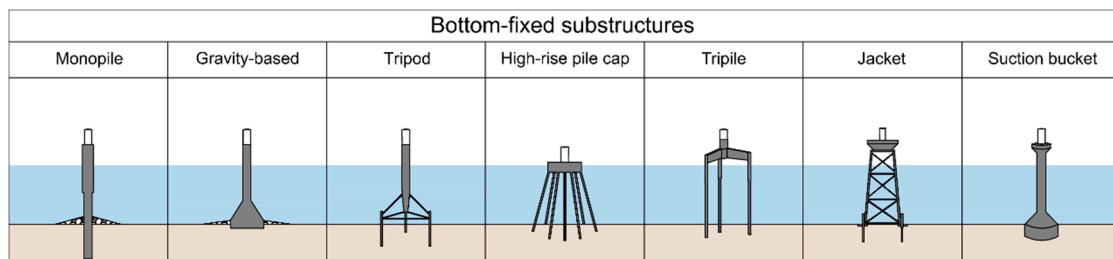


Figure 4. Different types of bottom-fixed substructures for offshore wind turbines.

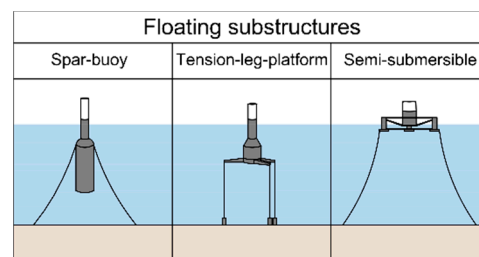


Figure 5. Different types of floating substructures for offshore wind turbines.

In the early days of offshore wind technology, gravity-based concrete substructures were used in several offshore wind farms. It was a natural choice to take a solution proven to work for onshore sites and use it for nearshore sites with shallow water depths, for

example in the first offshore wind farm (“Vindeby”), built in Denmark in 1991 at water depths of less than 4 m [3]. Some years later, when the development of offshore wind installations accelerated and new sites were located in deeper waters, steel rapidly became the most commonly used material, as a large part of the support structures were built using monopiles (see Figure 6). There are also alternative types of steel substructures that have emerged in the last decade, such as jacket, tripod, and tripile substructures.

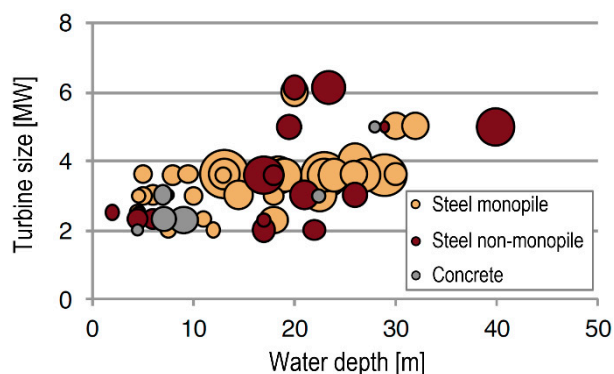


Figure 6. Offshore wind turbine foundation types, water depths, and turbine ratings of commercial-scale projects commissioned globally between 2001 and 2015 (reproduced with permission from [5], © IRENA).

In the past few years, the dominance of monopiles has become more pronounced, as illustrated in Figure 7. Over 85% of the substructures installed in Europe between 2010 and 2019 consist of monopiles. During this time frame, the number of wind turbines quadrupled, increasing from 1134 to 5256, but the number of installed gravity-based substructures only increased very slightly, since only about 30 new gravity-based substructures were built during this period and some substructures of older wind farms were decommissioned.

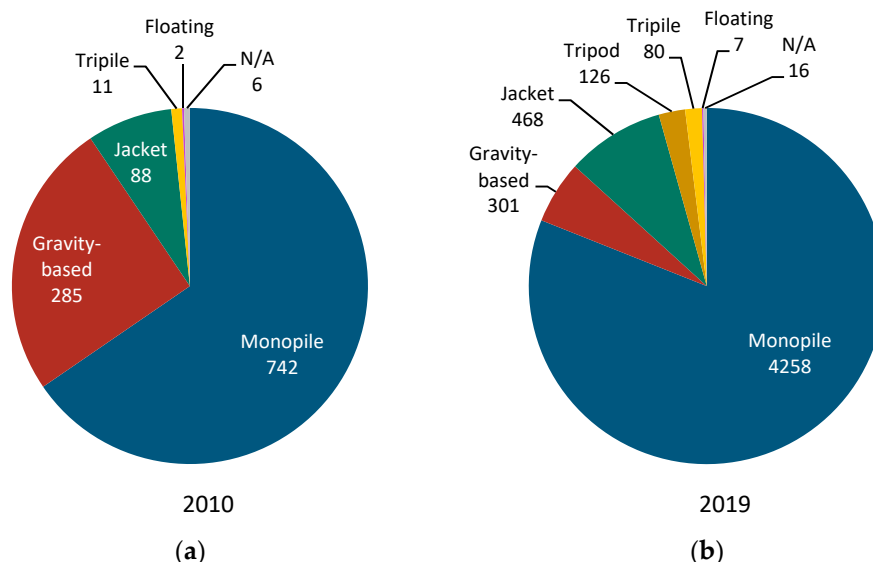


Figure 7. Share of substructure types of wind turbines connected to the grid in Europe: (a) by the end of 2010 and (b) by the end of 2019, elaborated with data from [10,24].

3.1.2. Gravity-Based Substructures

Gravity-based substructures are laid on the seabed, their stability being ensured by dead weight. They are almost exclusively built as massive structures or shell structures,

using reinforced or prestressed concrete. In Europe, they have been installed almost exclusively in the Baltic Sea, mainly because of the complex soil conditions encountered there. They are the most common type of foundation for onshore wind turbines and were therefore chosen for early offshore wind turbines situated in very shallow waters. In 2008, gravity-based substructures were installed in water depths of about 20 m at Thornton Bank (see Figure 8), which constituted the deepest application of this type of substructure for almost a decade, up until the installation of the gravity-based substructures for the Blyth Offshore Demonstration Project in 2017 at water depths of almost 40 m (described in detail in Section 4.2.1).

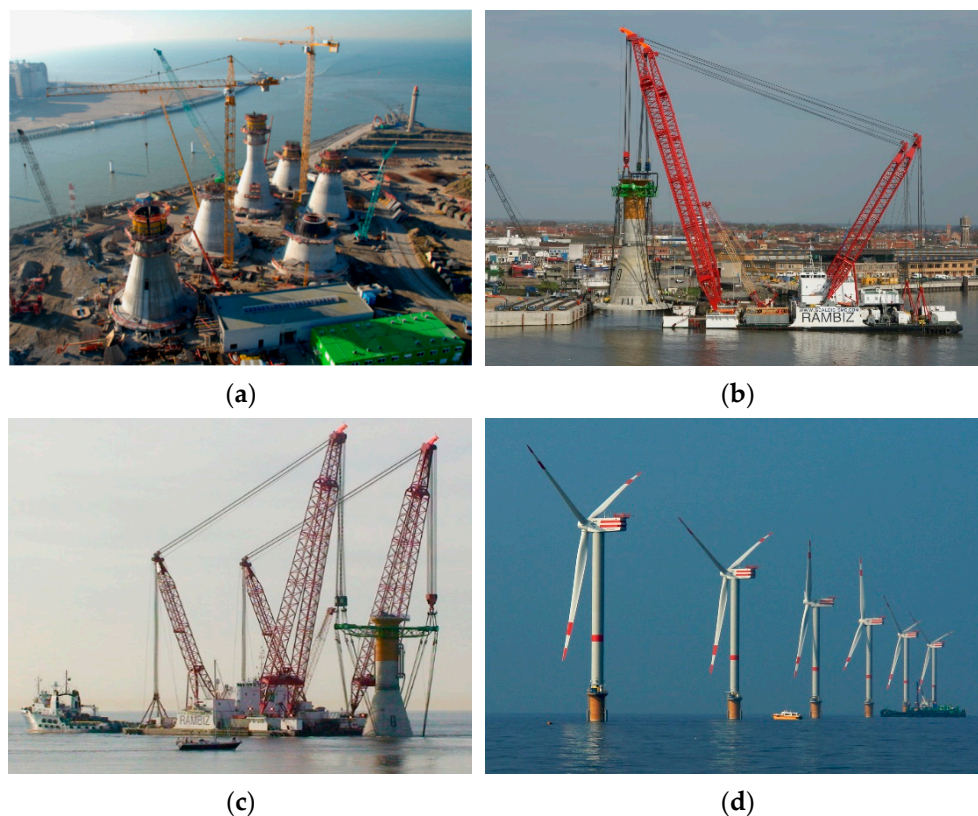


Figure 8. Construction and installation of gravity-based substructures for Thornton Bank wind farm: (a) construction yard by the access channel to the port of Ostend, Belgium, (b) load-out operation, (c) transport and installation and (d) after turbines installation. Credit: C-Power NV, reproduced with permission.

One of the drawbacks of gravity-based substructures is that they require soil preparation prior to installation, as well as extensive scour protection [47]. Due to their great dimensions and weight, they also necessitate a large onshore production and storage area with sufficient bearing capacity, as well as heavy lifting equipment to lift the substructure for transport and installation. Unlike piled foundations, which require hammering, the installation of gravity-based substructures does not generate a great amount of noise and vibration. It is expected that the low production costs of gravity-based structures and the development of new transportation and installation methods will make these substructures suitable even for deeper waters [19,48].

Recently, gravity-based steel substructures have also been used. Ten steel-shell substructures were installed in June 2017 for the Tahkoluoto wind farm in the Gulf of Bothnia, off the Finnish coast, to support 4-MW turbines at water depths of 8–15 m [3].

3.1.3. Monopile Substructures

Monopile substructures rely on a single large-diameter pile anchored over a certain length in the seabed. So far, only steel monopile structures have been built. Today, monopiles represent the most common type of substructure of offshore wind turbines. One reason for their predominance is the straightforward design and relatively simple installation and transportation processes, as several monopiles can be transported by a single vessel. The steel pile is manufactured by joining circular steel sections. Monopiles are driven into the seabed using steam or hydraulic hammers. A transition piece (recall Figure 3), consisting in a steel sleeve with a diameter slightly larger than the one of the pile, is connected to the top of the installed pile by grouting or bolting. The main functions of the transition piece are to facilitate the assembly and allow accurate levelling of the tower through a bolted flange connection, and to carry secondary structures, such as boat landing, access ladders and work platform.

Monopiles require no preparation of the seabed and less scour protection than other types of substructures with larger footprints. Today, monopiles are used even for wind farms with relatively large wind turbines (capacity > 5 MW) located in water depths of more than 30 m. For such wind farms, monopiles of very large diameters are required in order to ensure sufficient stiffness of the structure. The diameter of the monopiles is about 7.5 m in wind farms Gode Wind 1 and 2. Although there is no real technical limit with respect to the diameter for monopiles, such large diameters have led to an exponential increase in material and installation costs [49].

3.1.4. Multi-Leg Substructures on Piled or Suction-Bucket Foundations

In recent years, multi-leg substructures for offshore wind turbines have appeared on the scene. This type of substructure is anchored to the seabed by at least three piles. Due to the footprint of the piles, loads are transferred to the seabed by the compressive and tensile forces in the piles. The following types of multi-leg substructures have been used so far:

- Jacket substructures consist of a truss tower composed of slender tubular steel elements. They usually have three or four legs and each leg is anchored by means of a pile. Similar structures have been used in the oil and gas industry for several decades [50,51].
- Tripod substructures consist of a three-leg truss structure supporting a central tubular steel column. Steel tripods were used at the German wind farms Alpha Ventus, Trianel Windpark Borkum I and Global Tech I, to support 6, 40 and 80 5-MW turbines, respectively, at water depths of 27–41 m and distances of 45–110 km from the coast [52,53].
- Tripile substructures consist of three piles supporting a central transition piece located above sea level. These have been used, for instance, to support 80 5-MW turbines at the German offshore wind farm BARD 1 at water depths of 40 m and a distance of around 100 km from the shore [3].
- High-rise pile caps are usually made of concrete or of a combination of steel and concrete. The cap is supported by a large number of piles. This type of substructure has been used in several wind farms located in China and Japan [3,54].

For all these alternatives, a seabed suitable for the installation of the piles is required. To ensure correct positioning, the piles are typically driven into the seabed with the help of special guiding frames. The substructures, preassembled onshore and transported by vessels to their final positions, are lowered and fitted into these piles. The piles and substructure are then connected by grouting. As an alternative to this pre-piling installation method, post-piling can be used, where the substructure is lowered first and only then are the piles driven through the sleeves of the structure.

Suction-bucket (or suction-caisson) foundations can be used instead of piled foundations to anchor the structure to the seabed. A suction bucket is a large cylindrical structure that is open at the bottom and closed by the bucket lid at the top. During installation, the bucket is lowered to the seabed, and the skirt penetrates slightly into the soil due to its self-weight. Water is then pumped out of the bucket, generating a vacuum below the lid, which causes the skirt to penetrate further into the seabed until the bucket lid comes to rest on it. Thus, the installation process for bucket foundations is quite simple and there is no noise or vibration emissions such as those associated with pile driving [55].

3.1.5. Floating Substructures

Floating substructures for offshore wind turbines are usually classified into three main categories: spar-buoy, semi-submersible or barge, and tension-leg platforms (as illustrated in Figure 5). These correspond to the categories of floating platforms that have been used in the oil and gas industry for several decades [56]. Several floating wind turbine prototypes and demonstration projects have been built in the last 15 years, e.g., the 80-kW Blue H turbine with a steel tension-leg platform, installed in 2007 in the Adriatic Sea 22 km off Puglia, Italy [57]; the 2.3-MW Hywind turbine with a ballast stabilized steel spar-buoy platform installed in 2009, 10 km off Karmøy, Norway, at 200 m water depth [58]; and the 2-MW WindFloat turbine with a steel semi-submersible platform installed in 2011, 6 km off Aguçadoura, Portugal, at 49 m water depth [59]. Following the previous demonstration of the Hywind concept, five 6-MW turbines were commissioned in 2017 at Hywind Pilot Park, offshore Peterhead in Aberdeenshire, Scotland, which constitutes the first floating wind farm [60]. These turbines are supported by a steel spar-buoy substructure, with a draught of about 85 m and a diameter of 14.4 m, at water depths of more than 100 m [61].

3.2. Concrete Substructures Installed Worldwide

The concrete substructures of offshore wind turbines of more than 0.4 MW capacity installed worldwide as of the end of 2018 are listed in Appendix A. Concrete has been used primarily for gravity substructures in Europe, as well as for high-rise pile caps in Asia. Figure 9 illustrates the evolution of gravity-based substructures used in offshore wind farms in Europe over the last 20 years, showing how substructures have become much larger due to increasing turbine sizes and water depths.

3.3. Use of Concrete for Other Parts of Support Structures

Concrete has been used in several wind farms to build the ice cones as well as the work platforms of the support structures (see Figure 10) [62,63]. The main advantage of using concrete for these particularly exposed parts is the increased robustness and reduced amount of required maintenance compared to steel alternatives. Although concrete towers are often used to support onshore wind turbines, their use has been restricted to few nearshore wind farms in the Baltic Sea [64].

It should also be mentioned that concrete grout is commonly used to join transition pieces and monopiles. Concrete has been used in a similar manner at the interface between monopiles installed by drilling and the surrounding rock, for instance in the offshore wind farm Bockstigen [3].

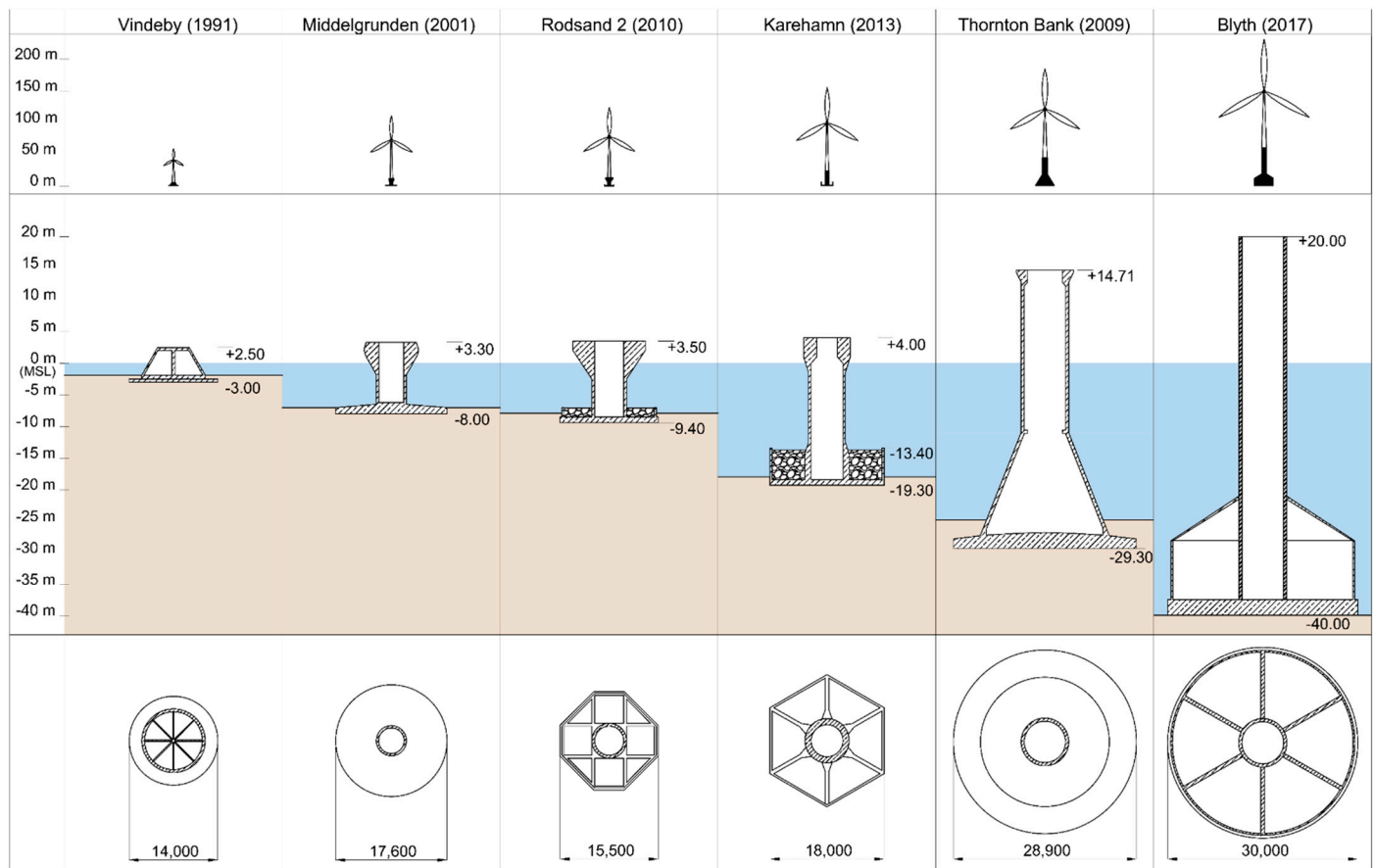


Figure 9. Gravity-based substructures installed in various wind farms.

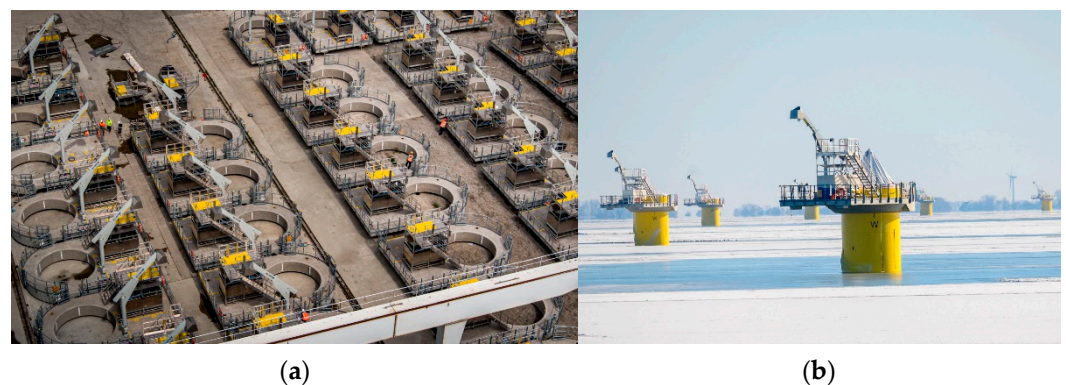


Figure 10. Work platforms for the Fryslan wind farm in the Netherlands: (a) mass production at the construction site, (b) installed work platforms. (a) Credit: Per Aarsleff A/S, reproduced with permission, (b) credit: Windpark Fryslan, reproduced with permission.

3.4. Design and Construction of Offshore Concrete Structures

Concrete structures have been used for many decades in the offshore oil and gas industry and have exhibited high durability [18]. One of the main degradation mechanisms for concrete structures in marine environment, that needs to be taken into account in the design, is the corrosion of the reinforcement steel due to penetration of chloride from sea water in the concrete. This aspect needs to be addressed by (1) adequately designing the protective concrete cover for the reinforcement according to the exposure class (XS2 for the permanently submerged parts and XS3 for tidal, splash and spray zones [65]), the service life of the structure, concrete strength and quality control measures during produc-

tion, and (2) ensuring that crack widths in the concrete due to load and temperature effects, creep and shrinkage remain within acceptable limits. Crack width limitation is particularly important to fulfil tightness requirements for floating structures, making the use of prestressing almost always necessary to avoid through-thickness cracks. The use of supplementary cementitious materials (SCMs), such as fly ash, silica fume and ground granulated blast furnace slag, has the potential to enhance the durability of concrete structures in marine environments due to improved chloride ingress resistance and reduced risk of early-age thermal cracking [66,67]. In addition, using SCMs, when locally available, contributes to reducing the environmental impact of concrete structures, as these materials are less intensive than cement in terms of energy consumption and greenhouse gas emissions.

Concrete structures are large and heavy and require an assembly and lay-down area during the different phases of production: placing of reinforcing steel, erection of formwork, casting and curing of the concrete. In previous projects, substructures have been produced on quay areas (e.g., at the Thornton Bank offshore wind farm, see Figure 8a), on floating barges (e.g., at the Lillgrund and Kårehamn offshore wind farms), and in dry docks (e.g., at the Middelgrunden and Blyth offshore wind farms) [68]. Once the substructure is produced, its installation process consists of some of the following phases: load-out, transport at sea, heavy-lift, ballasting. These need to be coordinated with other scheduled offshore installation activities, e.g., seabed preparation, trenching and installation of electrical cables, mooring and anchoring for floating substructures, and transition piece and turbine installation. Issues previously encountered during the production and installation of gravity-based concrete substructures for offshore wind turbines include, among others, early-age thermal cracking of concrete, damage of substructures during installation at sea, tight tolerances and durability issues at the interface between the substructure and the tower [16,69,70].

4. New Developments and Future Trends for Concrete Support Structures

4.1. List of New Concepts

Various concepts for concrete substructures for offshore wind turbines are currently being developed. An overview of the concepts presented in this study is provided in Table 1. Gravity-based concepts are categorised according to their installation method: whether they are carried (transported by a heavy-lift vessel or on a barge) and lifted during installation or floated during transport and installation, and whether the turbine is installed in a harbour or offshore.

Table 1. List of concrete support structure concepts developed in recent years or under development. The concepts are indicated by their names, when available, and the main technology owners or developers are indicated within parenthesis.

Gravity-Based Bottom-Fixed Substructure			
Gravity-Based Substructure (Carried and Lifted for Installation)		Gravity-Based Substructure (Floated During Installation)	
Substructure Only	Pre-Assembled with Turbine	Substructure Only	Pre-Assembled with Turbine
Fécamp Offshore Wind Farm (Bouygues, Saipem, Boskalis) [71] n/a (COWI) [19] n/a (Skanska) [19] n/a (MT Højgaard) [19] n/a (Bilfinger, Aarslef) [19] n/a (Sprogø) [19] n/a (Arkil A/S) [19]	DTI-50 (Concrete Marine Solutions) [72] GBF (Ramboll, BMT Nigel Gee, Freyssinet) [19,74] CGS (Vici Ventus) [74,77] n/a (Strabag, Boskalis) [19]	SeaTower Cranefree Gravity (SeaTower AS) [19,73] Gravitas (Hochtief, Costain, Arup) [19,75] n/a (BAM, Van Oord) [19,74] n/a (Grontmij, Skanska, Boskalis) [19]	Sea Breeze (Ocean Resource) [19] Elisa (Esteyco Energia) [76] Seawind (Dr. techn.Olav Olsen) [78] GRAVI3 (EDP) [79] MonoBase Wind (idem) [80]
Pile and Suction-Bucket Bottom-Fixed Substructure			
Monopile Substructure	Mono-Suction-Bucket Substructure	Hybrid Monoleg Substructure (Gravity/Piled)	Multi-Leg Substructure
Concrete monopile (Ballast Nedam) [81,82] Hybrid monopile (Ma, Yang) [88]	Composite bucket (Tianjin University, Daoda Company) [83] WindBucket (Leibniz University et al.) [89,90]	Hybrid piled concrete foundation (Kim et al.) [84,85]	HyConCast (Leibniz University) [86,87] Hybrid gravity-jacket (Siemens Gamesa) [3] Gravity Tripod (OWLC) [91,92] Hybrid gravity (-based jacket) type (Electric Power Development Co., Ltd.) [93]
Floating Substructure			
Spar Buoy	Semi-Submersible	Tension-Leg Platform	Anchors for Floating Substructure
Hywind (Equinor) [22] Hybrid spar (Toda Construction) [22,97] SeaTwirl (SeaTwirl AB) [22] WindCrete (UPC-BarcelonaTech) [22] Telwind (Esteyco) [99] DeepWind (DTU et al.) [22] DTI-F (FWT Ltd.) [101]	VoltturnUS (DeepCWind) [22,94] Floatgen (Ideol) [22,31] Semi-Spar (Cobra) [3] OO-Star Wind Floater (Dr.techn.Olav Olsen) [98] Nezzy SCD (Aerodyn Engineering) [22] Sea Flower (Fincantieri) [100] n/a (Naval Energies) [102] SATH (Saitec) [103]	GICON-SOF (GICON) [95] Eco TLP (Mocean, DBD Systems, Ewind) [22] Hybrid TLP (Blue H Engineering) [57]	3D-printed concrete anchors (RCAM Technologies, FWTC, Purdue University) [96]
Tower		Work Platform	
Elisa's telescopic tower (Esteyco Energia) [76] 3D-printed tower (GE, COBOD, LafargeHolcim) [104] 3D-printed tower (RCAM Technologies, University of California) [105] Hybrid steel-concrete towers (various) [64]		Concrete Working Platform (Aarsleff) [62]	

4.2. Concrete Substructures for Medium Water Depths

4.2.1. Gravity-Based Concrete Substructures

Although the last time a gravity-based substructure was used in a commercial wind farm in Europe was in 2013 and the installation at the greatest water depth occurred in 2008, many new concepts of gravity-based concrete substructures for deeper waters are currently being developed (see Figure 11). For instance, the three conceptual substructures Gravitas, Vici Ventus and Seawind are reported to be suitable for water depths of up to 60 m, 30–100 m and 40–90 m, respectively [75,77,78]. Besides, these novel types of gravity-based substructures are being developed to carry the new generation of wind turbines of 6 MW to 10 MW capacities.

New-generation gravity-based substructures are already being used off the coast of Northumberland, in the north-east of England, at the Blyth Offshore Demonstrator Project which constitutes a milestone in the use of this type of substructures in deeper waters. Five concrete gravity-based substructures were built and installed in 2017 at water depths of up to 42 m, in order to support 8-MW turbines; see Figure 12 [3]. In France, 71 concrete gravity-based foundations will be installed at the Fécamp Offshore Wind Farm, whose construction started in June 2020, to support 7-MW turbines at depths between 25 and 30 metres and at distances between 13 and 22 km from shore [71]. These 71 foundations in this last wind farm alone exceed the number of gravity-based foundations installed in Europe since 2010 (see Figure 7).

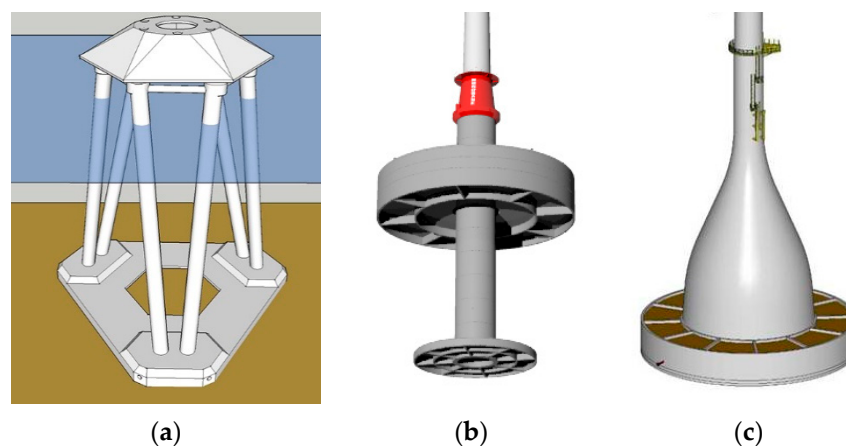


Figure 11. Gravity-based substructure concepts: (a) OWLC Gravity Tripod (Credit: OWLC, reproduced with permission), (b) Monobase Wind (Credit: MonoBase Wind, reproduced with permission), (c) Vici Ventus (Credit: Dr. techn.Olav Olsen, reproduced with permission).



Figure 12. Construction of gravity-based concrete substructures for the Blyth Offshore Demonstrator Project: (a) reinforcement placing, (b,c) construction of the concrete base and steel shaft of the substructures in the dry dock, (d,e) transport of the self-floating substructures using tugboats. Credit: BAM Nuttall, reproduced with permission.

4.2.2. Multi-Leg Concrete Substructures

New concepts for concrete multi-leg substructures, following the example of steel tripod and jacket substructures, are being developed. These types of substructures can be supported by piles or suction buckets which can consist of either steel or concrete. One

such example is HyConCast (Figure 13), which consists of a hybrid substructure with tubular elements, made of high-strength concrete, that are connected by thin-walled joints consisting of ductile cast iron [86]. The advantage of this concept is that the uniaxially loaded braces are made of prestressed concrete, whereas the knots subjected to bending are made of cast iron.

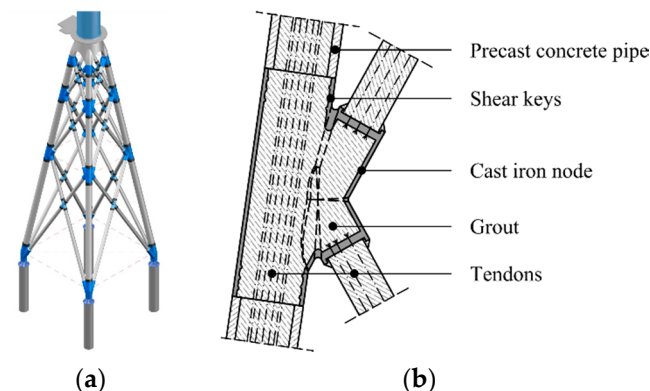


Figure 13. (a) HyConCast substructure with tubular concrete members shown in grey and cast-iron connections shown in blue, (b) connection detail of the HyConCast substructure. Reprinted from [87] with permission from Elsevier, credit (a): SSF Ingenieure.

Concrete truss structures have the advantage of requiring less material and being lighter than concrete shell substructures because they are structurally optimized. However, while they are cheaper to produce than equivalent steel structures, they are also heavier, which can lead to higher installation costs [86]. They require cranes of higher capacities if they are to be lifted, or the addition of external floaters during installation if they are to be floated out, which is an option currently being investigated for the installation of the HyConCast substructure. At the time of writing, these novel concrete multi-leg substructure concepts did not yet go beyond the laboratory validation stages.

An example of another type of hybrid steel-concrete multi-leg support structures is the gravity-jacket substructure conceived by Siemens Gamesa, which boasts a concrete transition piece on top of a steel jacket and is anchored to the seabed by suction buckets or piles. This concept was used for the first time at the demonstration wind farm Nissum Bredning in Denmark, in shallow nearshore waters, with four 7-MW turbines that came into operation in 2008. Figure 14 shows the construction and installation of the Nissum Bredning's substructures. The gravity-jacket substructure appears to be a cost-effective solution compared to traditional steel jacket substructures and the concrete transition piece has been reported to be up to 30% less expensive than a steel one [106].

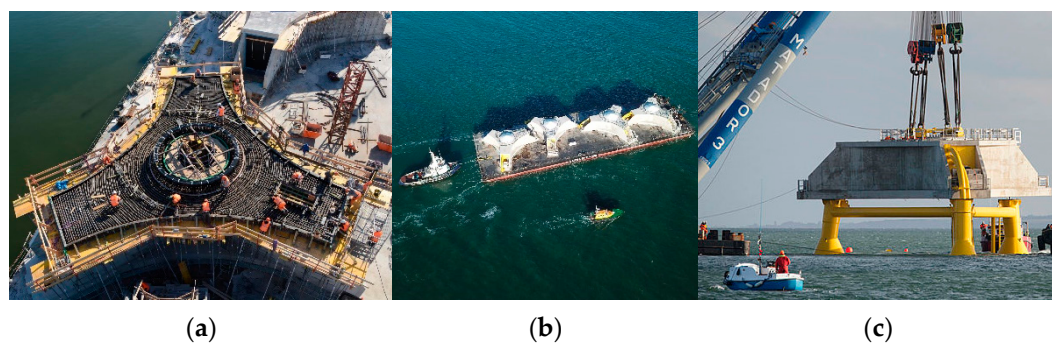


Figure 14. Gravity-jacket substructure: (a) construction, (b) transport and (c) installation. (a,b) Credit: Per Aarsleff A/S, reproduced with permission, (c) credit: Siemens Gamesa, reproduced with permission.

These hybrid solutions combining steel and concrete seek to make the best use of each material. This allows structurally efficient and cost-effective structures to be designed. Opportunities to standardize parts of the structures are also offered, which can lead to further cost reductions. However, the structural design of these types of structures also requires more technical knowledge: for example for the design of the connections between the different parts and for the use of ultra-high-performance concrete (which is often of particular interest for these types of structures).

4.2.3. Concrete-Monopile and Mono-Suction-Bucket Substructures

Concrete monopiles have been developed together with suitable installation methods which reduce environmental disturbance. For instance, the concept developed by Ballast Nedam is composed of prefabricated concrete ring elements assembled using post-tensioning [81]. As for steel monopiles, these concrete monopiles can be floated to the installation site and installed using a heavy-lift installation vessel [82]. The installation is based on vertical drilling, whereby a rotating cutter head is lowered inside the monopile and is expanded as it reaches the bottom of the monopile in order to match the outer diameter of the monopile [81]. Studies have also been conducted to study the feasibility of using hybrid monopiles consisting of double skin steel tubular structure filled with ultra-high performance concrete [88].

Following the development of suction-bucket foundations for offshore wind turbines in the last decade and their first applications in commercial offshore wind farms, such as wind farms Borkum Riffgrund 1 and 2 [3], alternative concrete structures are beginning to emerge. In 2010, a steel–concrete composite bucket was installed at the nearshore test facility in Qidong City, China. The bucket has a diameter of 30 m and a height of 7.2 m and supports a 2.5-MW turbine with a hub height of 80 m [107]; see Figure 15. An arc-shaped transition piece made of prestressed concrete is used to connect the tower to the concrete bucket [83]. Several steel-concrete composite bucket foundations have been installed in China in the last years: at the Xiangshui wind farm in 2017 to support two 3-MW wind turbines and at the Dafeng wind farm in 2019 to support eleven 3.45-MW and two 6.45-MW turbines [108], as shown in Figure 16.

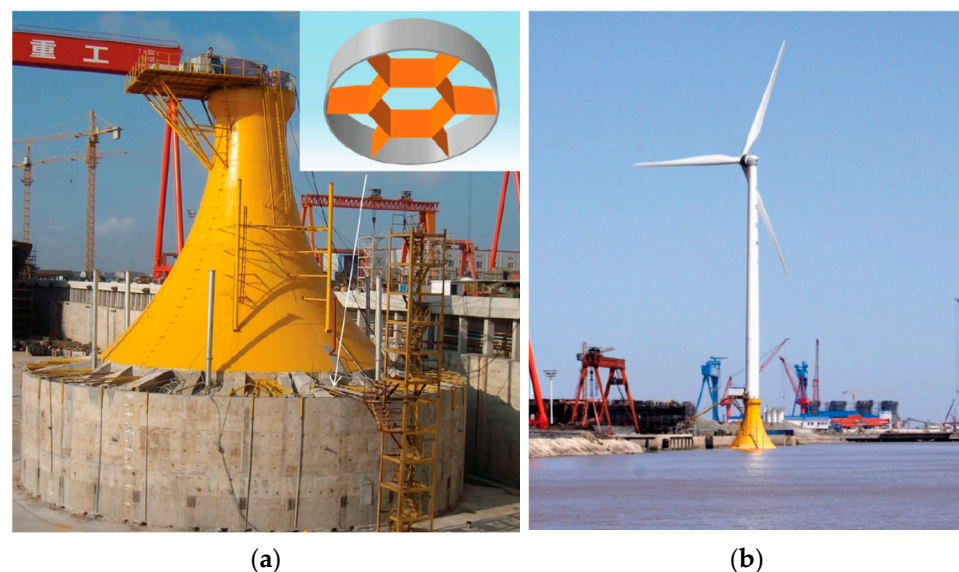


Figure 15. Composite bucket substructure (a) during construction and (b) after installation of the 2.5-MW turbine. Reprinted from [109], with the permission of AIP Publishing.

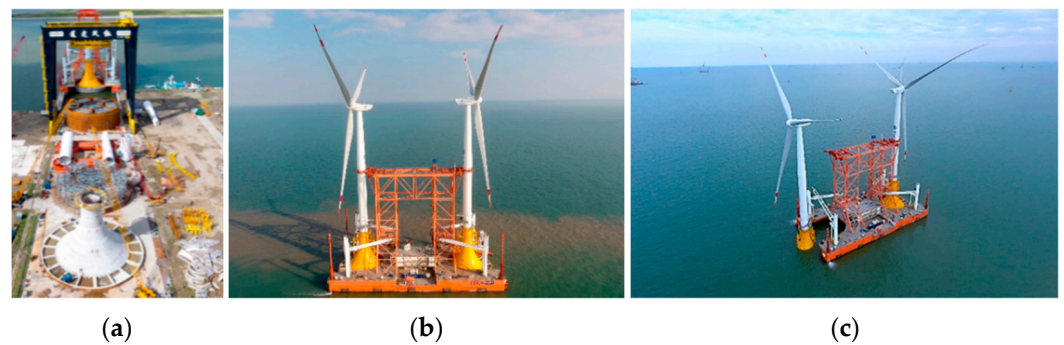


Figure 16. Construction and installation of two wind turbines with composite bucket foundations at the Dafeng wind farm, in the Sanxia Dafeng Sea, Jiangsu, China: (a) onshore prefabrication, (b) transportation and (c) installation using a dedicated vessel. Reproduced from [110], licensed under CC-BY 4.0.

The feasibility of using concrete suction buckets was also studied in the research project WindBucket [90], where this type of foundation was used to support the jacket of 5-MW wind turbines in water depths of 30–40 m. The conclusions drawn from this project highlight that concrete is advantageous for suction-bucket foundations compared to steel, particularly as the risk of the bucket walls buckling during the installation process is eliminated and production times and costs are reduced. In addition to eliminating noise disturbance during installation, suction-bucket foundations also allow for the total removal of the foundation when the wind farm is decommissioned, which is achieved by reversing the installation procedure [109], although more research is needed on this procedure [53].

4.3. Floating Concrete and Hybrid Support Structures for Deep Waters

Several concepts for floating support structures for offshore wind turbines are currently being developed [22,111]. The majority of these concepts use steel as the main building material [112]. Nevertheless, concepts using concrete are being developed for all three types of floating substructures (see Table 1).

A notable development in floating concrete structures is the installation, in 2018, of Ideol's semi-submersible Floatgen prototype with a 2-MW turbine off the French Atlantic coast. A special feature of this concept is that the platform has a central opening which acts as a damping pool to reduce the motion of the structure due to wave loads [31]. This prototype consists of a square frame, made of reinforced and prestressed concrete, with a side length of 36 m and a height of 9.5 m. A lightweight self-compacting concrete was used with a strength class of C55/67 and a density of 2000 kg/m³, obtained by the use of lightweight aggregates [113]. The substructure was built on three barges secured together at a quayside in Saint-Nazaire harbour (see Figure 17a). When the substructure was completed, it was tugged to a dry dock where the barges were filled with water and sunk, and the substructure was floated while the dry dock was filled with water. The transition piece and the 2-MW turbine were then assembled on the substructure at a wharf (Figure 17b). Finally, the floating turbine was transported to its final location by two tugboats (Figure 17c) and moored 22 km off the coast of Le Croisic in France at a water depth of 33 m (Figure 17d). This project was followed by the construction of another prototype off the northwest coast of Kitakyushu, Japan, based on the same concept but this time in steel [114]. A study was conducted to compare concrete and steel designs of Ideol's floater for a 6-MW turbine [115]. It showed that the concrete design was associated with 50% lower material costs than the steel alternative and led to 40–50% lower greenhouse gas (CO₂e) emissions. Both platforms had similar outer dimensions, were equivalent in terms of sea-keeping performance, and although the concrete platform was almost four times heavier than the steel one, both reached approximately the same weight after ballasting [115].



Figure 17. Construction and installation of the Floatgen turbine: (a) construction site for the substructure in Saint-Nazaire harbour, (b) turbine installation, (c) towing of the pre-assemble turbine and substructure, (d) moored and operating floating turbine at the Sem-Rev offshore test site off the French Atlantic coast. (a–c) Credit: IDEOL/ABOVE ALL, reproduced with permission, (d) credit: Valery Joncheray, licensed under CC-BY-SA 4.0.

Nowadays, the first commercial floating wind farms are emerging. Building on the experience of the Hywind Demo and Hywind Pilot Park, described previously in Section 3.1.5, construction started in October 2020 for the Hywind Tampen wind farm which is based on the same floating technology, but this time with spar-buoy substructures made of concrete instead of steel. The choice of concrete is part of a strategy to reduce costs by 40% compared with the previous Hywind Pilot Park project [61]. Hywind Tampen will consist of eleven 8-MW turbines with a rotor diameter of 167 m mounted on concrete spar substructures in the North Sea, 140 km off the Norwegian coast, at water depths ranging between 260 and 300 m. The demonstration of floating concepts for larger wind turbines is on-going. In 2020, the EU founded the Horizon 2020 FLAGSHIP project aiming at the full-scale demonstration of a 10-MW floating offshore wind turbine, based on the OO-Star semi-submersible concrete platform concept. The installation of the platform in the Norwegian North Sea is planned in 2022 according to the project's plan [116].

Like the Hywind and the Floatgen substructures, many of the floating concepts can be built almost interchangeably in concrete or in steel. In particular, concrete appears to be a suitable alternative for other floating concepts primarily developed in steel, e.g., for Naval Energies' semi-submersible concept [117] and for the vertical-axis concept SeaTwirl (based on a spar-buoy that rotates with the turbine) for which concrete could be an option for future developments of the technology for multi-megawatt turbines (M. Rosander, personal communication, 9 December 2020). Besides, hybrid solutions combining concrete

and steel are being developed, such as the hybrid spar floater supporting the 2-MW off-shore wind turbine Haenkaze, off the coast of Kabashima Goto, Nagasaki, in 2013, which consists in a floater with a lower part in concrete and an upper part in steel with a maximum diameter of 7.8 m [118]. This highlights the suitability of both concrete and steel for most types of floating support structures.

4.4. Use of High-Performance Concrete

Until now, concrete substructures have usually been built from normal-strength concrete (mainly concrete of strength class C45/55) in order to satisfy the requirements of building standards. There is now a trend towards the use of higher-strength concrete, as new concepts that are being developed often rely on high-strength concrete (characteristic compressive strength, f_{ck} , higher than 50 MPa [65,119]), e.g., the Floatgen substructure [113], or on ultra-high-performance concrete (f_{ck} higher than 120 MPa [120]), e.g., the Hy-ConCast substructure [86]. Using these types of concrete allows the weight of the substructure to be reduced in order to facilitate transportation or to achieve a reduction in the size of the floating structures. However, there is still a lack of experience regarding the use of ultra-high performance concrete, and the relevant design standards still contain insufficient rules about the application of this material [121].

4.5. Industrialization of the Production Process

Modern wind farms usually contain between 50 and 100 turbines (see Figure 2b), and there are a number of large wind farms in operation and under construction that contain more than 100 turbines, such as London Array (commissioned in 2013) and Hornsea 1 (commissioned in 2019) in the United Kingdom, and Gemini (commissioned in 2017) in the Netherlands with 175, 174 and 150 turbines, respectively, which are all supported by monopiles [3]. This requires the production of a large number of similar support structures, possibly with some minor variations in order to accommodate the different water depths across the area of the wind farm. For floating offshore wind turbines, identical support structures can normally be used for the whole wind farm, as differences in water depths are accommodated by adapting the mooring system. This standardization makes support structures for offshore wind turbines particularly suited to industrial production and assembly (reinforcement, formworks, concreting). All the concepts described in this section presuppose the production of the concrete support structures in a harbour. A factory-like production process can be used, during which the support structures are moved along the production line by a rail system or by self-propelled modular transporters (SPMT). The large concrete elements required for the support structures are achieved either by sequentially casting the whole structure or by assembling standardized precast concrete elements. A large onshore production and assembly area with sufficient bearing capacity, quayside, and draft for load-out operations is required. An efficient solution for reducing the onshore storage space required could be the temporary wet storage of the completed concrete support structures at quayside or at a nearshore location. This is especially interesting for self-installing and floating support structures as described in Section 4.6.

4.6. Efficient Transport and Installation Solutions

4.6.1. Self-Installing Gravity-Based Substructures

In order to avoid the need for expensive heavy-lift vessels, self-buoyant gravity-based concrete substructures are being developed. These structures can be towed to the installation site and then positioned and installed by standard tugboats without the use of costly heavy-lift installation vessels [5]. Once in position, they are submerged by being filled with water and ballast.

This technology was used to install support structures (Seatower concept) for a meteorological mast at the Fécamp site in February 2015 [122] (Figure 18) and wind turbines

at the Blyth Offshore Demonstrator Project in July 2017 [3]. Decommissioning of such structures is also facilitated by using this technology, as it can be performed by reversing the installation process [5,123].

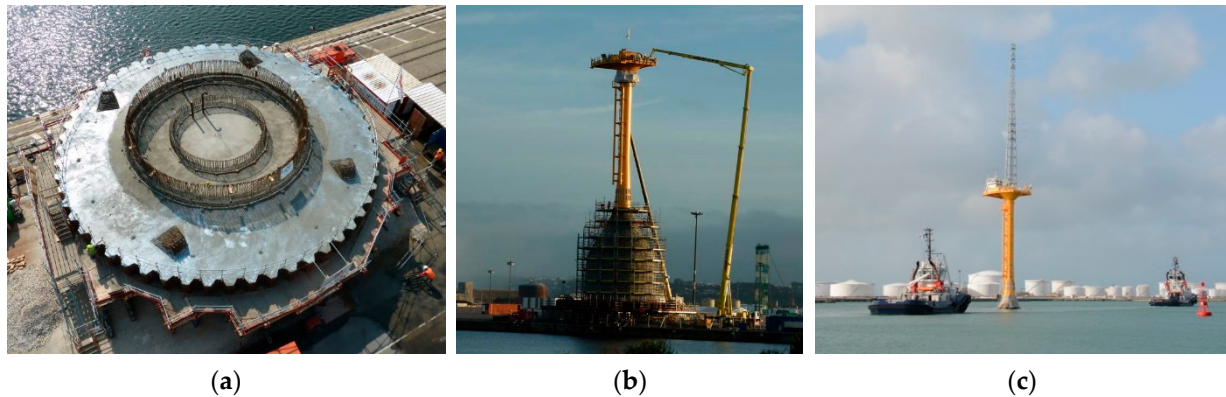


Figure 18. Construction and transport of the Seatower Cranefree substructure for the Fécamp met mast: (a) construction of the substructure in Le Havre harbour, France, (b) installation of the met mast, (c) towing of the self-floating structure. Credit: Seatower/EDF EN, reproduced with permission.

4.6.2. Preassembled Support Structure and Rotor–Nacelle Assembly

Experience from past projects has shown that installation operations are inevitably costlier and riskier when they are carried out offshore [124]. In an effort to address these challenges, many technical concepts are being developed to reduce the number of activities that need to be performed offshore, reduce uncertainties due to weather conditions, and decrease the costs associated with using heavy-lift vessels. Many gravity-based and floating support structures are developed to be installed with the turbine pre-installed in sheltered conditions in the harbour. This was achieved, for instance, for the Floatgen 2-MW turbine previously described (Figure 17). Special vessels for transporting the preassembled support structure and rotor–nacelle assembly are also being developed (recall Figure 16b) [19,48].

A solution for reducing the loads during the transportation and installation stages of fully assembled float-and-sink turbines is being developed by Esteyco through the Elisa and Elican projects [33]. The concept is based on a telescopic concrete tower made up of three sections, which allows to bring down the centre of gravity of the assembled structure during installation, as illustrated in Figure 19. A full-scale prototype was constructed in the harbour of Arinaga, Spain, with a 5-MW turbine. The concrete gravity-based substructure, with a diameter of 32 m and a height of 7 m, was built in a dry dock before being floated out. In order to avoid any offshore installation, all components were preassembled in the harbour, where the low height of the collapsed telescopic tower permitted the mounting of the turbine with conventional cranes (see Figure 20a) [33]. The tower consists of 12 precast concrete panels and reaches an elevation of 115 m when fully extended. The installation was conducted using tugboats and a specially designed platform to increase stability during transport and installation and facilitate maintenance activities (see Figure 20b). The prototype was installed and grid connected in 2018 at the Plocan offshore site, 1.5 km east of the island of Gran Canaria, at a water depth of 30 m [3,76].

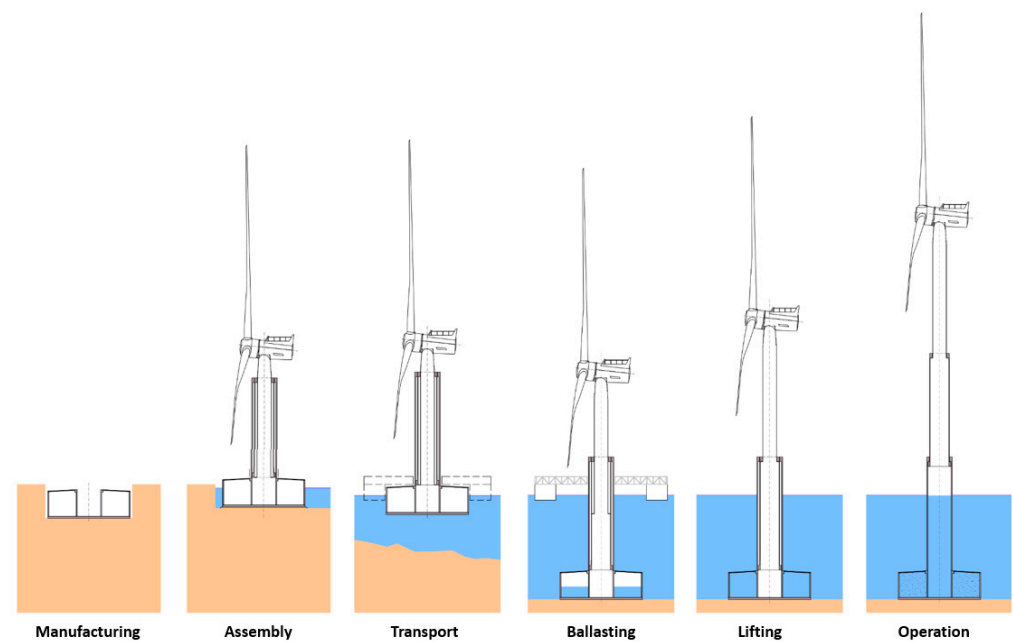


Figure 19. Sketch of the production and installation process of the Elisa support structure concept with a self-installing gravity-based concrete foundation and telescopic concrete tower. Credit: Esteyco, reproduced with permission.

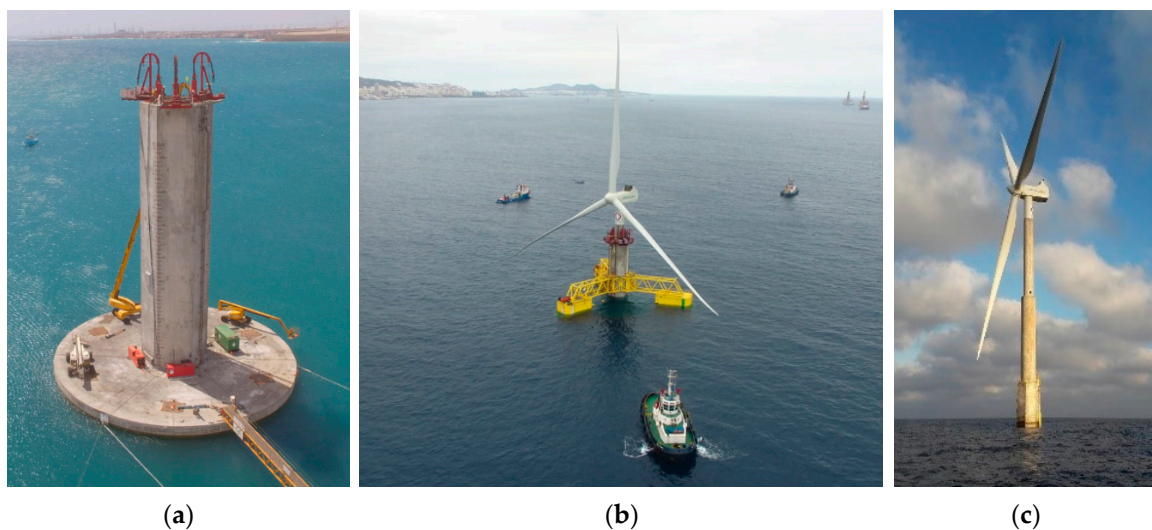


Figure 20. The Elican prototype based on the Elisa support structure: (a) under construction, (b) during transport and (c) during operation at its final location in Gran Canaria, Spain. Credit: Esteyco, reproduced with permission.

4.6.3. Gravity-Based Foundations That Accommodate Soil Irregularities

Soil preparation prior to the installation of gravity-based foundations is time- and labour-intensive. This has been one of the greatest drawbacks of gravity-based foundations compared to piled foundations which often do not require soil preparation. Some technical solutions to tackle this challenge are starting to emerge. Gravity-based foundations with underlying circumferential concrete or steel skirts are being developed. They allow concrete to be injected into the voids between the foundation and the seabed encircled by the skirt. This method was used, for instance, by the Seatower substructure supporting the Fécamp met mast [73]. Following the same principle, Rockmat makes use of flexible cofferdam bags, which allows the concrete to be poured into any crevices or depressions in the seabed underneath the substructure, after accurate levelling of the substructure by hydraulic jacks fixed to its edges has been carried out [125].

It has been reported that soil preparation could be greatly reduced or even avoided, leading to substantial time and cost reductions, if skirted gravity-based foundations are used, as these can accommodate differences in seabed level of up to 1 m [68,125]. However, not much detail about this is available in the literature. More research would be needed to prove the reliability of these solutions and the magnitude of the differences in seabed level that can be accommodated.

4.7. Concrete Towers

The emergence of self-installing concrete substructures combined with the development of towers made of ultra-high performance concrete could turn concrete into a suitable alternative to steel for wind turbine towers. As described previously, the Elisa concept makes use of a telescopic concrete tower consisting of three parts which are only extended after the foundation has been laid, in order to facilitate the transportation process at sea (see Figures 19 and 20) [33]. Hybrid towers consisting of a lower part made of concrete and an upper part made of steel are sometimes used for onshore wind turbines [126] and can be a suitable option for offshore wind turbines as well.

5. Discussion—Potential of Concrete Support Structures for Future Offshore Wind Projects

There is surely no one best support structure for all types of projects, due to the different conditions encountered (water depth, geotechnical conditions, wind turbine type, environmental conditions, etc.) that influence the choice of support structure, its design, and its production and installation methods. Hence, these aspects need to be decided on a case-by-case basis. Offshore wind power generation is a relatively new field where the cost of finances plays an important role in project implementation. Risk management is paramount in order to avoid unforeseen problems that can cause production delays and lead to additional costs. Therefore, the following aspects are also very important for making technological choices concerning support structures: previous experiences with the technology, its supply chain, its production and offshore installation processes (for example, required installation equipment and weather window) and structural design and durability aspects. In the past decade, monopiles have constituted the preferred solution with respect to these aspects, as they represent the most mature solution for offshore wind substructures, have a well-developed supply chain, and tailor-made installation vessels are available. However, as conditions for offshore wind farms change, it is important to be aware of alternative options and to develop those that are potentially cheaper and more effective. This is especially true as the initial implementations of a new technology are inevitably associated with higher costs. This may result in a technological lock-in towards inferior existing solutions that have been developed and optimized over a long period of time. In addition, it is important to take into account social and environmental considerations in the choice of the support structures in order to minimize the negative and enhance the positive associated impacts during the life cycle of the structures (e.g., carbon footprint, impact on marine life, acceptance by local communities).

Based on the challenges, new developments and future trends identified in this study and previously described, the potential of concrete support structures is studied on the basis of a SWOT analysis (Table 2), with focus on the following areas: application range and experience, structural behaviour, durability and design, supply chain, construction and installation, and economic environmental and social.

Table 2. SWOT analysis of the use of concrete support structures for offshore wind turbines.

	Strengths	Weaknesses
Application Range and Experience	Long and extensive experience of offshore concrete structures from oil and gas industry Already long experience from first offshore wind farms with concrete substructures	Mostly used in shallow waters until now Long road for certain concrete solutions identified to be considered proven solutions
Structural Behaviour, Durability and Design	Excellent fatigue and buckling resistance Good durability of concrete in marine environment results in almost maintenance-free support structures over their design life	Structural design not as straightforward as for monopiles Gravity-based support structures have typically required seabed preparation and extensive scour protection
Supply Chain, Construction and Installation	Production of concrete structures is more flexible and versatile and has higher local content than the one of steel structures Supply not dependent on only a few suppliers as for steel	Large production area onshore are required Heavier than equivalent steel structures Relatively complex logistics and quality control for production of concrete structures of this size heavily reinforced Heavy lifting equipment is required if the substructure is to be lifted during transport and installation
Economic, Environmental and Social	Lower carbon footprint than equivalent steel structures Lower production costs and less volatile prices than steel Low operational costs due to low maintenance needs Lower disturbances to marine environment during installation compared to piled foundations (noise and vibrations)	Large installation costs using traditional methods
	Opportunities	Threats
Application Range and Experience	The development of offshore wind capacity will accelerate and is planned to be extensive over the next 30 years Many concrete concepts under development for wind turbines larger than 5 MW and more than 30 m water depth New developments make concrete support structures suitable for all depths and a wide range of soil conditions	Experience of monopiles and natural evolution to XL monopiles Experience of offshore wind practitioners leaning towards steel structures
Structural Behaviour, Durability and Design	Good durability of concrete structures allows for extension of operational life or reuse Potential for design optimization of new concepts	Lack of experience and limitations from design standards regarding the use of ultra-high performance concrete The evolution of wind turbine technology makes design life extension or future reuse of foundations uncertain
Supply Chain, Construction and Installation	More global development of the offshore wind industry is underway Float-out and self-installing concrete solutions reduce costs and time of installation and decommissioning, the dependence on scarce heavy-lift installation vessels, and the risks of offshore construction works Skirted foundations remove/reduce the need for soil preparation Novel solutions aim at facilitating the removal of the structures at the end of their service life	Existing supply chain and installation equipment favour monopiles and steel structures Supply chain needs to scale up to be able to meet the growing demand for offshore wind Local availability of conventional SCMs may be limited
Economic, Environmental and Social	Production of concrete structures benefits the local economy Hybrid steel-concrete solutions lead to cost reductions by making the best use of each material Cost reductions by industrialized mass production Reduction of environmental impact by use of SCMs	Cost reductions from optimization of steel structures

Despite the relatively scarce use of concrete for offshore wind structures in the last 10 years, concepts in concrete are being developed for all types of bottom-fixed and floating support structures, making them suitable for all types of offshore wind conditions. The extensive experience of marine concrete structures from other fields (e.g., oil and gas, bridge, and port infrastructures) is beneficial. Concrete structures exhibit better durability and require fewer protective measures and less maintenance (e.g., surface coating) than steel structures in aggressive marine environments. Concrete structures could certainly be kept in use much longer than the current operational design life of wind energy structure, which is commonly 20–25 years, as demonstrated by the experience of other types of marine concrete structures. However, the extension of the design life of the support structures is unlikely in the near future due to the rapid evolution of the size of wind turbines, which makes the refurbishment or replacement of undersized turbines not economically attractive.

The first wind farms have only in recent years started to reach their end-of-life, and the number of projects being decommissioned will follow the exponential growth in offshore wind installations with a two-decade offset. These decommissioning projects will provide learning opportunities on the removal and recycling of support structures, that should be transferred to future projects. It is also important to keep studying reuse and service-life extension options for the support structures in future projects, as these may become viable alternatives by the end-of-life of the wind farms constructed today or in the coming years.

Concrete support structures are cheaper to produce than their steel counterparts but require a more complex production process and quality control. A prerequisite is to have access to appropriate onshore infrastructures with sufficient space and bearing-capacity to produce these heavy and bulky structures. Labour-intensive and time-consuming construction activities (e.g., reinforcement placing, formworks, concrete casting and curing) are required to produce the structures, but the production can be adapted anywhere and is more beneficial to the local economy than the one of steel structures. The differences between the steel and concrete designs are not very significant when it comes to floating structures, and many concepts can be adapted to be built using either concrete or steel, depending on other factors such as the local market or stakeholder preferences.

Many concepts under development are self-installing and do not require heavy-lifting equipment, which addresses one of the main drawbacks of concrete structures. Other substructures that are not self-buoyant during installation, such as truss structures, may be more optimized in terms of material-consumption for medium water depths applications, but their installation process may constitute a barrier to their adoption if new transport solutions are not developed for these solutions. It is possible that the development of concrete substructures that are floated out during installation with the turbine pre-installed will also facilitate the use of concrete for the towers of the turbines. It can be expected that further cost-reductions will be achieved through further technological development of the new concepts, but above all through mass production and the use of innovative construction methods adapted to this new generation of concrete structures.

6. Summary and Conclusions

So far, two materials have been used for the construction of support structures for offshore wind turbines: concrete and steel. There has been a clear distinction in their scope of application: concrete has been used for gravity-based substructures and steel has been used for monopiles and multi-leg substructures. Increasing turbine sizes and water depths have led to the re-emergence of concrete support structures for current and future wind power plant developments. These developments partly use gravity-based support structures adapted to deeper waters, as well as new types of bottom-fixed or floating support structures made of concrete. It is likely that the current clear distinction between steel and

concrete substructures will become less clear in the future, with the development of floating structures (for most of which both steel and concrete are suitable) and hybrid structures (for which the two materials are used in combination). Furthermore, the distinction between the different types of support structures is also becoming more complex due to the emergence of solutions combining different aspects of the formerly well-differentiated types. The development of these new solutions requires new knowledge, for example to compare alternatives made of different materials, in order to optimize solutions using both materials and to develop efficient and reliable connections between the structural parts.

Since installation costs have so far represented the largest obstacle to using gravity-based concrete substructures, self-installing support substructures based on float-out-and-sink concepts, as well as pre-mounted rotor–nacelle assembly on support structures, appear to be very promising technologies for future concrete support structures. To date, however, only monopiles can be considered to constitute a mature technology for substructures of offshore wind turbines. All the other types of support structures that are currently being implemented and the concepts that are being developed for new wind turbines are still in their early stages of development. Therefore, it will be necessary to keep developing and testing alternatives that could prove suitable in specific conditions.

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Appendix A

Table A1 provides a global summary of concrete substructures for offshore wind turbines in operation before 2018.

Table A1. List of concrete substructures for turbines of more than 0.4 MW capacity used in offshore wind farms worldwide between 1991 and 2018, elaborated with data from [3,34].

Project Name	Commission Date	Country	Location	Type of Structure	Average Distance to Shore [km]	Average Water Depth [m]	Turbines Number × Capacity [MW]
Vindeby	1991	Denmark	The Belts	Gravity	1.8	3	11 × 0.45
Tunø Knob	1995	Denmark	The Belts	Gravity	5.5	5.5	10 × 0.5
Middelgrunden	2001	Denmark	The Sound	Gravity	4.7	4.5	20 × 2
Rønland	2003	Denmark	Limfjorden	Gravity	0.1	1	8 × 2–2.3
Nysted	2003	Denmark	Western Baltic	Gravity	10.8	7.5	72 × 2.3
Setana	2004	Japan	Sea of Japan	High-rise pile cap	0.45	10	2 × 0.66
Breitling	2006	Germany	Breitling	Gravity	0.2	1	1 × 2.5
Lillgrund	2007	Sweden	The Sound	Gravity	8.2	8.5	48 × 2.3
Thornton Bank 1	2009	Belgium	North Sea	Gravity	27.5	20	6 × 5
Hywind	2009	Norway	North Sea	Spar floater	8.5	220	1 × 2.3
Vindpark Vänern	2009	Sweden	Lake Vänern	Rock-anchored ring	6.8	9.5	10 × 3
Sprogø	2009	Denmark	The Belts	Gravity	10	11	7 × 3
Dafeng demo.	2009	China	East China Sea	Gravity	n/a	n/a	1 × 2
Donghai bridge demo.	2010	China	East China Sea	High-rise pile cap	12	8	34 × 3
Longyuan Rudong trial	2010	China	East China Sea	High-rise pile cap	2	0	16 × 1–3
Rødsand 2	2010	Denmark	Western Baltic	Gravity	8.9	9	90 × 2.3
DDHI composite bucket	2010	China	East China Sea	Suction bucket	0	1	1 × 2.5
Avedore Holmes	2011	Denmark	Kattegat	Gravity	0.2	2	3 × 3.6
Wind float prototype	2011	Portugal	Atlantic	Semi-sub. platform	6.7	50	1 × 2
Xiangshui pilot	2011	China	East China Sea	High-rise pile cap	1	1.5	3 × 2–2.5
Zhongmin Fujian test	2012	China	Haitan Strait	High-rise pile cap	0	2.5	1 × 5
Jiangsu Rudong	2012	China	East China Sea	High-rise pile cap	5.2	2	1 × 5
Choshi demo.	2013	Japan	Pacific Ocean	Gravity	2.25	10	1 × 2.4
Kitakyushu demo.	2013	Japan	Sea of Japan	Hybrid gravity–jacket	2.4	14	1 × 2
Kårehamn	2013	Sweden	Central Baltic	Gravity	5.4	13	16 × 3
Xiangshui pilot GW	2013	China	East China Sea	High-rise pile cap	0.4	0	2 × 3
Sakata North Port	2014	Japan	Sea of Japan	High-rise pile cap	0	4	5 × 2
Rudong demo. 1	2014	China	East China Sea	Gravity	1.9	2	10 × 2
Donghai bridge 2	2015	China	East China Sea	High-rise pile cap	8.3	9	28 × 3.6
Longyuan Putian Nanri	2015	China	Taiwan Strait	High-rise pile cap	6.8	6	4 × 4
Sakiyama	2016	Japan	Goto–Nada Sea	Hybrid spar floater	4.1	n/a	1 × 2
Rudong demo. 2	2016	China	East China Sea	Gravity	4.4	3.5	20 × 2.5
Fujian Putian City Flat Bay	2016	China	Taiwan Strait	High-rise pile cap	9.1	10	10 × 5
Xiangshui demo.	2016	China	East China Sea	High-rise pile cap	9.1	7	37 × 4
Shanghai Lingang demo.	2016	China	East China Sea	High-rise pile cap	16.7	4.5	28 × 3.6
Huaneng Rudong (S+N)	2017	China	East China Sea	High-rise pile cap	25.0	9.0	20 × 4–5
Blyth Offshore demo.	2018	UK	North Sea	Gravity	6.1	39	5 × 8.3
Nissum Bredning demo.	2018	Denmark	Nissum Bred.	Hybrid gravity-jacket	2.5	3.5	4 × 7

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