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Overview of offshore wind turbines: foundations, connections to grid and perspective in the Romanian coastal environment

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1. Introduction

Climate change is a visible element that requires the attention of all political and socio-economical stakeholders. With this regard, the European Union is becoming a leading force towards a greener and sustainable future, by launching major agreements that ensure a common target as well as the financing methods. The most ambitious goal of the European Union is the Green Deal (2019), which is an accord that pushes for a climate neutral continent by 2050, as well as a reduction of emissions of at least 55% by 2030. Yet, there are only two instruments which viably approach these targets: a significant increase in renewable energies and a rise in energy efficiency. It is anticipated that the transportation and heating sectors will see the biggest changes in the next decades.

It is expected that offshore wind generation capabilities will expand significantly in the next years. Presently, approximately 22 GW are already installed in Europe, with the majority being located in the North Sea. However, ENTSOE expects this capacity to reach 70 GW by 2030, and 112 GW by 2040. Most existing offshore wind power plants are located close to the shore. However, in the future, as technology will evolve and high water depth will not pose a challenge, there will be much development further from the shore.

The potential of floating wind turbines is high, and it is being demonstrated by an increasing number of installations. "Based on IRENA's target of 2000 GW which would be required to achieve carbon neutrality and sustain a Paris – compliant pathway, GWEC Market Intelligence foresees Asia emerging as the world's most

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prominent offshore wind region, home to nearly 40% of installations by 2050, followed by Europe (32%), North America (18%), Latin America (6%), the Pacific region (4%) and Africa and Middle East (2%)(Fig. **1**).” [1].

According to GWEC Market Intelligence, global floating offshore wind (FOW) project installation capacity stands at 71.3 MW of which 32 MW is located in the UK, 25 MW in Portugal, 12 MW in Japan, 2.3 MW in Norway and 2.5 MW in France. As project activities grow with increasing interest, almost 16.5 GW of FOW turbines are forecasted to be operational by 2030. [1]

In Europe, there are regions with high density of wind turbines, especially onshore as well as near-shore, in countries such as Germany, the United Kingdom and Norway. Furthermore, there is some opposition from coastal residents regarding new projects due visual pollution, noise and preference. A proposed solution to this issue is the use of floating wind projects, a concept which is now being validated in Europe and Japan. [2]

In the United States the biggest challenges related to the implementation of offshore wind power plants comes from the fact that, due to high water depths even at close distance to the shore, conventional turbines are not feasible. As such, even though there is sufficient wind, nearly 60% of the possible locations have a depth higher than 60 m. Again, in such situations, floating wind power plants can provide a solution. [2]

With the expansion of offshore generating units, other opportunities will also emerge. More specifically, by exploiting the generated energy from the offshore wind power plants as well as the subsea cable network, future oil or gas rigs will be able to tap into these networks in order to cover their consumption requirements. Considering that indirect greenhouse gas emissions (GHG) that result from oil and gas processes amount to approximately 15% of the total industry GHG, it is therefore a major opportunity to “greenify” sectors that are traditionally pollutive. Most of the greenhouse gases are produced while generating electricity. This stems from the fact that, due to a high power consumption (even close to tens of megawatts), it is necessary to use multiple gas turbines. There are also gas turbines that are kept online (with low loads) in order to have redundancy in case of main supply failure. By using the power generated from offshore wind power plants, most gas turbines will be abandoned.

“In the first offshore wind-to-hydrogen solution, surplus offshore energy that would otherwise be curtailed – or purpose – built offshore wind capacity for hydrogen generation – will power electrolysis that split water molecules into hydrogen and oxygen. Green hydrogen is then compressed and stored in a tank system, waiting to be offloaded when energy is needed.

With an offshore hydrogenation platform available, liquid hydrogen (LH2) can be converted to synthetic natural gas (SNG), better known as methane, before being shipped to end user for multiple purposes” [1]). Another solution incurs the deployment of electrolysis in coastal areas connected by HV submarine cables to substation to transport the green hydrogen directly with on-land hydrogen pipelines or by truck after compression.

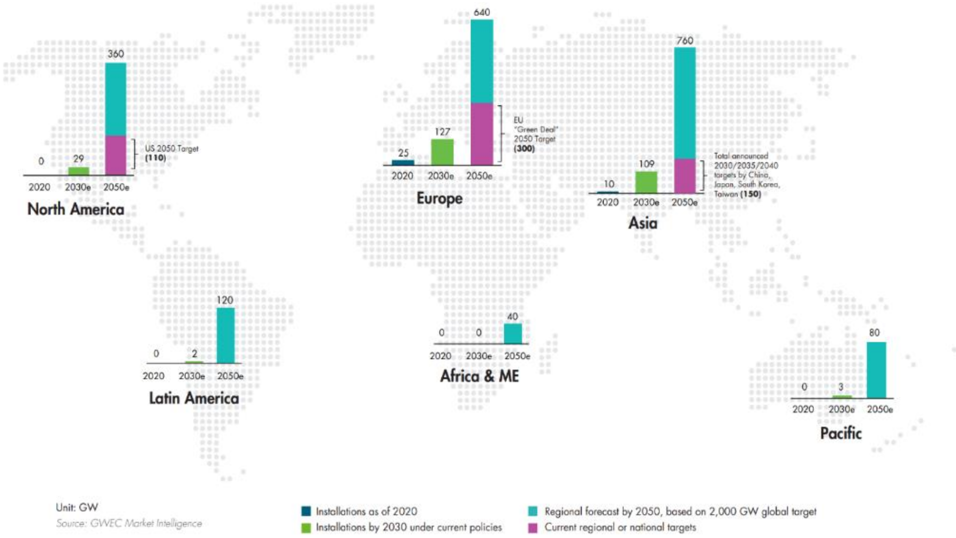


Fig. 1. Offshore wind generation capacity in 2018 and forecasts for 2030 and 2050 [1]

2. Offshore wind power plant structure

2.1. Structure of a large AC wind park

A large AC wind park system usually deploys a lower voltage grid, connected to a transformer, as well as a high voltage transmission system (Fig. **2**). In this case, transformer and associated switchgear are located on a distinct offshore platform [3]. The main components of an AC offshore wind power plant (OWPP) are summarized in Fig. **3**. More specifically, there are variable speed wind turbines (WT) that output the generated power using medium voltage submarine cables (typically 33 – 66 kV) that are linked at the collecting endpoint, which is located on an offshore platform. Afterwards, using a step-up transformer (with the output voltage being in the range of 132 – 200 kV), power is further transmitted over long distances, without unacceptable voltage profiles. This aspect is important as it can severely influence design decisions regarding the number of AC collector platforms. Furthermore, a collector platform can be positioned inside or outside the wind farm perimeter. AC transformers in OWPP are important because these reduce the current that flows through cables and as a consequence, reduce power losses.

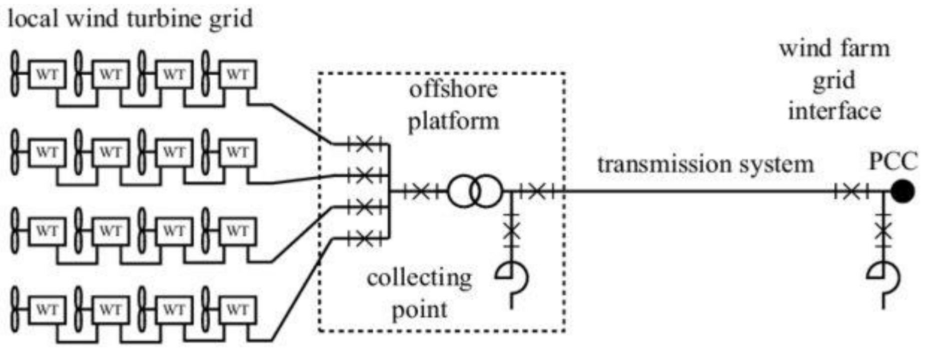


Fig. 2. Structure of a large scale AC wind power plant [3]

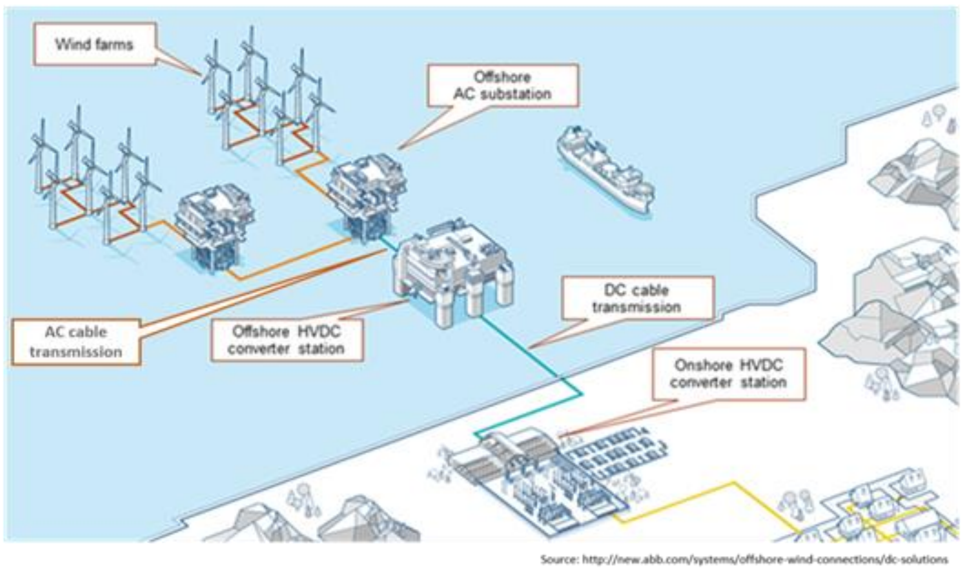


Fig. 3. Overview of offshore wind power plants [4]

The offshore AC substation can be connected to the onshore network using either HVAC cables or HVDC cables (usually 320 kV) via power electronic converters. The use of HVDC is the preferred solution in long distance applications, due to cost effectiveness.

Each turbine consists of a generator, power electronics equipment, mechanical gears, a transformer as well as other auxiliary equipment (for control, protection, etc.). [5]

2.2. Electrical system configuration

A wind turbine uses a power electronic converter to control its rotational speed and, as a consequence, to output the highest amount of available power. The most used topology is the AC/AC converter. However, there are solutions that use

intermediary DC conversion (AC-DC-AC, Fig. **4**.*a*). Still, the last stage of conversion can be eliminated using a DC grid, as seen in Fig. **4**.*b*.[6]
Efficiency of an offshore AC grid is measured using losses associated to cable transmission as well as converter losses. In the configuration with DC grid, transformers that are normally located on offshore HVDC platforms are replaced with DC/DC converters. On the turbine side, the most promising technology is the permanent magnet synchronous generator (PMSG). A PMSG necessitates a full converter to be included into the main grid. However, various types of converters can be used depending on the type of offshore grid, the most applied being back-to-back configuration with voltage source converters (VSC).

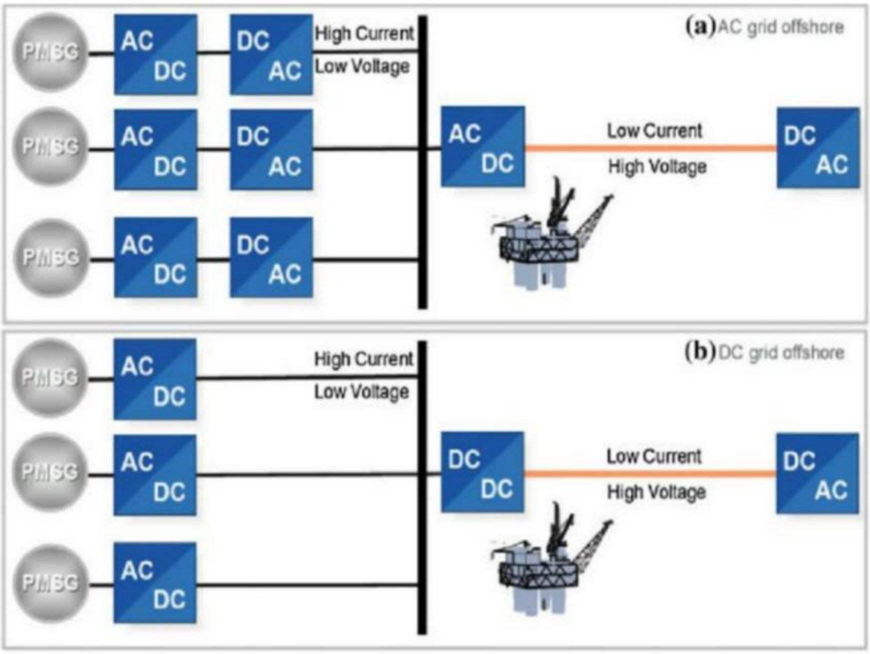


Fig. 4. Offshore grid configuration: a) AC grid; b) DC grid [6]

Every DC/DC converter needs to function at increased voltages in order to enable long distance power transmission. This leads to various DC grid configurations. In a simple DC grid with parallel connection (Figure 5.*a*), the DC/DC converter must increase the voltage level of the line from the generator (usually 690 V). This can be achieved through one or multiple DC/DC converters, in stages. In Figure 5.*b*, series connected turbines are deployed. Because the offshore grid and the transmission lines have the same low current, greater efficiency can be achieved. Moreover, the centralized DC/DC converter can be eliminated, thus reducing investment costs.

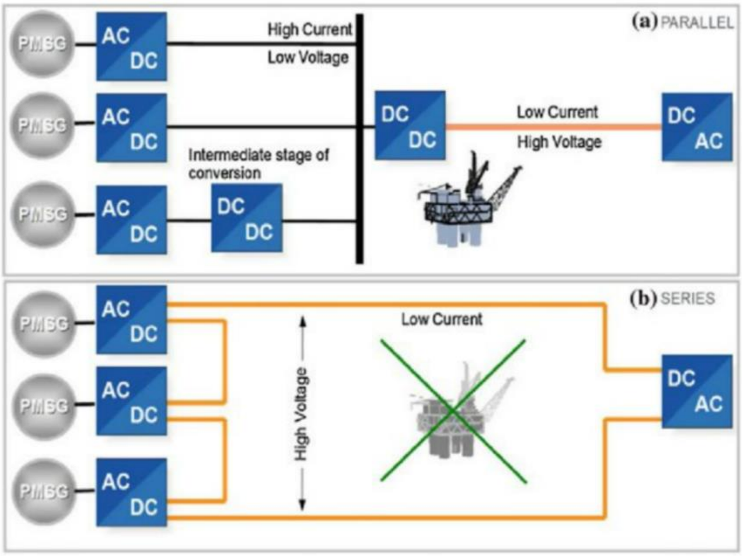


Fig. 5. DC grid configurations: a) parallel connection; b) series connection [6]

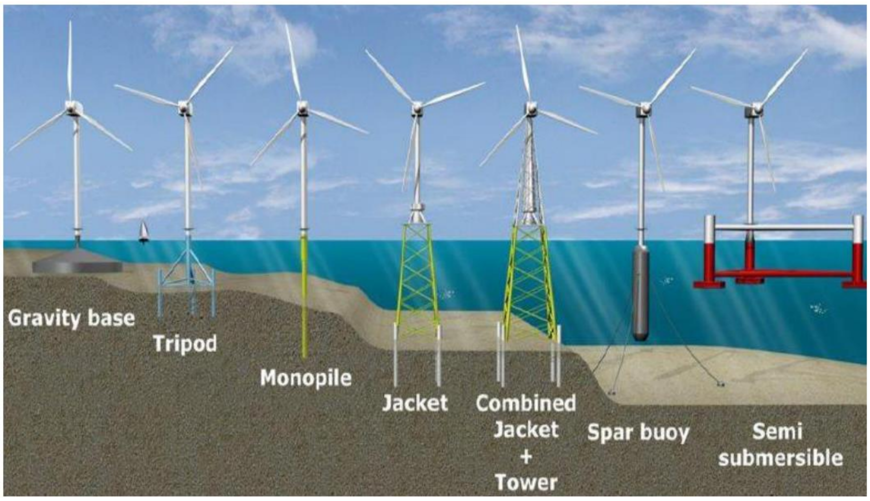


Fig. 6. Offshore wind turbine foundation [8]

Most modern turbines use either doubly-fed induction generators(DFIG), which have the power electronics equipment on the rotor side, or generators which have the power electronics equipment directly on the stator side [7]. The first solution ensures continuous power even during variations of ±30% of the rated speed, while the second ensures operation for the complete range of speed. Even though the second approach is more efficient, it is significantly more expensive due to equipment sizing. In the second solution, turbine power converters consist of a rectifier and an inverter, that connect to a step-up transformer.

Most existing offshore wind power plants are located at places where the water depth is relatively small. This is because the cost of construction for such an approach is much lower. In fact, water depth influences the way a wind turbine pillar is fixed on the waterbed. The most used foundation solutions are presented in Fig. 6 [8].

For water depths of less than 50 m, the foundations that are usually used are gravity, monopile, monopile with guy wires, tripod and jacket. For depths higher than 50 m, floating solutions can be adopted. These are not so common but are presently of high interest and are heavily researched [9].

The first large-scale floating wind turbine was built in 2009 and was installed, for performance evaluation, in the North Sea close to Norway, operated by Hywind. Its rated power was 2.3 MW. A second floating wind turbine was installed in 2011, near Aguçadoura (Portugal), at approximately 4 km from the shore, having a rated power of 2 MW.

3. Foundation Options

The main factors that determine a given foundation usage are underwater ground geology and water depth. As such, shallow waters are associated to depths ranging from 0 to 30 m, transitional waters from 30 to 50 m and deep waters for depths over 50 m.

Table **1** summarizes these aspects.

Table 1. Summary of foundation types [10]

Foundation	**Structure Type**	**Water Depth [m]**	**Ground Type**	**Expected Depth [m]**	**Distance [km]**
Monopile	Fixed	<35	Sandy-clayed	50 (with guy wire)	100
Gravity base structure	Fixed	≤30	Requires previous preparation of terrain	30-50	30
Jacket	Fixed	>30 (25-50)	Different types of soils (non-rocky)	<50	70
Tripod	Fixed	≈30	Different types of soils (non-rocky)	>40	120
Semisubmersible	Floating	>60	-	>60	
Spar-buoy	Floating	>60	-	>120	
Tension leg platform	Floating	>60	-	>100	

An observation which can be made in connection with

Table **1** is the fact that most fixed structures reach a maximum depth of 50 m. Over this value, fixed structures are no longer financially viable and only floating structures are considered possible.

3.1. Fixed Offshore Structures

The most used structures in wind power plants are monopile, gravity based, jacket and tripod (Figure 7).

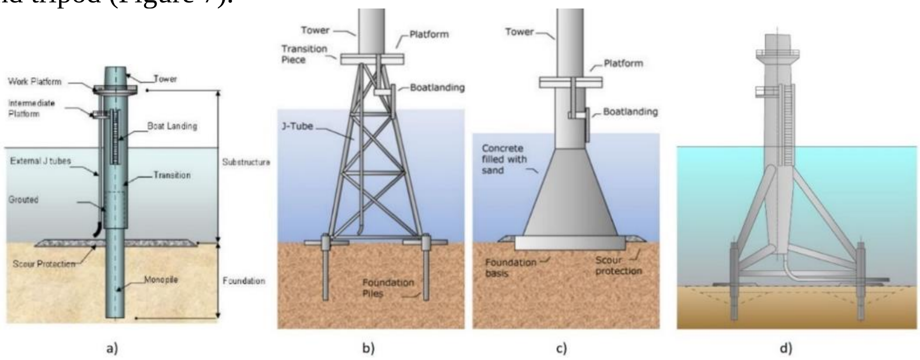


Fig. 7. Fixed foundations structure: a) monopile; b) jacket; c) gravity based; d) tripod [9] [11]

Monopile turbines are the most common installations, amounting to over 80% of the total number of turbines globally. The reasons behind this usage are ease of design and streamlined manufacturing. Its simplicity permits a standardized design which favors series production, leading to shortened construction and installation times as well as lower costs. Furthermore, a monopile structure is highly adaptable, so that it can be targeted to various dimensions and characteristics, without needing to make significant design and manufacturing changes. Lastly, its stable behavior against external environmental forces makes it the best choice for water depths of up to 35 m. A monopile is made from a single steel tube, having a diameter of 4 to 6 m. It is also provided with restrains that limit lateral movements which can be generated by environmental conditions. Over the pile, there is a transition piece, that has a larger diameter (Figure 7.*a*). The transition piece has, in fact, an overlap over the pile of approximately 10 to 12 m, and its purpose is to facilitate the turbine connection and to correct the vertical tolerance of the monopile. Installation of a pile is done with help from large ships that have sufficient cranage to lift the structure and powerful hammers that push the pile 20 to 30 m into the seabed. This type of installation is also difficult to remove.

The monopile structure is the oldest foundation choice for offshore wind power plants. It began to be widely adopted in 2002, when offshore turbines became a viable alternative to fossil fuel power generation (e.g. Horns Rev 1, 160 MW, Denmark, Vestas V80 – 2.0 MW, North Sea, Denmark, etc.) Recently, there are new designs regarding large diameter monopiles, called XXL monopile, that can be used instead of jacket substructures for deep water applications. Presently, the world's heaviest monopile has a diameter of 7.8 m and a weight of 1300 tons, and it is deployed in Veja Mate offshore wind farm.

Jacket foundations (Fig. 7.*b*) are four-legged steel frames that are driven into the seabed in order to ensure proper stability at higher water depths (30 to 70 m) and under severe climatic conditions. However, because of higher design and manufacturing complexity, this foundation has started to see increased adoption only since 2015. These are the preferred solution for most projects in the North Sea and Irish Sea. Furthermore, there are such installations built by Iberdola in the Baltic Sea at Wikinger (Germany), Saint Brieuc (Brittany, France) and East Anglia ONE (UK). In Wikinger wind farm (350 MW; 70 turbines of 5 MW each), the jackets have four legs (Figure 8), a 59 m length as well as a weight of 625 t. In the Saint Brieruc project (496 MW, 62 Siemens turbines of 8 MW each), the jacket foundation was the most appropriate solution for the existing seabed conditions. Other existing installations with this foundation type are Beatrice (588 MW, 84 Siemens Gamesa turbines of 7 MW) in Northern Scotland (50 m depth) and Alpha Ventus in Germany (30 m depth). It is expected that, with the increase of projects that use jacket foundations, its design and manufacturing costs will start to decline.

Fig. 8. Jacket foundation for the Wikinger offshore wind farm [12]

Gravity based structures (Fig. 7.*c*) are used in approximately 20% of the existing offshore projects. The main difference compared to monopile turbines relates to the fact that the gravity based structure is fixed on the sea-bed using its own weight, which is comprised of the pillar weight as well as additional ballast. This solution was adopted in the first offshore wind power plant on the Danish coast, in 1991, in shallow water less than 10m. Most of the existing projects use this structure for water depths up to 25 m. However, there are proposed designs that allow for depths up to 50 m. The pillars are made from concrete and are placed on rockfill or loose stone. This means that additional works are necessary to ensure proper composition of the seabed. At Thornton Bank wind farm, located in Belgium, gravity based structures have been used at 30 m depths. Steel gravity based structures are compatible with various soil conditions, and are preferable for deeper water than concrete based applications. Because these are lighter than concrete based, transportation and installation are much eased. However, if the soil is erosion prone, this can significantly increase costs due to cathodic protection requirements.

Suction caissons were developed in order to provide an alternative to conventional skirted foundations that were being used for oil and gas platforms [13]. The first implementation of a concrete caisson was in 1991 for the Snorre A tension leg platform located in the North Sea. Afterwards, steel buckets were also successfully used on various projects. A suction caisson is made from a skirted section and a lid, that is reinforced using stiffeners. By applying a suction pressure to the upper part of the lid, a resulting pressure difference is created between the inner and outer part of the bucket, thus sucking the foundation into the seabed. Therefore, the complete installation procedure is simple and straight-forward, which makes it extremely promising for offshore wind turbines. As such, single suction caissons are being used for offshore power plants, hence permitting installations for a wide range of depths (usually between 5 to 55 m). Suction caissons have been successfully used at Horns Rev 2

T*ripod foundations* (Figure 7.*d*) are three-legged metallic structures, that are usually used at transitional depths (20 to 80 m). This central shaft transfers the forces from the tower into three vertical or inclined steel piles, that are driven 10 - 20 m into the seabed. The legs are connected by a central shaft, that supports the rest of the tower. If the legs are installed with a jack-up drilling rig, then an inclined position is adopted. From the central shaft upwards, the structure is similar to that of monopile turbines. Therefore, the tripod combines the structural advantages of a jacket foundation with the increased flexion resistance of a monopile. This type of structure has a good stability and overall stiffness. The most recent implementation of the tripod foundation is in the Alpha Ventus project, which support 5 MW turbines that weigh approximately 700 t. In the same project, jacket foundations are also used for additional 5 MW turbines that weigh about 500 t (Figure 9.a). This demonstrates the fact that tripod foundations are able to support more weight even with reduced manufacturing complexity (less joints and one less pile). Furthermore, such advantages can lead to lower production costs. [10]

Twisted jacket is a modified traditional jacket with the legs angled around a central column, which used less steel and is cheaper. The twisted jacket technology has been successful demonstrated in the oil and gas industry as suitable for a wide range of seabed conditions(Figure 9.*b*).

There is still much ongoing research that is aimed at cost reduction, simplified manufacturing as well as adaptation to deeper waters. This research has given promising foundations such as:

- *Tripile foundation* (also named jacket-monopile hybrid structure), has a three-legged jacket structure in the lower section which is then connected to a monopile in the upper part of the water column (made of cylindrical steel tubes). This type of technology has been used at Bard Offshore 1 wind farm. Moreover, such a structure has been used in the German North Sea, to support a 5 MW wind turbine, for the installation of 400 MW.

a) b)

Fig. 9.a) Jacket foundation in foreground and monopile structure in background, at Alpha Ventus [14]; b) Twisted jacket foundation [14]

- *Monopile suction bucket*, constructed using concrete piles formed by prefabricated segments. An implementation of this foundation has been installed in the German Baltic Sea, to support a 5 MW wind turbine at around 30 m.

3.2. Floating Foundations

Floating foundations are a recent technological breakthrough, bringing forth several major advantages. Firstly, these facilitate offshore installations at depths over 200 m, thus significantly increasing the exploitable area. Secondly, floating turbines can be assembled near the shore, being afterwards towed to the destination zone. The same principle can also be applied to maintenance, because floating turbines can easily be retracted back to the shore. Thirdly, there is minimal influence to the migration trajectory of birds (a phenomenon which takes place close to the shore). Finally, there is less visual impact.

However, there are also some disadvantages which need to be taken into account. Mainly, anchoring elements need to be of high mechanical resistance and to receive periodical inspection. Secondly, underwater elements (anchor, cables etc.) might gave a negative impact on marine wildlife.

There are three main categories of floating structure: semisubmersible, spar-buoy and tension leg platform (Fig. 10).

Fig. 10. Types of floating wind foundations [15]

In Europe, there are already implementations of floating wind turbines in places like Scotland and Portugal, with several other projects already in development. In the USA, only pilot projects have been commissioned, an example being University of Maine's low cost floating hull technology. However, there are some commercial projects in development on the East and West Coast, with a commissioning timeframe of 5-10 years. Quest Floating Energy has identified projects representing more than 26.2 GW of floating wind turbines scheduled for commissioning worldwide to 2035, a number that will grow exponentially following the addition of newly sanctioned projects. [16]

3.2.1. Semisubmersible

This type of floating foundation is used in most existing projects. It consists of a structure which remains partly submerged, as well as catenary mooring lines which anchors it to the seabed. This design is highly stable, if the entire body of the turbine has a sufficiently high mass. An implementation of this foundation can be found in WindFloat project (implemented by American company Principle Power), which deploys turbines of 2.3 MW at 5 km offshore from Agucadoura (Portugal) (Fig. 11).
In the WindFloat project, the floating foundation has three legs (similar to a tripod), one of which being the supporting element for the turbine pillar. The foundation, which has approximately 3500 tons, is semi-submerged and fixed to the seabed by three catenary lines. Each leg column contains additional ballast in order to lower the overall center of gravity and to increase platform stability.

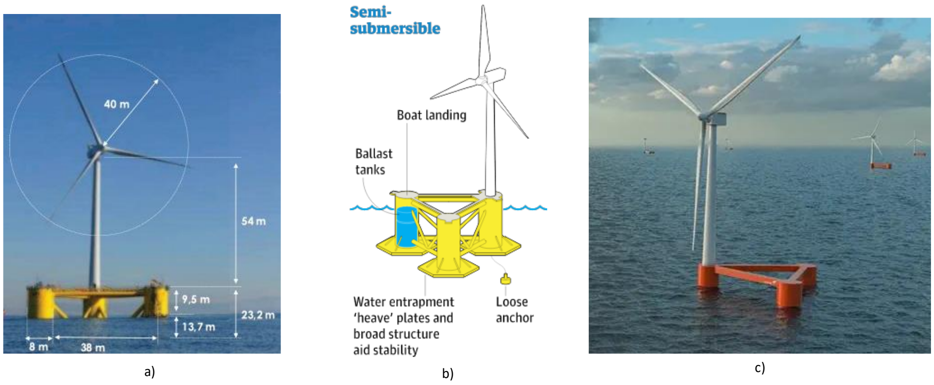


Fig. 11. a) A wind float semisubmersible triangular platform at Agucadoura, near Porto, 2011 [17]; b) Overview of a semisubmersible platform [18]; c) Wind Semi foundation of Equinor [19]

By leveraging the experience earned in the Hywind project, Equinor proposed a new concept, the Wind Semi, which is a semisubmersible wind turbine foundation (Figure 11.c). All improvements related to this concept provide manufacturing flexibility. Furthermore, this foundation is suitable for harsh waters and has a passive balance system, thus reducing the probability of system failure as well as maintenance costs.[19])

A French company Ideol, offers Damping Pool concept, which is compatible with all wind turbines on the market, whatever their power. Its dimensions remain compact, 35 to 50 meters side for a wind turbine of 2 to 8 MW. Ideol recommend a concrete construction but also offers a steel solution. From 2018, Damping Pool by Ideol is positioned on Floatgen project off Le Croisic , at 33 meters water depth (Figure 12). [20]

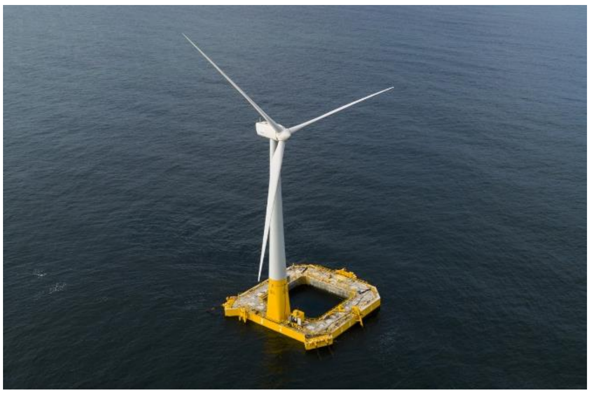


Fig. 12. Damping Pool by Ideol

BW Ideol is the only floating technology provider with two full-scale assets in operation in two markets for floating wind turbines , France and Japan. Recently, BW Ideol has joined two commercial scale floating wind projects in Taiwan and

Italy. A new 40 MW FWO pilot project – based on Damping Pool technology will be installed off Vandenberg Space Force Base in Santa Barbara County, California.

3.2.2. Single Point Anchor Reservoir Buoy

The single point anchoring reservoir (SPAR) buoy is a type of floating foundation that is characterized by the use buoyance chambers inside a vertical circular cylinder (Figure 13.*a*). As such, the entire structure is sufficiently stable to withstand vertical wave forces. Moreover, at the bottom of the cylinder there is a heavy ballast section, which lowers the center of gravity, thus keeping the pillar upright with low roll and pitch motion. Summing up, buoyancy is ensured by the geometry of the cylinder, while stability is kept by the ballast section. Therefore, if turbine size is increased, it is necessary to also increase cylinder length, thus making this solution challenging o manufacture, transport and install.
Assembly of SPAR buoy is much more demanding due to stability requirements, necessitating heavy lifting cranes.
How do wind turbines float? As illustrated in Figure 13.*b*, "the turbine is supported by a deep spar, which is moored to the seabed. Archimedes' principle states that the wind turbine experiences a buoyancy force F_b, which balances the weight of water displaced by the immersed spar. This force acts at the center of buoyancy CB, which is the center of mass of the displaced water. The weight of the wind turbine F_w is directed opposite F_b, and acts at the center of mass CM of the solid body. In still water, the wind turbine floats if its total weight and the buoyancy force are equal in magnitude. Thus, the spar is partially hollowed to reduce the wind-turbine weight and avoid sinking. The wind turbine is further in equilibrium if CM and CB are aligned. When it moves away from equilibrium, the misalignment of CM and CB generates a torque. As shown by Figure 13.*c*, the torque restores the equilibrium position when the center of buoyancy is located above the center of mass. The windturbine position is said to be stable. Otherwise, the wind turbine destabilizes (Figure 13.*d*). In practice, the spar is ballasted to ensure stability of the wind turbine by placing the center of mass well below the center of buoyancy." [22]

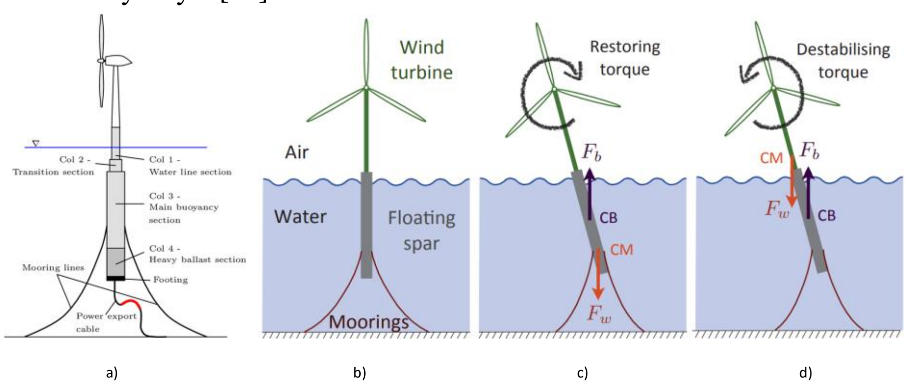


Fig. 13. a) Overview of SPAR buoy [21]; b) sketch of a spar-buoy floating WT in equilibrium; c) stable position; d) unstable position; [22]

One implementation of this foundation is the Hywind project, carried out by Norwegian Statoil in 2009. It uses 2.3 MW Siemens turbines that are positioned 10 km from the coast of Stavanger (Norway), at a location that has a water depth of 90 m. This SPAR buoy has a low water plane and consists of mooring lines and bridles that prevent any excessive rotation. A more complex installation was the Hywind Scotland project, which is considered the first large-scale commercial floating wind park. It started production in 2017 and uses five 6 MW Siemens turbines, that have a total pillar length of 75 m, a rotor diameter of 154 m and an overall height of 254 m. It is located in an area with water depths of 95-120 m. Furthermore, air speed in that region is around 10 m/s.
The second floating wind farm, 25 MW Wind Float Atlantic consisting of 3x 8.3 MW MHI Vestas turbines, was located 20 km offshore, 100 m water depth, off the coast of Viana do Castello, Portugal, 2019. The Kincardine offshore wind farm with highest capacity turbine 5x 9.5 MW MHI Vestas turbines and one operational 2 MW, installed on a floating structure, was locate 15 km offshore of Aberdeen, Scotland (2020), at 60-80 meters depth. Also from 2020 four floating wind farms are under development in Grand Canaria, totalling a capacity of 200 MW.
Recently, Equinor (former Statoil) announced *Hywind Tampen*, the 88 MW floating wind farm that will be consisted of 11 x 8 MW WTs to meet about 35% of the annual power demand of Snorre A and B, and Gullfalks A, B and C offshore wind platforms for oil and gas. On the contrary from the previous Hywind Projects, Tampen foundations are the first concrete spar structure for an offshore project on the Norwegian continental shelf since Toll A in 1995. The concrete technology developed for petroleum industry is now utilized in a renewable project. Water depth at the wind farm site ranges between 260 m and 300 m, and is located at 140 km off the Norwegian coast. The WTs will be connected in a loop by a 2.5 km long, 66 kV dynamic inter-array cable system [23].

3.2.3. Tension Leg Turbine Platform (TLTP)

This floating solution is appropriate for moderate water depths and consists of three or more submerged arms that are anchored to the seabed using tension legs. The mooring lines need to be able to withstand buoyancy and drift due to weather conditions. Among the advantages of TLTP are lower construction cost and easier handling during installation and towing, as compared to semisubmersible concepts. Furthermore, like the semisubmersibles, the TLTP can be towed to shore for easier maintenance, leading to increased availability. Due to optimizations in foundation structure, floating foundation hull steel weight is significantly reduced. It is expected that commercial scale operations of such turbines will lead to further cost optimization. An implementation of this foundation can be seen in Pelastar project which deploys TLTP with 5 branches. Moreover, it is anchored to the seabed using 5 tension legs and supports a 6 MW turbine (Figure 14 a). [24]

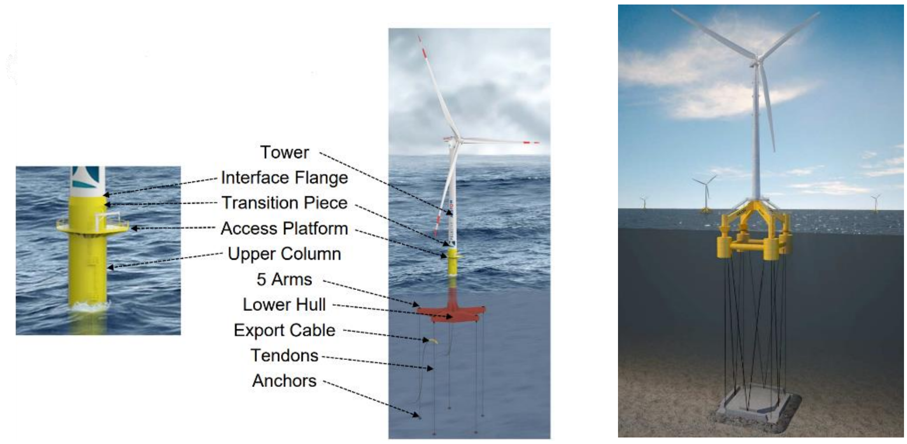


Fig. 14. a) Pelastar tension leg platform [24]; b) Gicon-SOF TLTP[25]

A similar project is Gicon – SOF, implemented by German company Gicon. The proposed research floating turbine has a square structure, held under the water surface by 4 vertical mooring lines and 4 taut oblique lines that improve the stability of the entire construction. It is advertised as being appropriate for depths between 18 and 500 m. The main difference of this solution is the use of ultra-high performance concrete elements instead of classical welded steel. It also uses a lowerable gravity anchor which can be used to tow the turbine in position (Figure 14.*b*). In the permanent position, this anchor is ballasted to the seabed. Therefore, the costly driven or drilled anchors are replaced by gravity anchors, thus reducing installation costs significantly. [25]
In 2017, Gicon and Golsten joined resources to develop an optimized TLTP. This resulted in a unique solution that levelized energy cost to the lowest level of any floating solution (approx. 76 USD / MWh) for a 6-8 MW turbine.

3.2.4. Other major Floating Foundation Offshore projects around the world

In 2013 GE/Alstom installed a floating turbine prototype off the coast of Ostend harbor (Belgium). The project, called Heliade, was at that moment the largest offshore wind turbine. Between 2014 and 2016, GE/Alstom and DCNS developed a 6 MW floating turbine, for the Heliade 150 project, that is based on the tension stabilized concept. In the same year, the French Environment and Energy Management Agency (ADEME) approved the installation of two floating wind projects which are based on the Heliade 150 turbine concept.
The first offshore wind farm in the US received approval for construction in December 2020. This project, called Vineyard Wind 1 is located 25 km off the coast of Martha's Vineyard in Massachusetts and will contain 62 turbines Haliade-X 13 MW each, and to be commissioned in 2023.
A promising region for offshore wind turbines is Dogger Bank, which is an isolated sandbank within the central to southern North Sea, in the vicinity of UK, Germany,

Denmark and Holland. In this 8660 km^2 region, the water depth varies between 18 and 63 m. It is expected that, in the near future, this zone will host four offshore wind farms with a total capacity of 4800 MW. Project ownership in this region is divided between major stakeholders. More specifically, since 2017, SSE and Equinor won Dogger Bank Teesside A (renamed as Dogger Bank C), while Dogger Bank Teesside B was taken by Innogy and renamed Sofia Offshore Wind Farm (Fig. 15).

Fig. 15. Sofia offshore wind farm HVDC grid connection [26]

The construction of Sofia project is expected to commence in 2023 and it will host 100 Siemens Gamesa turbines of 14 MW each. Dogger Bank C will contain GE Heliade turbines, of 14 MW, with construction expected to begin in 2026. In October 2019, the company Aibel won a contract to deliver two converter platforms for Dogger Bank A and B, with a potential to expand the contract for one more platform at Dogger Bank C. Construction of the platform is coordinated by Aibel in Haugesund (Norway), while platform construction is performed in Thailand. Construction is expected to be finalized in 2022, with a potential placement at the final location (at Dogger Bank) in 2023. The timeline for construction completion for platform B is 2024 while Dogger Bank C is scheduled for 2025. Due to the distances of each Dogger Bank phase from the shore (between 130 km and 200 km), this project will host *the first HVDC connected wind farm in the UK*. For this task, Hitachi ABB Power Grids has already been commissioned to deploy its HVDC Light solution.

Fukushima floating offshore wind farm demonstration project (Fukushima FORWARD) was completed in 2013 and consists of three floating wind turbines and one floating power substation (Fig. 16.*a*) that is located near the coast of Fukushima. Each turbine has a power rating of 2 MW (Fukushima Mirai). Moreover, the floating substation, which is a world first implementation of such a concept, is rated at 25 MVA (Fukushima Kizuna). The second phase added two 7MW turbines (which are the largest in the world) and was completed in 2015. An additional floating turbine of 5 MW was installed at Fukushima Hamakaze in 2016 (Fig. 16.*b*).[27]

a)

b)

Fig. 16. a) Towing of converter platform; b) Fukushima Hamakaze turbine being towed to final location [27]

4. Transmission Solutions in Offshore Wind Energy

An offshore wind farm (OWF) contains four main parts: the collector system, offshore substation, transmission system and onshore substation.

4.1. Collector System Topology

The collector system's main role is to collect all generated power from each wind turbine in the offshore wind farm to the offshore substation in order to forward it towards the shore. The general schematic diagram of an OWF electric power is showed in Figure 17.

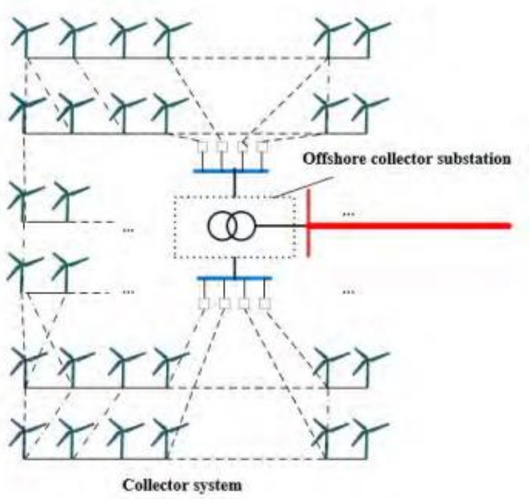


Fig. 17. Schematic diagram of a collector system [28]

The devices in an OWF can be separated into two categories: connected devices (i.e. wind turbines, offshore substations equipped with transformers and/or power converters) and connecting devices (i.e. cables). Most present-day offshore projects operate in AC because wind turbines generator are operating at AC voltages. Standard configurations of wind farm layouts are: radial, single-sided ring, double-sided ring, multi-ring and star topology (Fig. 18). [28]

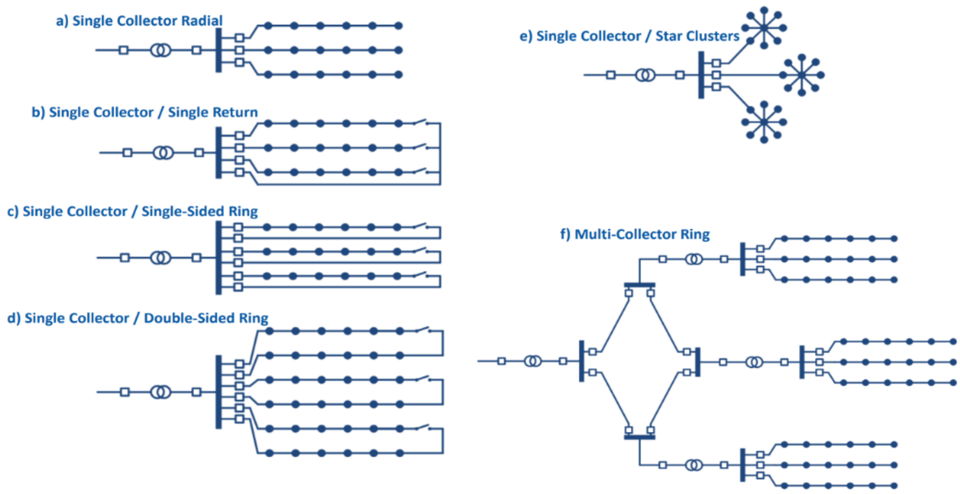


Fig. 18. Offshore AC Collector system configurations [28]: a) radial collection; b) single return; c) sigle sided ring; d) double-sided; e) star clusters; f) multi-collector ring

The most common cheapest and simplest topology is the radial configuration, meaning that a single cable connects all turbines in string. However, there are limitations regarding cable maximum current as well as installed power capacity. Moreover, there are disadvantages regarding low reliability of the system because any fault can lead to multiple turbine elimination. Therefore, alternative configurations, such as ring or star, are preferable. Reliability in a ring configuration can be increased by deploying redundant cables in a loop configuration. If a single sided ring is adopted, an additional cable is added to connect the last turbine of each string with the hub. In the double-sided configuration (Figure 18.*d*), the last turbine is connected to the collector via an additional cable. The most reliable configuration is the star cluster (Figure 18.*e*), but adds upfront significant costs, because each turbine is connected to the collection point with an individual feeder.

4.2. Offshore and Onshore Substations

Offshore substations/ platforms have the role to increase voltage before it is exported to the shore. The rated voltage of AC array cable strings is usually up to

200 kV, and +/- 320 kV for DC export cables from offshore substation to shore. In order to increase reliability, two offshore platforms can be built in order to decrease the impact of a single point of failure. However, an alternative implementation can be deployment of multiple transformers on a single platform. However, if the offshore wind power plant project has a smaller scale, it might be sufficient to directly connect the turbines to a collector located onshore. This is especially valid for wind farms of 100 MW or less, and for distances lower than 15 km.[29]

The most relevant foundation structures for offshore platform (both collector and HVAC or HVDC platforms) can be a monopile (similar to the wind turbines), hybrid or gravity-based (built up to a concrete caisson with the steel leg structure mounted on its top) or a jacket construction. The last of these is made up of three or four main legs (depending on the seabed conditions and the platform weight) and supported by piles in each corner of the foundation structure. Moreover, it contains J-tubes to route the inter-array cables from the offshore collection grid onto the platforms. The jacket structure is designed to bear against multiple constraints such as the impact of the waves, corrosion or the flow of the sea water streams and tides, among others. All platform are assembled on land and then transported out to the sea. Typically, platforms topsides can weight about 2000 tones and a height of 25 m above sea level.

The onshore substation has the role to forward the power received from the offshore cables towards the transmission system, either by adapting the voltage level if AC is used, or by converting from DC to AC and then stepping up the voltage if HVDC is employed. The cost of an onshore substation is usually half from that of an offshore substation, due to the fact that equipment availability and installation is much more widespread.

4.3. Transmission Systems

Power transmission from offshore collection substations (Figure 17) towards the onshore substation and the electrical grid is a highly exciting topic, even though there are various established technologies. However, for the past 20 years, these technologies have evolved significantly, considering the advancements in materials (for cables, transformers, etc.), electronics (for monitoring, control and protection systems), and new technologies related to power conversion.

Export cables connect the wind farm to the electrical grid, using either AC or DC. AC cables consist of three phase conductor, usually rated up to 220 kV. DC export cables are made from two single-core conductors, with ±200 kV to ±320 kV. Because of reactive power flow, HVAC cables are usually restricted to application that have distances no longer than 150 km from the shore. From that point forward, HVDC is normally deployed, ensuring lower losses but with higher initial investment.

In case where the location of offshore plants is less than 15 km from the shore, it is possible to directly use medium voltage AC underwater cables. However, for longer distances, there are two main solutions which guarantee the flow of power from the offshore plants to the onshore grid: high voltage AC transmission (HVAC) and HVDC transmission (Figure 19).

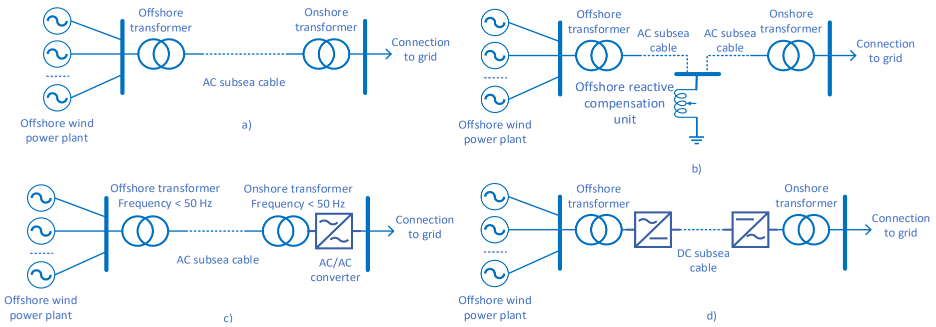


Fig. 19. Various offshore network configurations: a) classical HVAC network; b) HVAC with reactive compensation; c) HVAC with operating frequencies less than 50 Hz; d) HVDC network

AC transmission is an acknowledged solution for cases in which the distance of the submarine cable is relatively small (Figure 19.*a*). However, for long distance cables, two possible solutions can be implemented in order to overcome such limitations. Firstly, it is possible to install a offshore platform, at specific distance from the shore, that entail compensation unit (Figure 19. *b*). This solution is cost effective in certain scenarios and allows for an extension of maximum permitted AC subsea cable length. Such an approach has already been implemented in offshore wind power plant Hornsea Project One (UK), in 2008 [30]. Secondly, there is much research regarding the possibility to use a reduced frequency (sub 60 or 50 Hz) for the offshore section of the HVAC grid, thus lessening the capacitive effect as well as decreasing losses associated to skin effect (Figure 19.*c*). This is called Low Frequency AC (LFAC) and its more developed variant is named Optimal Frequency AC (OFAC). [31]
The biggest advantage of HVAC over HVDC relates to the fact that HVAC can be easily deployed in a meshed or radial configuration, whereas HVDC is mostly used in a two- terminal configuration (Figure 19.*d*). This means that, if HVDC is adopted, there is one onshore terminal and one offshore terminal. Between the offshore platform with the HVDC terminal and the wind turbines, AC cables are used. For large power plants, turbines are organized into clusters which connect to one AC collector, and multiple collectors link to the HVDC rectifier platform. However, for the past six years, significant advancements have been made related to a multiterminal HVDC configurations as well as to DC/DC converters. This opens the door for new scenarios which allow for a more efficient technical and economical approach to offshore wind power generation, using direct DC connection. The first project of this kind is currently Kriegers Flak combining grid connections to offshore wind farms with an interconnector between Germany and Denmark (by December 2020).

From a control point of view, considering the existence of converters in each turbine, as well as the presence of one HVDC rectifier for a cluster of turbines, this opens new opportunities regarding optimized performance of the entire offshore wind power plant.

Event though there are various technical solutions, network design is mostly dictated by the best economical approach. In [32] the author identifies the most feasible approach depending on the subsea network length (Figure 20). It is clear that, for lengths less than 110 km, it is better to use HVAC (in its various formats). For cable distances greater than 110 km, OFAC and HVDC become good alternatives. Furthermore if it is necessary to go further than 130 km from the shore, then HVDC becomes the most economical solution.

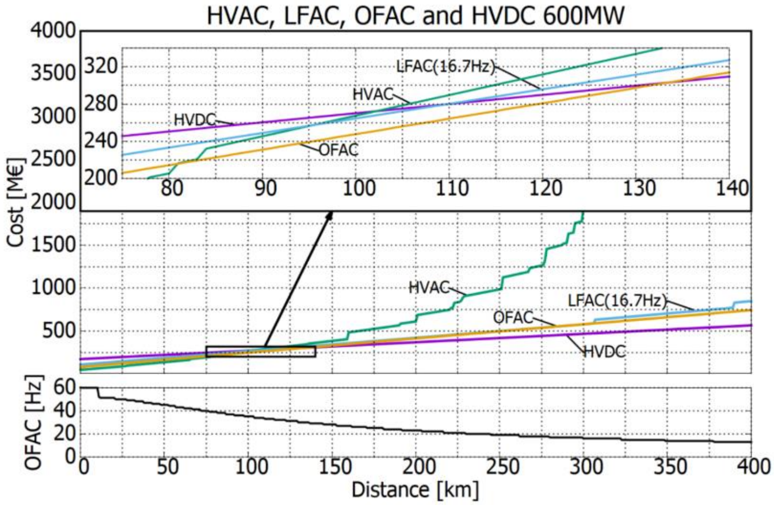
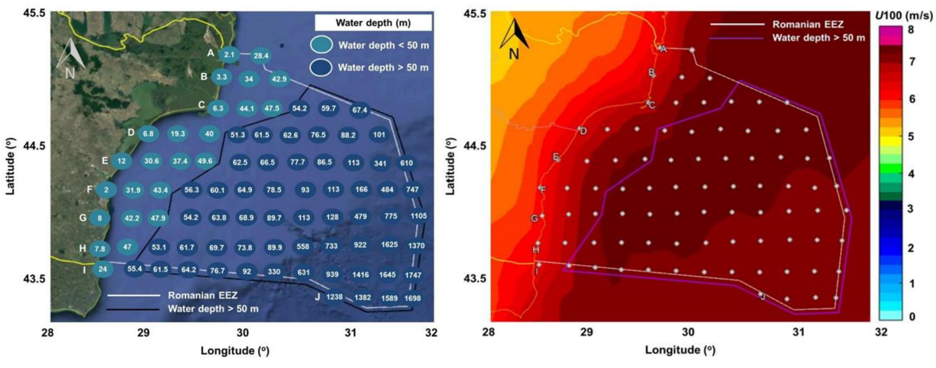


Fig. 20. Economic analysis of various transmission technologies for 600 MW [32].

In all situations, there are several requirements which need to be met regarding the connection to the existing onshore grid [7]. One relates to *voltage or reactive power control capability*. If a HVAC solution is adopted, then additional equipment needs to be installed, such as capacitor banks , STATCOM or VAr compensators. However, if HVDC with voltage source converters is used, then the inverter terminal is able to independently control active and reactive power. A second topic is *fault ride-through capability*. This entails Zero Voltage Ride Through, Low Voltage Ride Through and High Voltage Ride Through. The offshore system, needs to provide the rated power at voltage levels between 0.9 and 1.1 pu of the rated voltage. *Active power and frequency control* is another matter that needs to be addressed, considering the need to have constant active power for frequency ranges between 49.5 Hz and 50.5 Hz. Moreover, *frequency support needs to be ensured by the offshore network*.

5. Towards the Energy Transition by Offshore Wind Potential of Romania

In the context of energy transition, offshore wind power is one of factors which can enable net-zero greenhouse gas emission by 2050, as required by the European Green Deal. In this perspective, a recent study regarding Romania's offshore wind potential (ERA5) has been performed by Energy Policy Group and Dunărea de Jos University of Galați [33],[34]. The results show an estimated maximum generation capability of 94 GW, out of which 22 GW can be obtained with fixed turbines. This leads to a total annual energy production (AEP) of 239 TWh, or 54,4 TWh using fixed turbines. One of the input data for this research is based on a power density of 5 MW / km^2, for each 24 values per day, which is a suitable value for offshore wind potential in European studies. Moreover, the ERA5 study excluded from calculations those zones within 20 km from the shore as well as the region with depths higher than 150 m. At such high depths, turbine installation costs are so great that these make investment uneconomical. Furthermore, areas with wind speeds lower than 7 m/s were also disregarded, due to low return of investment. Finally, ERA5 study took into consideration losses of 15% that can be attributed to icing, maintenance downtime, transformer losses etc. Wind speed measurements were accounted at a height of 100 m and the model of wind turbine that was introduced in the calculations was MHI Vestas V174 9.5 MW [34].
Fig. 21.*a* shows the map of the Romanian exclusive economic zone (EEZ), with highlight on water depth. It contains a grid of 84 points, that have a distance between them of 20 km along the latitude and longitude lines. As can be observed, there is water depth of approximately 600 m towards the extremity of the continental shelf, while at even greater distances the depth reaches over 1700 m.



a) b)

Fig. 21. Water depth (a) and wind speed distribution (b) in the Romanian exclusive economic zone [33],[34]

Because there is a significant part of the EEZ with depths greater than 50 m, that region is more suitable for floating wind turbines.
The Wind Europe 2020 strategy [36] showed that a majority of offshore wind projects in Europe is located at distances up to 60 km from the shore, which is

overlapping with the transitional area from shallow (<50 m) to deep water (>50 m). However, because such long-distance AC cables are not economically feasible, the use of HVDC connections is recommended in order to significantly reduce losses. Yet, HVDC requires greater upfront investment. Figure 21.*b* shows the spatial distribution of the average wind speed, as measured at a height of 100 m, between 2000 and 2019. It shows that the wind speed increases further away from the shore and that the highest speeds can be recorded in the central of the deep-water sector. During the winter, wind speeds in the central region can reach 8 – 9 m/s.

Average wind speed is an important factor in the process of choosing a specific wind turbine technology. As an example, the capacity factor which shows the efficiency of a particular generator is shown in Figure 22.*a* in correspondence with a MHI Vestas V174 9.5 MW turbine.

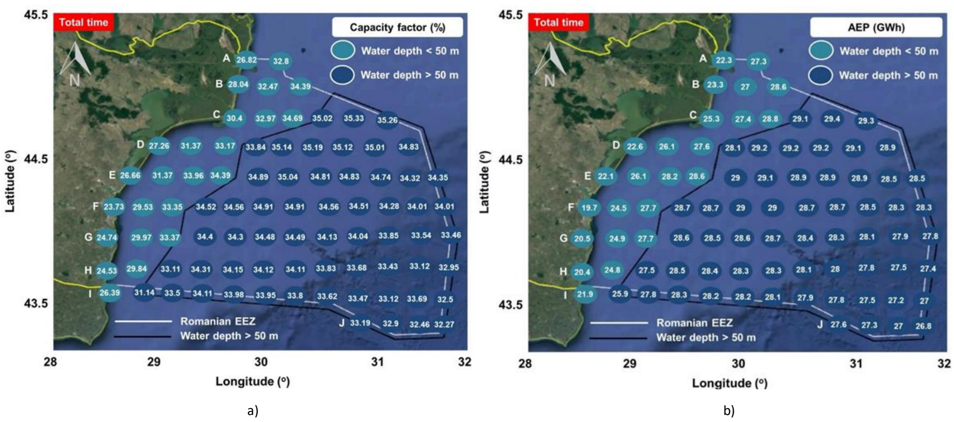


Fig. 22. Capacity factor (a) and annual energy production (b) [33],[34]

In close proximity of the shore, turbine capacity factor stays at around 24 – 28 %, reaching 35 % only at the limit of 50 m. In the central zone, capacity factor increases to approximately 35 %. In the winter, this value reaches 47 % in the central zone, or 40.5 % closer to the shore.

Figure 22.*b* depicts an estimation of the annual energy production (AEP). Based on the annual energy production data, it is observable that, for a MHI Vestas V174 9.5 MW turbine, the output will not exceed 30 GWh/year. Because the Romanian EEZ has water depths greater than 50 m over a large area, it can be concluded that floating wind turbine technologies are favored.

Presently, fixed turbines are the most cost effective and technologically established solution. Based on the results presented in [33] (Figure 23), it can be concluded that there are two major clusters that can offer the most favorable condition for deployment of offshore wind turbines:

a) The orange cluster, which contains zones with a capacity factor between 33 – 35%, in water depths below 50 m and at 40 – 60 km from the shore;

b) The pink cluster, with zones having a capacity factor above 34%, in water depths moreover than 50 m and at approximately 40 km from the shore.

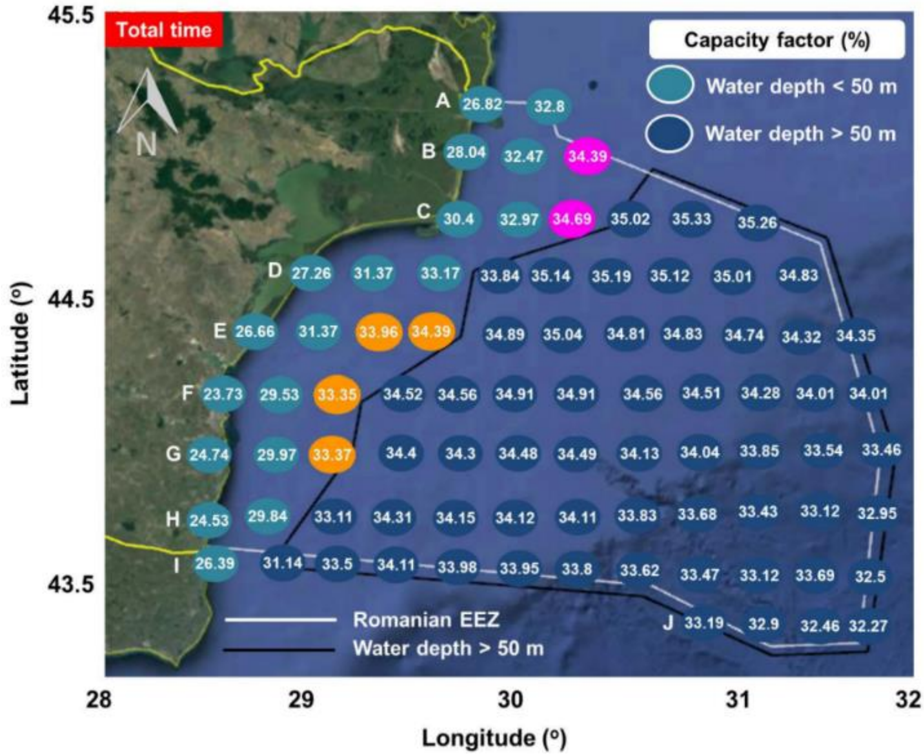


Fig. 23. Most promising offshore zones, based on capacity factor [33],[34]

6. Conclusions

Concerning the Vision from the [37], approximately 80% of the offshore wind resources is located in waters with a depth higher than 60 m, where bottom-fixed offshore wind is not economically attractive. Therefore, there is increasing interest for floating offshore wind turbines (FOW), because these can be installed in various scenarios, thus being able to increase the share of renewable resources in France, Spain, Portugal, Ireland and UK. All these countries have large, deep territorial waters, significant wind resources offshore, high population and industrial activity near the coastline. By taking this into consideration FOW is the logical long-term of Europe's offshore wind energy.

The cost of FOW in Europe steaming from operational projects today is in the order of Euros 180 to 200/ MWh for pre-commercial projects. Industry expects the costs to reach Euros 100 - 80/ MWh for the first commercial scale projects using existing proven technologies and reaching final investment decision (FID) between 2023 and 2025, when FOW would pass 1 GW of cumulative installed capacity in Europe. Costs are expected to decrease even faster at " mature" commercial-scale, reaching Euros 40-60 MWh by 2030 given the right visibility in terms of volume and industrialization.

It should also make use of EU Marine Strategy Framework Directive, which already outlines four possible regions suited for cooperation: the Baltic Sea, the North –East Atlantic, the Mediterranean Sea and Black Sea.

Large scale deployment of FOW depends on a number of factors such as availability of suitable port and onshore grid availability. However, this is also true for bottom fixed offshore wind turbines. The installation and hook-up of the mooring system and the dynamic electrical cable is crucial part of the installation process in FOW. Industry needs to reduce the cost of such key components as well as the related offshore operations. The movements of the turbine and the floating substructure increase the loads on the dynamic section of the cables. Monitoring the aging of these components under cycling loads and marine growth can significantly contribute to cost reduction through lifecycle management. In waters deeper than 100 m it is difficult to fix the array cables to the seabed. Different solutions of electrical substation- fixed, floating, underwater- need to be investigated.

In the context of energy transition for Romania, it is necessary to continue research and development of future offshore wind power plants in the exclusive economic zone of the Black Sea.

From the results presented by the authors of Energy Policy Group [33,34], we can choose two major clusters that can offer the most favorable conditions for first stage deployment of offshore wind turbines in the Romanian EEZ: the zones with capacity factor between 33-35 % in regions that have a water depth of less than 50 m and at distances 40-60 km from shore, respectively in zones with a capacity factor above 34 % in water depth more than 50 m at approximately 40 km from shore.

Future trends in the Romanian offshore wind power plant development might include the use of Constanta Port as a base for assembly for wind turbines and its foundation and for towing to final location. Moreover, due to close proximity of Constanta Sud Electrical Substation (owned by Transelectrica) from the Black Sea region, it is expected that future projects will use this facility to connect subsea cables. Furthermore, offshore oil and gas platforms might use this opportunity to have alternative power supply. Finally, future development in the Black Sea will likely include fixed as well as floating wind turbines.

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