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OFFSHORE WIND POWER FLOATING IN ITS INDUSTRIAL AND TECHNOLOGICAL DIMENSION

Michel CRUCIANI

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Center for Energy

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Cover: The Floatgen floating wind turbine, equipped with the Ideol float, installed on the SEM-REV (Centrale Nantes) off Le Croisic. © Ideol/V. Joncheray

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In these jobs, he followed the liberalization of the gas and electricity industry in the United States and in Europe, as well as the rise of environmental concerns, leading to the adoption of climate policies, a new role for nuclear energy and the promotion of renewable sources.

Executive Summary

Bottom fixed offshore wind already belongs to mature renewable energy sources, with remarkable technical and economic performance. The European Union is the largest development hub for this technology, with 18.3 gigawatts (GW) installed by the end of 2018 (more than half of them in the UK), but other countries have also commissioned significant capacity (4.6 GW in China) or are preparing the launch of major fleets (East Coast of the United States). However, wind turbines on foundation can only be installed on a shallow ocean floor, such as in the southern part of the North Sea, an uncommon characteristic round the world.

Floating offshore wind technology breaks free from this constraint. Several European countries[1] have encouraged its development by testing various models of floats, firstly with prototypes, then with industrial-scale demonstrators, and today with pre-commercial farms each with a capacity of several tens of megawatts (MW). Every step allows to validate technical answers to the formidable difficulties to face, in particular to ensure the greatest possible stability to the turbine despite the swell, in order to reduce the amplitude of vibrations, a destructive phenomenon for the components. Five float models have passed this test and are now found in various projects at pre-commercial stage; these are aimed at garnering further progress in mooring and electrical connection.

Floating facilities that reach the pre-commercial stage use conventional turbines, which equip bottom fixed offshore wind turbines, and their floats were designed by companies with long experience in the oil industry or shipbuilding. In parallel, innovative models of floats and turbines are being tested and could break through later on. All projects receive financial assistance, in the form of subsidies or attractive loans, and the electricity they generate is purchased at a fixed subsidized price. These are small series (three to five machines) and their novelty involves risks for capital providers and insurance companies.

Floating wind turbines have a major advantage: they are assembled in the port and then towed on site by an ordinary tugboat, which can also tow them back to shore for heavy maintenance or final dismantling. This specificity nourishes the conviction that the technology will become

1. France, Norway, Portugal and United Kingdom (Scotland).

competitive when it benefits from scale effects generated by the launch of long series and from learning effects reducing operating costs. However, the European States that have supported the launching of this technology up to the present day are reluctant to pursuing their efforts on a larger scale, in a period of budgetary discipline and acute international competition, which makes it necessary to keep energy prices as low as possible.

Europe has gained a significant lead in the management of floating offshore wind due to its valuable skill set in this area; in addition, floating wind turbines use multiple components developed for the offshore oil and gas industry, whose value chains are partly European. However, the EU could be caught up or overtaken by competing countries that have perceived the potential of this sector and want to participate in its industrial deployment. Because they lack visibility on opportunities in Europe, our pioneering companies ineluctably establish partnerships overseas, with the aim of making the most of their achievements.

The analysis suggests that the sector is likely to take an important role in the upcoming energy transition. Since no European State alone can assume the costs of boosting this technology, it would seem wise to set up a "European alliance of floating offshore wind" to accelerate its development and reinforce the position held by our industry in its global deployment.

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Introduction

Several countries in the world initiated an energy transition long ago, giving a major role to renewable sources. Taking into consideration the natural limits of bioenergy or geothermal energy, renewable electricity has emerged as the preferred response; thanks to technical progress and decreasing costs, two new generation technologies, wind and photovoltaic, have already acquired significant shares in energy balances.

In this process, European States with a maritime area have laid out their intention to exploit their offshore potential. In a previous study, we highlighted the pioneering role of Europe in the offshore wind industry.[2] At the end of 2018, Member States of the European Union (EU) and Norway accounted for 79% of the installed offshore wind capacity worldwide, with a commissioned capacity of 18.3 GW. Their sole rival is China, with 20% of the world's capacity (4.6 GW). United States, South Korea and Japan together achieve only 1% of the global fleet (0.27 GW).[3]

The study pointed out that this performance was based on a local particularity, the existence of a shallow and windy area in the southern half of the North Sea, with offshoots in the Irish Sea and Baltic Sea. As a result, operators were able to transpose at sea a well-mastered onshore technology, wind turbines on foundation, which can be grounded into seabed up to a water depth of about 60 m. Such a maritime configuration is found in some parts of the world (including the South China Sea and the East Coast of the United States), but ultimately the number of suitable locations remain small. Globally, most of the well-winded coastal areas are bathed by waters that are too deep for bottom fixed turbines to be built on but are suitable for floating offshore wind, a nascent technology. Opportunities for this technology seem tremendous, with a very high technical potential for Europe and the West Coast of the United States in particular, and an accessible market of 100 GW by 2050.[4]

This article assesses the industrial perspectives for floating offshore wind. A first chapter succinctly reviews the technical characteristics and

2. M. Cruciani, "The Expansion of Offshore Wind Power in the North Sea: A Strategic Opportunity for the European Union", *Études de l'Ifri*, July 2018, available on: www.ifri.org.
3. Global Wind Energy Council, *Global Wind Report 2018*, April 2019, pages 26 et 29.
4. R. Proskovics, *Floating Offshore Wind: A Situational Analysis*, ORE Catapult October 2018, page 17.

the specific difficulties it faces. A second chapter describes the main projects which are already underway or in the process of being launched and discusses the options open to actors, whether industrial or public. The description shows Europe's remarkable advance in floating offshore wind technology, with six pre-commercial projects (compared to one in Japan and one in the United States).[5] These projects represent a key step in initiating the cost reduction phase that will lead to a large-scale competitive offer. A final chapter is dedicated to public policies and industrial strategies that would reinforce the European lead and place European players from the sector in an advantageous position on a global market providing great prospects.

5. Carbon Trust, *Floating Wind Joint Industry Project – Phase I Summary Report*, 2018, page 16.

Technical characteristics and difficulties to be overcome

The aim of stability

The primary goal of any floating offshore equipment designer is to provide the greatest possible stability for their product. When a floating platform undergoes oscillations as the waves swell, it pulls and releases the mooring and the components that connect it to the ground (whether pipes or electrical cables). Alternating stress causes a "material fatigue", which degrades components much faster than a constant strain (permanent traction or compression).

In the case of floating wind turbines, the fatigue is increased due to vibrations related to blade rotation. These vibrations occur as soon as the axis of rotation leaves a rigorous alignment with the direction of the wind; they are observed on all wind turbines, onshore and offshore, during turbulent winds. In the case of a floating wind turbine, to the fluctuations of the wind are added the possible movements of the float, which may cause a pivoting around the vertical axis (yaw), a rocking back and forth (pitch) or port side on starboard (roll).

Figure 1: Three axes of movement

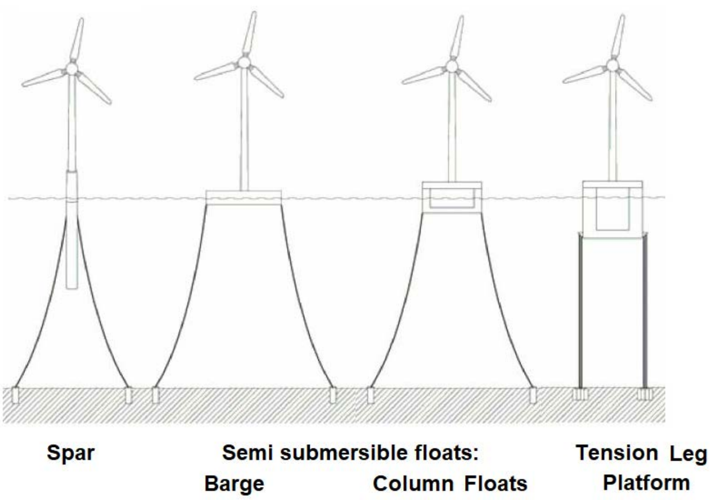
Source : ORE Catapult (2018)

In addition, the rotation of a turbine appears regular, but it is not perfectly: at the moment when a blade runs in front of the mast, the pressure of the wind is altered, modifying punctually the equilibrium of the forces. The repetition of this alteration also induces a vibration in the support. Oscillations of the whole equipment can increase in amplitude if the movement caused by the swell is combined with that created by the rotation; it then generates a phenomenon of mechanical resonance.[6] The risk of resonance is also there for offshore wind turbines on foundation subjected to the regular impact of the waves, but the grounding in the soil ensures a diffusion of the energy and limits the amplitude of the oscillations. In addition, floating facilities are often designed to be located in areas exposed to stronger waves and winds than bottom fixed offshore turbines.

Mooring

The main quality that is required from a float therefore concerns the stability it confers on the installation, in order to reduce the oscillations and, in so doing, minimize the fatigue of the materials. Two important factors contribute to improving stability: the lowering of the centre of gravity and the mooring. Therefore, a float is designed from the outset with its mooring equipment.

Figure 2: Four models of floats with their mooring



Source: Figure freely inspired by the image on the publication DNV-GL, "Floating wind turbine structures DNVGL-ST-0119", July 2018, page 17.

6. This phenomenon can be depicted by remembering that giving a push to a swing when the seat is at the highest will gradually increase the amplitude of the swaying without having to exert a greater pressure with each thrust.

The simplest mooring consists of several chains that end either with a very heavy load such as a marine anchor, the weight of which slows the movements of the float, or with a sealing on the seabed, the safest technology to avoid slipping. Sealing is often done by means of a suction anchor, a sort of hollow cylinder that sinks vertically into the sea floor. Each chain is most often connected to the float by a cable, made out of metal or synthetic fibres. The cables can be anchored directly to the ground, but in this case the number of cables and sealings must be increased. Some floats are designed for vertical tension cables; this technique provides excellent stability but it assumes a sturdy docking point on the sea floor, a more complex and more expensive construction than other devices, and makes it difficult to disconnect later for heavy maintenance purposes.

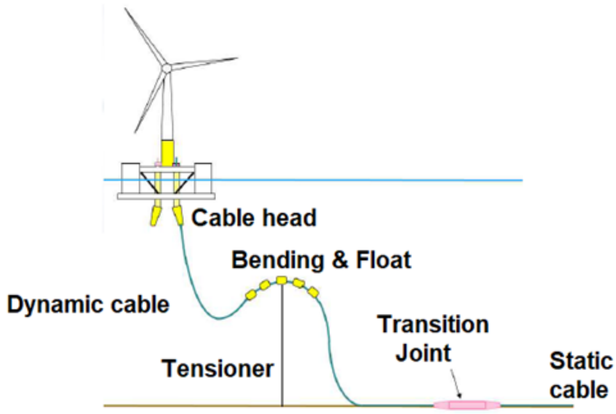
Whatever the solution, materials with high resistance to fatigue and corrosion are chosen, the latter coming from both the saline environment and the rapid colonization of underwater components by the oceanic flora and fauna ("marine growth").

Grid connection

For all offshore wind farms, the electrical current is transmitted by means of a cable connecting each turbine to a substation, at a voltage of 33 or 66 kV, depending on the power of the turbines. From the substation, a higher voltage cable (typically 150 kV) reaches the mainland. All these cables are static and suitable for alternating current.

In the case of a floating offshore wind, oscillations of the installation reverberate in the cables, which undergo a permanent movement: we now speak of "dynamic cables". The experience of floating offshore installations in the oil industry shows that the highest stress occurs at the cable head, i.e. at the point of connection with the portion fixed on the float. To reduce these constraints, and therefore the fatigue of this part of the cable, it is necessary to give an "S" shape to the portion located just underneath the connection, using a bending device, including floats and a tensioner, a technology perfectly mastered in offshore oil.

Figure 3: Outline of grid connection



Source : RTE (2019

In the current state of the art, dynamic cables are well mastered up to a voltage of 66 kV; it is therefore possible to route the current from a single floating wind turbine. However, higher voltage cables use insulators and external coatings of a different composition, which does not tolerate fatigue. The design of a floating substation therefore involves overcoming serious difficulties if it is to be provided with a dynamic cable of 150 kV AC, for example, up to the shore. The outlook remains encouraging in the medium term though, as a dynamic 115 kV cable has been successfully tested since 2010 by ABB group to supply alternating current to the Gjoa floating platform, operated by Equinor (formerly Statoil), for the extraction of oil and gas in the northern part of the North Sea.

ABB Group reached a new milestone in 2013 with the development of a dynamic 123 kV cable serving the Goliat floating platform, jointly operated by ENI and Equinor in the Barents Sea, again for gas and oil.[7] Finally, the French companies Ideol and Atlantic Offshore Energy (a subsidiary of the Chantiers de l'Atlantique group) unveiled on 4 June 2019 a complete floating substation project, designed in cooperation with ABB, which marks a new step forward.[8]

We note that it would also be possible to convert the alternating current to direct current, whose technology might be more suitable for dynamic cables. In a long-term vision, one could imagine that the substation is converting electricity into hydrogen, the removal of which being made by ship, allowing floating wind turbines to be installed far from the shore.

7. ABB, *World's longest, most powerful dynamic AC cable - Goliat floating oil and gas platform, Barents Sea*, Press Release, available on: https://library.e.abb.com

8. Ideol, *Ideol and Atlantique Offshore Energy launch the commercialization of the world's first floating electrical offshore substation*, Press Relase, 4 June 2019, available on: https://www.ideol-offshore.com.

The portion of the cables which rests on the seabed is always protected, either by trenching and backfilling in the sediments, or by laying rocks or a cover made of concrete or cast iron. Some projects foresee the possibility of disconnecting the dynamic cable from the static cable (as shown on figure 3 above). This manoeuvrable transition joint thus plays the role of the socket of a home appliance, which may be disconnected if necessary. The possibility of connecting or disconnecting the installations induces an additional cost, but it offers several advantages: it makes it possible to schedule the laying of the cables on the seabed before the arrival of the machines, to disconnect and bring them back to land for purposes of maintenance, and finally avoid tearing off cables in the event that a wind turbine breaks its mooring and starts drifting away.

First steps

Attracted by the prospect of a considerable market and pushed by governments anxious to promote a new source of clean energy, several industrial actors have been studying the floating offshore wind sector for more than a decade in a multi-step process. At the end of a preliminary phase on a computer, when the studies prove to be engaging, they proceed to the realization of a prototype on a reduced scale, then to the construction of a demonstrator of industrial size and then to the commissioning of a pre-commercial installation. The success of each step is of course required before getting the green light to engage in the following one. We find projects in the world at each of the four stages summarized above; none has yet reached the ultimate stage, which would be an installation competitive under existing market conditions.

The demonstrator stage followed the chronology below:[9]

- 2009: The first industrial scale facility was launched off Karmoy (Norway) by the Statoil group (now Equinor). Called Hywind Demo, it included a vertical float ("spar") and a 2.3 MW turbine supplied by Siemens, not specifically designed for this purpose.
- 2011: The Portuguese group EDPR, associated with the Spanish oil and gas operator Repsol, then put into service in Aguçadoura (on the Portuguese coast) the WindFloat model, equipped with a semi-

9. Statoil, *Hywind floating offshore wind 2017*, January 20, 2017; Energias de Portugal, "The Windfloat project", conference Atlantic Forum October 30, 2012; Japan Wind Power Association, "Offshore wind power development in Japan, February 28, 2018; Floatgen, press releases on the Internet site of the Floatgen Project, downloaded on May 9, 2019, available on: https://floatgen.eu

submersible 3-column float designed by the American group Principle Power Inc. and a 2 MW Vestas turbine, also from the standard range.

- 2016-2018: Japan took over, with four demonstrators of different models, installed one at Goto-Kabashima (2 MW), two at Fukushima (5 MW), all equipped with Hitachi turbines, and the last one at Kitakyushu (2 MW), implementing a semi-submersible Ideol barge with a two-bladed turbine.
- 2018: France connected to the grid in 2018 first the Floatgen wind turbine, off Le Croisic, equipped with a 2 MW turbine delivered by Vestas mounted on a semi-submersible barge designed by Ideol and built in concrete by the Bouygues group, and later on the innovative Eolink model (see box 1).

It should be noted that the three European pioneers formed consortia in which at least one actor has experience in offshore hydrocarbon exploration and production (Equinor, Repsol and Ideol). Indeed, large floating industrial structures have long existed in offshore oil and gas. They are often used as support for offshore loading or unloading facilities, near drill platforms or ports. Depending on the needs, various types of floats have been developed, combined with various types of mooring to prevent the installation from drifting with the currents. These models have been proven to withstand the constant onslaught of waves, including sometimes waves of storms, waves of typhoons and hurricanes or even "rogue waves" of enormous height.

Their approach attracted other providers from the oil and gas industry, who in turn designed models soon to be in the demonstration phase. Two examples are given here, coming from manufacturers convinced that the floating wind market will develop rapidly and that the components should be standardized for mass production at the lowest achievable price. In both cases, these are modular floats that are relatively easy to assemble:

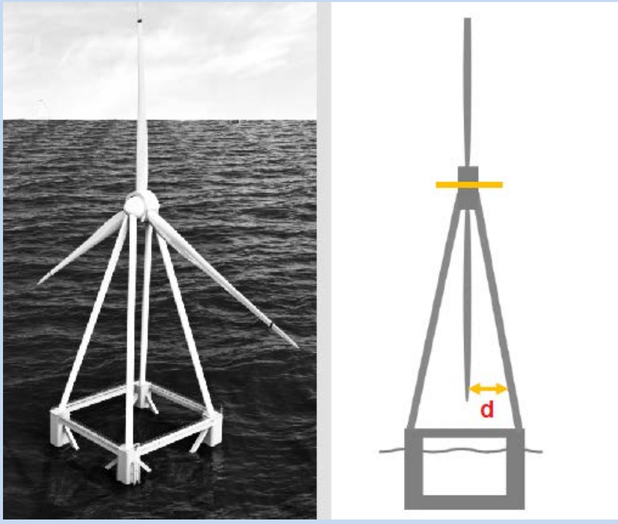
- The Shell Group, together with the German operator Innogy, is expected to test in 2020 the Tetraspar model, designed by the German operator Stiesdal, offshore Norway, with a 3.6 MW Siemens-Gamesa turbine.
- The Italian group SAIPEM plans to commission its Hexafloat model in 2022 on the west coast of Ireland. The manufacturer indicates that its float will be delivered in "kit" and that it will be able to receive any conventional turbine up to 15 MW.

All of the above-mentioned actors have transferred a proven expertise to a new sector of activity. They minimize the risks, but this choice has a setback: it leads to ignore the most innovative projects, led by newcomers (see box 1). The difficulty for the latter to break through stems from research work carried out in small structures, laboratories or universities, without sufficient links with large companies, thus facing obstacles to raise capital.

Box 1: Innovative projects

More than thirty models of floating wind turbines have been studied and many have successfully passed the prototype stage. We can mention two achievements at the demonstrator stage: the Eolink project, currently in test off Saint-Anne-du-Portzic (France) since 2018 and the X1Wind project, which will begin testing in 2020 in the Canary Islands (Spain). These are two very innovative models, which operate turbines designed exclusively for floating installations, with supports made out of charred metal girders, much lighter than ordinary masts, forming the edges of a pyramid (Eolink) or a tetrahedron (X1Wind). Moored on site by a single anchor point, they spontaneously orient themselves against the wind, which in turn reduces the cost of control devices and improves the load factor. In addition, the Eolink model offers a large distance between the end of the blades and the four supports (distance marked "d" in Figure 4); the risk of shock being reduced, lighter materials can be used for these blades; being less heavy, their rotation generates less fatigue in the structure. Eolink and X1Wind will now have to prove the reliability of the electrical connection, subject to higher degrees of freedom than in installations with multiple mooring points.

Figure 4: Specificities of the Eolink model

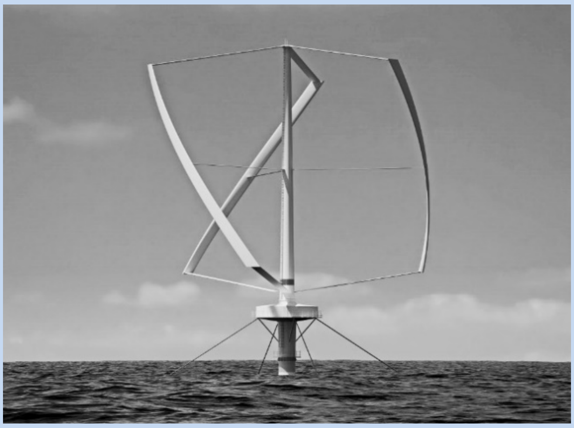


Source : Eolink (2019)

The SeaTwirl project is even more disrupting with the concepts in force today, since it implements a turbine with vertical axis, according to the principle studied in the last century by the engineer Georges Darrieus. By placing the rotor very close to sea level, this model significantly lowers the centre of gravity of the installation. Therefore, a float of small proportions is sufficient to ensure stability, an interesting point since the float represents a high fraction of the cost of a floating wind turbine (up to 40% in some cases).[10] The position at the bottom of the rotor also facilitates maintenance operations. Last but not least, Darrieus wind turbines can withstand shifting winds and seem little sensitive to the wake effect, which allows them to be set up at short distances from each other, hence reducing the required surface on the maritime domain. This design also limits the impact of roll and pitch. The SeaTwirl project has received financial support from NorSea, a specialist in offshore logistics, and the Belgian group Colruyt, whose subsidiary Parkwind operates large offshore wind farms in the North Sea. SeaTwirl anticipates the commissioning in 2020 of a 1 MW demonstrator off the Norwegian coast.

10. ECN, *Cost modelling of floating wind farms*, March 2016, page 28.

Figure 5: The SeaTwirl model



Source : SeaTwirl.(2019)

Finally, the Swedish group Hexicon is supervising the construction of a 10 MW demonstrator with a triangular semi-submersible float common in the oil industry. On two peaks of the triangle will be placed a wind turbine of 5 MW; to remain always facing the wind, the float will pivot around the third peak which receives the mooring and the electric cable. The launch is scheduled for early 2020 on the Dounreay-Tri site in Scotland.

Figure 6: The Hexicon model

Source : Hexicon(2019)

Achievements and projects

The pre-commercial stage

The validation of the first two demonstrators, Hywind and WindFloat, allows them to reach the stage of a wind farm gathering several identical machines.

The Hywind vertical float designed by Equinor has been selected in two projects:

- "Hywind Scotland", off Peterhead (Scotland), developed by Equinor (75%) and the Masdar Fund (25%): it includes five spar floats, each with a 6 MW turbine delivered by Siemens-Gamesa. Commissioned at the end of 2017, its availability rate approaches 95%, indicating low maintenance interruptions, and its load factor is close to 57%, confirming the choice of a well-winded location. Equinor says the investment cost per MW has dropped by 60 to 70 percent compared to its predecessor, Hywind Demo.[11]
- "Tampen": Equinor is now considering the construction of an 88 MW Hywind farm (11 floating wind turbines of 8 MW) at the Tampen site, to supply power to the Gullfaks and Snorre oil platforms in the Norwegian zone of the North Sea. Despite a cost per MW of 30 to 40% lower than Hywind Scotland, the project still requires a subsidy to become profitable.

Developers have adopted the WindFloat technology developed by Principle Power Inc. for three projects:

- "Windfloat Atlantic" (25 MW), located off Viana do Castello in Portugal: it will comprise three 8.4 MW turbines supplied by MHI-Vestas, under the WindPlus consortium, 79% owned by EDPR. Commissioning is planned for the end of 2019. This project has received European support under the NER 300 program and a loan from the European Investment Bank.
- "Kincardine" (50 MW), southeast of Aberdeen (Scotland), will consist of a 2 MW turbine and five 8 MW turbines, all commissioned from MHI-Vestas. The Spanish group Cobra Wind International holds the

11. N. Altermark, *Experience from Hywind Scotland and the way forward*, Hywind Scotland, conference FOWT-2019, 24 April 2019, slides 4, 6 and 9.

majority of shares in the KOWL consortium that is carrying the project; completion of the work is announced for 2020.

- "Les Eoliennes Flottantes du Golfe du Lion" (EFGL), in the Leucate zone in the French Mediterranean Sea (24 MW): it will deploy four 6 MW Senvion turbines. Led by Engie, the project involves EDPR and the Banque des Territoires (subsidiary of the Caisse des Dépôts group). The Eiffage group will build the floats.

Three other models of floats appear in the pre-commercial projects launched in France:

- "Eolmed" (24 MW) in Gruissan, in the Mediterranean Sea, will benefit from the experience acquired by Ideol with its floats in semi-submersible barges; built by Bouygues Travaux Publics, they will receive four 6 MW Senvion wind turbines.
- "Provence Grand Large" (24 MW), in the Faraman area in the Mediterranean Sea, will be equipped with tension leg platforms designed by SBM and IFPEN, two highly experienced players in the oil sector, and will include three Siemens-Gamesa turbines of 8 MW. The project is managed by EDF Renewables.
- "Groix floating wind turbines" (24 MW), in Brittany, carried by the French operator EOLFI, associated with the Chinese group CGN, will consist of 4 turbines mounted on floats designed by Naval Energies (subsidiary of the French Naval Group, a major player in the shipbuilding industry, ex DNCS) and made in collaboration with Vinci. The 6 MW turbines were to be supplied by General Electric, but this manufacturer gave up; EOLFI will turn to another supplier.

Selected options

All European developers of pre-commercial projects have chosen float models that are called 'agnostic' because they can receive existing turbines from the manufacturer's catalogue. With this choice, the project holders benefit from already proven high-power equipment, years of experience on these turbines in bottom fixed offshore farms and prices corresponding to a production in long series. This conservative option benefited three suppliers, who captured all the orders (Siemens-Gamesa, Senvion and MHI-Vestas). Taking advantage of this new opportunity, they could thus distance innovative turbine manufacturers, despite the intrinsic qualities of their products (see box 1).

The choice of floats inspired by the models used in offshore oil and gas and turbines with proven performance has facilitated the financing of projects. Holders of capital and banks consider floating wind turbines as a sector whose risks remain difficult to assess; the use of components validated in other sectors gives them some guarantees. The same reasoning applies to insurers, who determine their rates based on claim track record. In the case of floating offshore wind, they can overcome the lack of specific record through comparison with neighbouring industries when the equipment has similarities. For now, insurers' concerns are focused on mooring and electrical cables; they indicate that nearly 80% of the losses recorded in bottom fixed offshore wind, in costs for the operators, come from electrical faults.[12]

Another option preferred by most developers is to plan that heavy maintenance operations will take place onshore, with the failed turbine being 'disconnected' and towed to the port. The increased complexity of the mooring systems and electrical connections that this choice requires is offset by the lower cost of maintenance, avoiding particularly the guarantees required by companies for staff working at height on installations oscillating with the swell.

While some options are common, others are divergent, and their motivations explain why several models share the eight pre-commercial operations listed above. A first consideration concerns the port feature. The Hywind model has a vertical float with a submerged portion measuring approximately 80 meters, for a 6 MW turbine, in order to give it the required stability. Therefore, shore-based assembly requires an equivalent depth along the wharf, which is only found in a small number of ports. For other models, a dock depth of 10 to 15 meters is sufficient, which greatly expands the scope of possibilities.

A second consideration pertains to the nature of the components. Several pre-commercial floats can be built in concrete instead of steel, a solution that offers three advantages: the price of concrete remains predictable in the long run (while the price of steel fluctuates with the global market), the construction is done on the site, with local supply, and the concrete resists the aggression of the marine environment. The choice on the origin of the components adds up to that of their nature. Acceptability of projects sometimes involves high local content; in this case the model that maximizes on-site interventions will be preferred. A diametrically opposed solution is to manufacture the various elements of the float in a factory, regardless of its location in the world, and deliver

12. David Young, Predicting Dynamic Subsea Cable Failure for Floating Offshore Wind, ORE Catapult, September 2018, page 3.

them in the port area for the final assembly. Floats of modular design meet this objective.

This brief overview of the options offered to project promoters suggests that the diversity of pre-commercial stage models will not necessarily lead to the selection of a single winning model, ready for success in all markets. It seems likely that several types of installations will prove their technical reliability and their economic interest, making each one suitable to fulfil a specific type of tender.

Economic aspects

Floating offshore wind turbines have strengths that should eventually open large markets. Let's reiterate that the assembly is done on the mainland; mooring requires only uncomplicated foundations; ordinary tugboats are suitable for installation, unlike bottom fixed wind turbines, which require very expensive jack-up vessels; they access favourably windy areas, providing a high load factor; finally, their dismantling is also carried out on land, resulting in almost complete recycling, after all the equipment has been brought back to the port. This last point is gaining importance given the challenge of recovering rare earths and other critical materials contained in the turbines.

At the pre-commercial stage, these assets are not sufficient to make the investment profitable, so that most of the projects can only come about with the help of grants. As an indication, the four ongoing projects in France will receive an investment aid totalling 330 million euros (M€) and the power generated will be purchased at a preferential rate of 240 €/MWh for 20 years.[13] For its part, the Windfloat Atlantic project in Portugal received contributions of 29.9 M€ from the European program NER 300 and 6 M€ from the Portuguese government, supplemented by a loan on preferential terms of 60 M€ from the European Investment Bank.[14]

The need for support is due to many reasons. In the first place, this technology does not yet benefit from mass production, which applies to offshore wind turbines on foundation (for example the Walney Extension farm in the Irish Sea has 87 identical machines). Secondly, on-site monitoring devices remain experimental; these are cameras or strain gauges to monitor sensitive parts in order to reduce maintenance costs. At

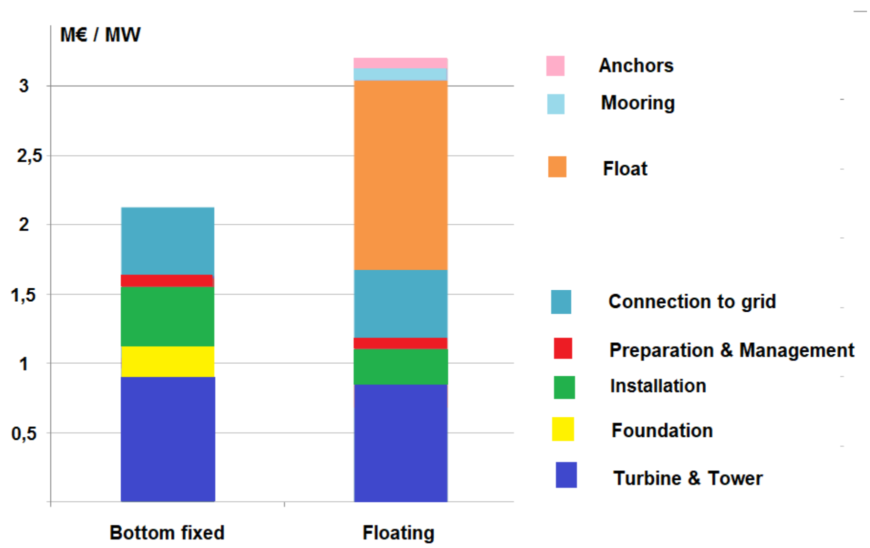
13. Ministère de la Transition Ecologique et Solidaire (MTES), "*Appel à projets pour le déploiement de fermes pilote éolien flottant en mer - Informations*", last update 4 Septembre 2018, available on the Internet site https://www.ecologique-solidaire.gouv.fr. Purchase price: *Enerpresse*, 13 April 2017.

14. European Investment Bank, Press Release, 19 October 2018.

this stage, it is therefore still impossible to pool the maintenance facilities, an action that noticeably contributed to reducing their cost in bottom fixed offshore wind. Thirdly, banks and investors do not appreciate the novelties; they demand a risk premium that significantly increases the cost of projects. The same goes for insurance companies, which only give their guarantee in exchange for high premiums. Finally, certification bodies also lack benchmarks and sometimes require costly measures to enhance the safety of projects, measures that can probably be adjusted with the accumulation of feedback.[15]

The coexistence of several float models in pre-commercial projects blurs comparisons with bottom fixed offshore turbines as the float accounts for a considerable fraction of the cost of a floating turbine. To overcome this unknown input, the reasoning is presented in terms of average cost. In spite of its artificial nature, this method points out components on which cost reduction appears to be paramount. Figure 7 clearly shows that the effort should be focused on the float. In this respect, concrete floats always cost less than their steel counterparts, which weigh between 1,000 and 1,500 tonnes depending on the model.[16]

Figure 7: Breakdown of the main CAPEX costs



Source: ECN, Cost Modelling of Floating Wind Farms, March 2016, page 28. Graphic adapted by the author. The ECN Research Center became TCO in 2018.

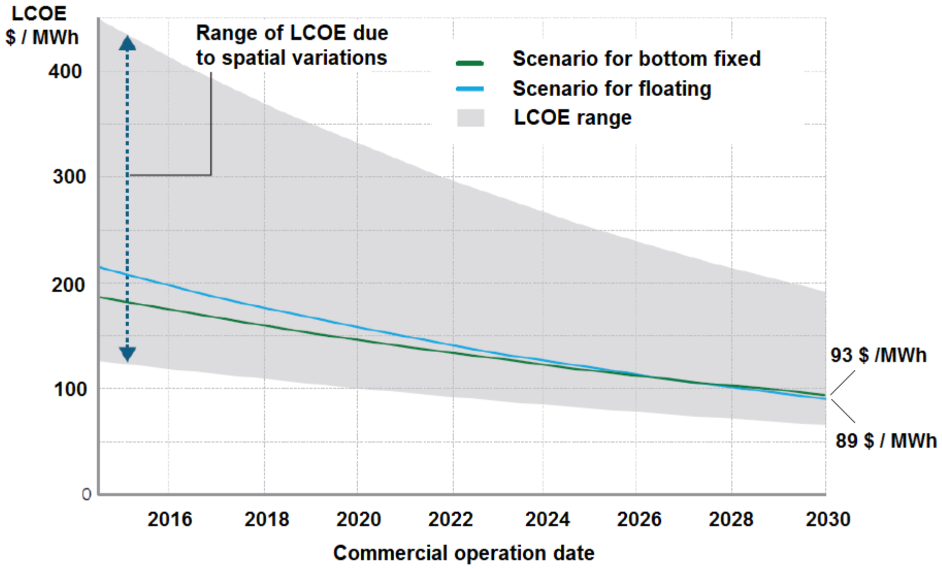
15. French projects suffer from an additional cost factor, linked to the weakness of scientific data available on the marine environment. Each site therefore calls for an in-depth study submitted to the Environmental Authority (body attached to the Minister in charge of the Environment) whose opinion determines the authorization to build and operate the facility. The lack of knowledge gives a great latitude of appreciation to this authority, which increases for the developers the uncertainty on its final opinion.
16. Carbon Trust, *Floating Offshore Wind: Market and Technology Review*, June 2015, pages 47 et 80. The exchange rate used here for the year 2015 is £ 0.72584 for one euro (Source: Eurostat).

Despite the difference on CAPEX, simulations show that the discounted cost (Levelized Cost of Energy - LCOE) of electricity generated by a floating offshore wind turbine should be lower than that of its equivalent on foundation. In fact, floating wind turbines will in principle incur lower maintenance costs (OPEX) and will generate more electricity per MW installed: being free from the constraint of depth, they can be installed in windier sites and on larger marine areas, thereby reducing the wake effect that impedes productivity. A 2016 British baseline study thus gives a theoretical cost of MWh slightly below 125 €/MWh for the floating wind turbine and slightly above it for a wind turbine on a foundation. The reality is other: contrary to simulations, floating wind turbines do not yet benefit from a capital cost identical to that of wind turbines on foundation, which dropped sharply in a few years, a crucial parameter in the final cost, and they have not yet reaped the benefits gained from the varied experiences and large series that now allow fleets on foundation to announce an LCOE significantly lower than 100 €/MWh.

A projection taking into account the learning effects and the effects of scale that will apply to floating wind turbines gives a drop in LCOE that is as fast as that observed for offshore wind turbines on foundation, as soon as the order book becomes comparable. If we assume that floating turbines will also benefit from some of the improvements expected for bottom fixed turbines (such as reducing the weight of the nacelle or lowering the cost of electrical components), the LCOE curves should cross before the end of the decade, according to an American study.[17] Figure 8 provides an illustration. The initial cost seems consistent with the LCOE disclosed in France, which includes the cost of electrical connection and the cost of preliminary studies. It stands at the same level as that of the first bottom fixed wind turbines awarded in France in 2012, higher than 210 €/MWh, and we have seen that this LCOE had dropped dramatically since 2019, falling to a reference rate of 44 €/MWh for the farm of Dunkirk.[18]

17. National Renewable Energy Laboratory, A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030, September 2016, page 119.
18. Commission de Régulation de l'Energie, Rapport de synthèse sur le Dialogue concurrentiel n°1/2016, page 9.

Figure 8: Cost reduction scenarios for offshore wind turbines on foundation & floating



Source: NREL (2016), op. cit.

Environmental impact and social acceptability

The impact of an offshore wind turbine on birds is the same for installations laid on foundation or floating; in contrast, it differs for marine animals. In principle, during the installation phase, a floating wind turbine generates less nuisance with ocean fauna than a bottom fixed wind turbine. With the latter, the driving of piles while building the foundation disturbs almost all the animals living in the work area. Anchoring a floating wind turbine remains much less intrusive. On the other hand, the movements of the float can be transmitted to the mooring chains and cables, causing noise and friction on the seabed, detrimental to their natural hosts. The precise impact varies with each site and calls for a thorough local study before any conclusion can be reached.

Beyond the building phase, a floating wind turbine imposes fishing restrictions higher than those of a wind turbine on foundation, in order to avoid mooring cables and chains being moved by trawls. A safety zone of about one kilometre in diameter applies, also prohibiting anchoring and underwater activities. The sole transit of small vessels remains authorized, up to 200 meters from the floats. This protected perimeter can become an area for animal conservation, as many marine species move away from the coast at the time of breeding. Here again, local studies, site by site, will be useful to fully appreciate the potential ecological benefits of a floating wind farm. Most operators of the first pre-commercial farms have agreed to contribute to these studies by equipping their facilities with monitoring devices and by respecting the observation protocols recommended by researchers.

Since floating wind turbines are less dependent on the depth and quality of the sea floor than bottom fixed offshore wind turbines, public authorities have greater freedom to choose the settlement area. As a result, sites with little attraction may be selected, away from the more touristic and fishing areas, and also from bird migration corridors, so as to reduce the nuisance and the risk of legal action against projects.

Box 2: Floating offshore wind in the United States

The USA exploited onshore wind power very early; by the end of 2018, they had achieved an installed capacity of 97 GW, or 17% of the world fleet, making it the second largest country, behind China, which commissioned 207 GW (45% of the world fleet).[19] Unlike China, the USA has shown little interest in offshore wind until 2016. That year, two federal departments, Energy (DOE) and Interior (DOI), submitted a joint report detailing the country's wind energy potential and unveiling a strategy for its development. This report highlights the benefits of floating wind.[20]

Three maritime zones show favourable wind regimes:

- The North Atlantic coast, facing New England,
- The Pacific, facing California,
- The shores surrounding the State of Hawaii.

These areas face precisely States sensitive to climate issues and determined to develop their renewable resources; California and Hawaii have adopted a target of 100% renewable energy by 2045.

At the end of 2018, the federal authority empowered to administer the maritime domain had awarded 15 concessions, all on the Atlantic coast. In May 2019, three projects had reached the next stage and their application for an operation permit was under way (Vineyard Wind, Deepwater Wind South Fork and Bay State Wind); all three are located in the State of Massachusetts and are appropriate for wind turbines on foundation.

19. Global Wind Energy Council, *Global Wind Report 2018*, April 2019, pages 26 et 29.
20. Department of Energy & Department of the Interior, *National Offshore Wind Strategy*, 2016.

The States of California, Maine and Hawaii, however, show a keen interest in the floating sector, as their windiest areas are located in marine areas too deep for bottom fixed turbines. Five areas are under preliminary study, three in California (north: Humboldt, centre: Morro Bay and Diablo Canyon) and two off Hawaii (Oahu North and Oahu South). California's prospects have sparked great industrial interest: no less than 14 consortia have filed an 'expression of interest' for the subsequent allocation of concessions (and four consortia for Hawaii).[21]

Maine, however, has been the first State to support a pre-commercial project, "New England Aqua Ventus I", consisting of two 6 MW VolturnUS-type concrete float turbines, a model developed by the State University. This project received a grant of $ 10.7 million from DOE.[22]

21. E. Lindow & J. Barminski, Bureau of Ocean Energy Management (US Department of the Interior), conference FOWT-2019, 25 & 26 Avril 2019.
22. Description of the project Volturn US "Offshore wind energy" available on the Internet site of University of Maine (May 2019): https://composites.umaine.edu/offshorewind/

Suggestions regarding public policies and industrial strategies

The strengths of Europe

The EU has adopted a target of 32% for the share of renewable sources in its final energy consumption in 2030. Its long-term strategy aims at a largely carbon-free economy in 2050, or eventually at carbon neutrality, which would imply a share of renewable energies between 81% and 85% in the electricity mix.[23] Projections available for this time horizon show that such a ratio calls for sustained growth in photovoltaic and wind capacity. Important 'fields' remain on land; however, competition between different uses in suitable areas increases the cost of land and limits prospects. The EU has a considerable resource in offshore wind energy, but the easily accessible fraction, already exploited by wind turbines on foundation, is concentrated in the southern part of the North Sea, restricting access to a small group of countries. About half of the most favourable zone is in the UK, which is about to leave the EU. The technology of floating offshore wind significantly expands the resource's perimeter in Europe and around the world, as most of the world's windy areas at sea are unsuitable for bottom fixed turbines. A rise in EU floating offshore wind industry therefore offers several benefits: increasing the chances of achieving ambitious targets, spreading electricity generation capacity in a larger number of States and opening up of a promising global market for European players, nowadays frontrunners.

Europe is home to the greatest number of achievements and advanced projects, giving its operators a competence still rare at international level. Their expertise is enriched by feedback from bottom fixed offshore wind farms, of which nearly 80% of the installed capacity on the planet is located in European waters.[24] Among the OECD members, our main commercial competitors, South Korea, the United States and Japan, have only recently discovered the benefits of this technology and engage with several years'

23. European Commission, In-depth analysis in support of the Commission communication COM(2018) 773, 28 November 2018, page 75.
24. Global Wind Energy Council, Global Wind Report 2018, April 2019, op. cit.

lag behind the path taken by Europeans. The EU holds a specific lead on South Korea and Japan, as both countries do not operate offshore oil or gas drilling platforms; yet we know that the floating offshore wind sector has multiple components developed for these platforms. China follows a different approach, by taking stakes in existing projects or pioneer companies (the China Three Gorges group holds, for example, 23% of the capital of the EDP group).

In the first chapter, we have highlighted the complexity of the physical phenomena to be taken into account when designing reliable equipment. The float layout involves modelling supported by mathematical tools such as time analysis and fluid and solid equations, which require high computing power. European consulting firms are well-equipped, both in terms of human skills and IT resources, to carry out this work. Europe has also opened several research and experimentation centres, associated with university teams, to complete the necessary tests. There are test sites in Scotland, France, Ireland, Norway, etc.

The first chapter also emphasizes the phenomenon of material fatigue, particularly pronounced in the floating offshore wind sector. Failing to completely remove this phenomenon, its consequences can be reduced by ensuring that each component is of high quality. This quality is achieved by the choice of special alloys, with the desired mechanical properties, as well as rigorous manufacturing processes, which avoid the formation of microcracks or fragile areas in the product. In this field too, firms from various European countries have the necessary know-how.

The preceding paragraphs thus raise a legitimate question: what would be the conditions for Europe to maintain its lead? This question becomes very important when floating is considered to be the dominant technology in offshore wind, including in shallow seas, because machines are assembled on land, do not require ships specialized for their implementation and seem little intrusive for the natural environment. An expert said that '*the float will be for the future of offshore wind what the battery is for tomorrow's car*'.

Considerations relating to the European framework

As floating wind technology is still in a nascent phase, public support for research seems essential. Companies will certainly undertake a private research effort, but given their concern for competitiveness on activities constituting their core market, available funds will remain limited. Public support comes from national research budgets or EU instruments; the latter primarily sustain actions selected in the Strategic Plans for Energy Technologies (SET Plans), intended to create synergies between research actors. The floating industry has been included in the SET Wind Plan, and the EU is fulfilling its role in supporting research. Of eight floating wind research projects recorded in the Horizon 2020 program at the end of 2018 and totalling an effort of 28.8 million euros (M€), EU funds provide 23 M€, almost 90% of the planned expenditure.[25] This amount, however, compares unfavourably with the recently announced 28 M$ by the US agency ARPA-E on the ATLANTIS project alone, designed to shape lighter turbine rotors for floating wind.[26] ARPA-E did not yet define a program dedicated to offshore wind, but its leaders have a freedom of action facilitating quick decisions.

Beyond support for research, the EU provides investment support in the form of soft loans through the European Investment Bank (EIB) or contributions from the NER 300 program. Several Member States also contribute to the financing by providing an initial grant. National contributions are subject to the approval of the European Commission. The services of the Directorate General of Competition, responsible for reviewing notifications, have so far approved without any difficulty subsidies paid directly by the States as well as guaranteed purchase rates for the electricity generated by the first pre-commercial farms. However, each project is subject to a specific review, so that neither States nor developers have long-term visibility. In addition, the rules governing support for renewable sources of electricity will come to an end in 2022,[27] and no one knows what will be the future state aid guidelines of DG Competition. The latter advocates in particular "technologically neutral" tenders that handicap emerging sectors.

The supremacy of competition law and the resulting uncertainties hinder any prospect of industrial policy, when the need for such a policy is expressed in various capitals and even by some European commissioners. Clearly, floating offshore wind could be one of the European industrial priorities and therefore benefit from a specific development framework. This framework would not be limited to the competition rules but would

25. See: Community Research and Development Information Service (https://cordis.europa.eu), page Project & Result, code Floating Wind. The 8 projects taken into account (9 May 2019) are: EDOWE, FLOTANT, FLOATMAST BLUE, LEADFLOAT, LIFE 50 PLUS, PIVOTBUOY, SAFS et SATH.

26. Advanced Research Projects Agency-Energy (ARPA-E), The Aerodynamic Turbines, Lighter and Afloat, with Nautical Technologies and Integrated Servo-control (ATLANTIS) programme, DE-FOA-0002051, 3 February 2019.

27. European Commission, Guidelines on State aid for environmental protection and energy for the period 2014-2020, 28 June 2014, ref. C 200/1. The Commission will prolong until end 2022 the validity of those State aid rules (Commission Press Release, 7 January 2019).

also include an effective enforcement of the European regulation on the filtering of foreign direct investment, recently approved by the Council and the Parliament. To understand the usefulness of this enforcement, we should remember that the Portuguese EDP group has been the subject of a takeover bid by China's Three Gorges group, wholly owned by the Chinese State; EDP is one of the world leaders in floating offshore wind through its subsidiary EDP-R, which has received a 60 M€ loan from the EIB for the WindFloat Atlantic farm project.[28]

Considerations relating to national policies

The price trajectories followed in bottom fixed offshore wind farms show a significant "scale effect": the average price falls as the volumes commissioned increase.[29] There is no reason why this virtuous trend would not apply to floating wind, should actors be assured of regular development over the long term. With such a visibility, port authorities will make the necessary investments, manufacturers will launch mass production, feedback will drive a fair allocation of financial risks, banks will lower their rates, capital will flow in, and so on.

Unfortunately, no European country seems ready for long-term commitments. France appears to be the sole State that has chosen floating offshore wind among renewable energy sources to be developed by 2030,[30] but according to a program that lacks continuity and remains unclear beyond 2022. The Minister indicated that the new version of the "Multiannual Energy Program", which is currently under consultation, would provide for three calls for tenders for commercial floating farms, one in southern Brittany in 2021 (250 MW) and two in the Mediterranean (250 MW each), expanded later to reach more than 750 MW 'in case of good performance on tariffs'.[31] For its part, the United Kingdom does not intend to differentiate its calls for tenders for offshore wind according to technologies; floating wind farms are expected to win against their bottom fixed rivals when their costs become lower.

28. European Investment Bank, Press Release, 19 October 2018.

29. Let us insist on the fact that we are talking about an average price, which may hide significant variations between projects.

30. Ministère de la Transition Ecologique et Solidaire (MTES), *Programmation Pluriannuelle de l'Energie – Synthèse*, 23 January 2019, page 22, available on www.ecologique-solidaire.gouv.fr. These indications are also included in the draft National Energy and Climate Plan submitted by France to the European Commission on the same date.

31. Ministère de la Transition Ecologique et Solidaire (MTES), Press Release, 14 June 2019.

The hesitations of France and its neighbours are explained by the existing constraints on public budgets and by the fear of a price of MWh still high during the first years of deployment of the technology, without certainty on the longevity of jobs created. Few people show the "willingness to pay" that has emerged in Denmark and Germany in favour of onshore wind and solar photovoltaic in recent decades, and the latter country has long distorted power prices to protect its industry, to the detriment of domestic consumers, a situation that is less well tolerated by DG Competition.

Governments, however, hold several levers for reducing the cost of projects; they pertain to the regulatory aspect. Clarify legislative texts, simplify administrative procedures, shorten deadlines for obtaining permits, speed up the processing of lawsuits, etc. These measures are not costly for the States and very beneficial to the actors. France has embarked on this process, which seems to have paid off for the latest bottom fixed offshore wind project in Dunkirk, a process that should also facilitate the preparation of the four ongoing floating wind farm projects. Public authorities could go further, taking responsibility for removing the risks of acceptability at an early stage of the projects regarding fishing, tourism, real estate, maritime traffic... This orientation does not mean a relaxation of the rules; on the contrary, strict provisions are all the more important to gain public acceptance of floating farms whose size is expected to grow; we are referring here to the implementation of these rules by public authorities (one-stop shop, processing time, etc.).

Considerations relating to industry

Operators face the need for closer cooperation between actors who have sometimes worked separately so far. Thus, turbine manufacturers have realized that they will have to take into account the weight constraints of the nacelles, the dynamic interactions between their machines and the floats, as movements of the latter generate particular constraints of bending and torsion on the masts. The small number of floating wind turbines in service complicates this analysis for manufacturers, who want to overcome the specificities of each site to process these data, but who also receive requests to deliver different turbines according to the local wind regime (strong or moderate winds for example).

In addition, European industrial players perceive the need to reach a critical size, considering the heavy investments required by each project; the recent ties decided between the French groups ENGIE and the Portuguese EDP-R illustrates this desire to combine forces.

For project developers too, the scheduling of operations calls for new cooperation. They already knew how to secure the chain of their suppliers; now they have to organize tasks that run in parallel. Indeed, the establishment of the electrical connection cables and mooring devices can take place before the arrival of the turbines on the site, so as to make the most of periods with good weather conditions. The assembly of the floats and the mounting of the wind turbine are carried out in the ports; these operations therefore require ground locations and dedicated docks.

Port developments for floating offshore wind inflict difficult decisions for managers. The first one is consenting to considerable investments to expand the areas of activity (a storage area may need 30 ha),[32] consolidate the soil (the load is around 30 t/m^2),[33] strengthen the wharves, build sheds, etc. without visibility on the development of the sector, which still depends on governmental choices. In this regard, tenders are now decided at the national level. Given the commitment of some regional authorities to floating offshore wind, these authorities could be allowed to launch a local call for tender; these regions would then solely assume a portion of the resulting burden, particularly on the MWh price.

A second decision regards the nature of the port development, which varies according to the float model chosen; however, there is still uncertainty about which models will become common in the future, beyond the first pre-commercial farms. Despite these doubts, some regions of Europe are establishing an appropriate port infrastructure for floating wind farms. For example, Scotland is organizing a real network of ports adapted to this technology, and three regions in France, Brittany, Occitanie and Région Sud (previously named Provence-Alpes-Côte d'Azur) are already developing dedicated ports (the Occitanie region values at 200 million € the works it launched on the site of Port-La Nouvelle).[34] It should be noted that this shore-based equipment, at the expense of local authorities, avoids developers having to support the high costs of using specialized vessels, since installations assembled at the port can then be transported on site by means of ordinary tugboats.

Will the burden falling on States (subsidies), local public authorities (port facilities) and consumers (high kWh price) be offset by a resurgence of economic activities and new jobs? The offshore bottom fixed wind power sector has set a happy precedent for the EU, with the committed States

32. A. Lee, "Port readiness for the construction of 1 GW wind farm – A Scotland case study", ORE Catapult, conference FOWT-2019, 25 April 2019, slide 4.

33. D. Massol, *Extension of Port-La Nouvelle*, Région Occitanie, conference FOWT-2019, 25 April 2019, slide 4.

34. *Ibid*.

having retained most of the added value and European companies having acquired expertise that they can value today in countries with an adequate maritime façade.

It is not certain that floating offshore wind will follow a similar path, as it is attracting international interest even before the technology has proven its reliability on a large scale. Thus, European groups are led to establish cooperation earlier than their predecessors in the bottom fixed wind power. In this way, they open their partners' access to their own assets. We can mention in this register the agreement between Equinor (Norway) and Korean National Oil Corporation (South Korea), those of Ideol (France) with China Steel Corporation (Taiwan), with Acacia Renewables (a wholly-owned subsidiary of Macquarie Capital Japan) and recently with Shinzen Energy (Japan), or that of EnBW (Germany) with Trident Winds Inc. (USA). All of these agreements respond to a business logic, eager to penetrate markets likely to develop rapidly. They will gain additional experience which will also benefit the EU, but which could also result in the EU losing its lead in the absence of a proactive policy.

Conclusion

In a world that is urged to accelerate the decarbonisation of its energy sector in order to be on a trajectory compatible with the Paris Agreement, floating offshore wind technology appears to be one of the most promising on a large scale. It opens access to an immense resource, relatively well-distributed on the surface of the globe and available over long periods while exerting a moderate environmental impact. This technology still requires progress; it faces a hostile natural environment and it implements equipment whose development is not yet completed.

Several European countries have revealed the potential for rapid progress in the sector, although the evidence of sustainability is not yet comprehensive; even better, their first tests led to the conviction that cost reductions are within reach in the medium term, likely to make this technology competitive with its rivals in the field of renewable energy. Four countries have reached the pre-commercial stage, with farms of a significant size, able to validate the different models of floats and prepare responses to future calls for tenders: France, Norway, Portugal and the United Kingdom (Scotland). These States, however, are reluctant to provide the additional effort that will remain essential for a few more years to achieve a decisive reduction in costs.

Their technological breakthrough has aroused strong interest from several non-European countries with a maritime façade, either because they lack other natural resources (South Korea and Japan), or they are very committed to renewable sources (West Coast States of the USA), or they sense a sizeable emerging market (China). These countries are expanding their research programs and launching pilot projects while their companies enter partnerships with their counterparts in the old continent and take part in European projects.

In the EU, there is often a lack of commitment to enter promising sectors, be they information and communication technologies or electric vehicles. Floating offshore wind has the characteristics of a sector with a promising future, because it involves a global market and because it retains considerable opportunities for improvement. It would be unfortunate if Europe were to lose its lead due to lack of support at the right time. This support cannot be limited at sub-national or national level; here we plead for the creation of a "European alliance of floating offshore wind", like the

"European battery alliance", with the EU facilitating exchanges within a network of industrial actors, structuring an extensive research programs, providing the missing capital for innovative projects, defining the required skills, identifying the necessary regulatory changes, etc.

While concerns are increasingly expressed about maintaining a vibrant industrial sector in Europe, floating offshore wind deserves to be deemed as strategic.

French Institute
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Relations