floating WIND turbines

To reach the most sustained and powerful winds, and to preserve the view, offshore wind turbine deployment needs to be practical in deeper waters.

By Dominique Roddier and Joshua Weinstein

Renewable energy is becoming an increasingly important component of the electricity-generating infrastructure. The European Commission, for instance, has mandated that 20 percent of all electricity generation in its member states must come from renewable sources by the year 2020. Although the United States has not yet set mandatory targets, the U.S. Department of Energy has recently initiated a $16.7 billion program focused, in part, on building the domestic renewable energy industry. The current administration is trying to encourage a goal of renewables achieving a 25 percent market share by 2025.

Among all available renewable energy sources, wind has the potential to make the most significant contribution. Wind turbine technology is mature and bankable, and wind resources around the world are abundant. But as wind farm developers install increasingly larger turbines, the visual impact and noise generated by the machines—as well as the need for large expanses of land to set up the farms—have slowed down terrestrial wind power expansion.

Those issues are not as problematic when wind turbines are built at sea, and so it was inevitable that wind farms would go offshore. Within the past ten years, the coasts of Denmark and the North Sea basin have become the sites of increasing numbers of wind turbines. According to data from the European Wind Energy Association, the total offshore installed capacity at the end of 2009 was 2 GW. The Crown Estate, which administers the seabed in the United Kingdom, recently approved devel-

Dominique Roddier is the CTO of Principle Power, and a partner at Marine Innovation and Technology, the engineering firm which developed the WindFloat. He is an ASME member and the Offshore Technology Symposium Coordinator of ASME's Ocean Offshore and Arctic Engineering (OMAE) conference. Joshua Weinstein is an engineer at Principle Power focusing on global business development and turbine manufacturer interface activities.

▲ Mounted on semi-submersible platforms, the floating wind turbines being developed by Principle Power can be built in shipyards and towed into place.

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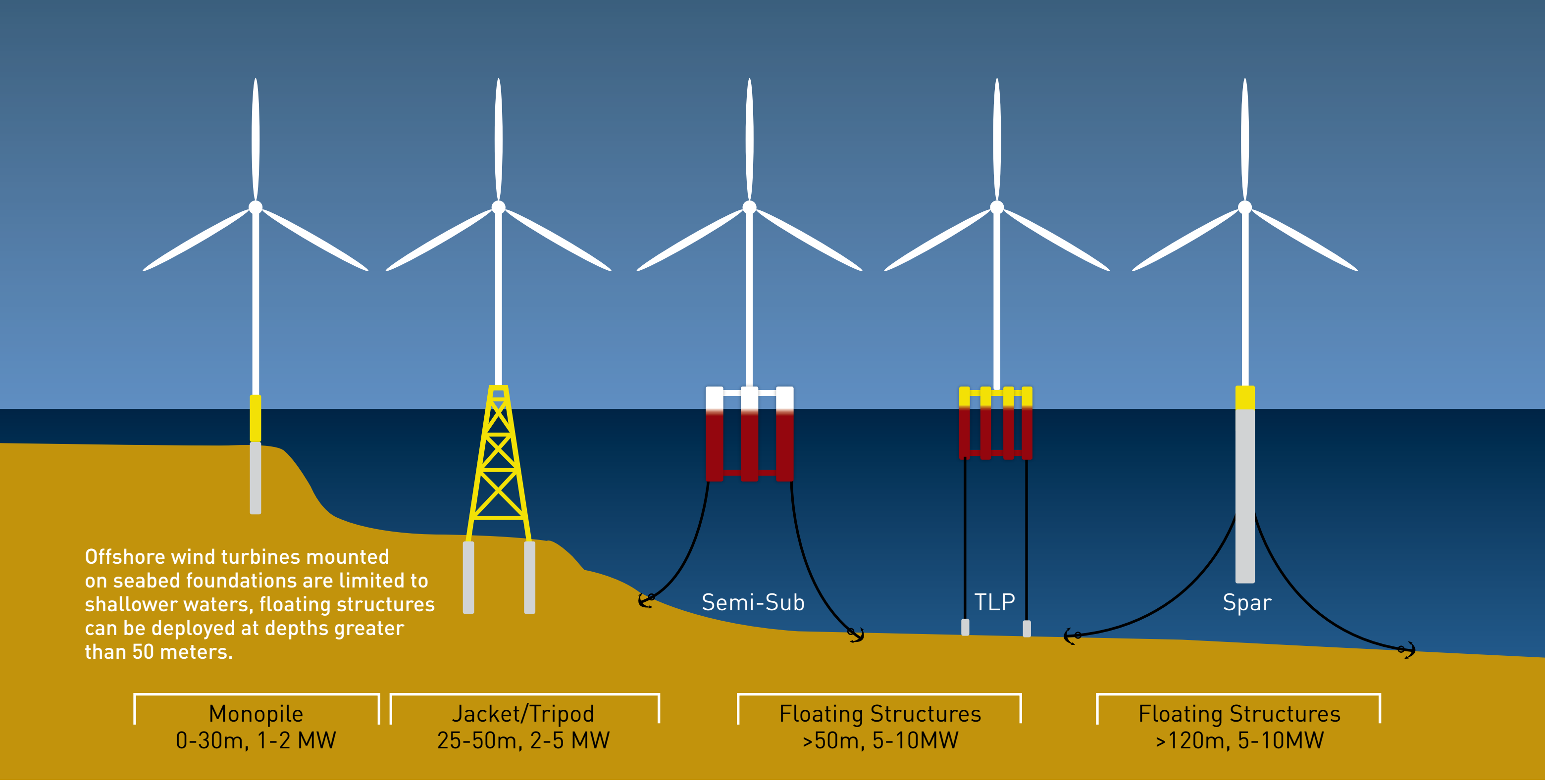
opment of nine new offshore wind farm sites in addition to several already in operation. With a target of 25 GW of wind power generating capacity by 2020, the U.K. is poised to be the largest offshore wind energy producer.

The offshore wind turbines that have been built so far all have foundations that extend to the seabed, and this necessitates shallow water sites generally close to shore. These sorts of sites, such as those found in the North Sea basin, are limited to geographical areas that do not always have the best wind resources. In the United States, government regulation and private sector opposition have limited deployment of offshore wind farms. The first proposed offshore wind project, Cape Wind in Nantucket Sound, has been stymied by litigation for years. The most recent setback has come from Native American tribes that argue that the wind farm would obstruct their view of the sunrise and adversely affect their religious and spiritual practices.

One way to avoid such litigation is to site offshore projects over the horizon, in deeper water. An added benefit to siting wind farms farther from shore is that the exploitable wind resource is superior. And many major cities in Europe, the West Coast of the United States, and Japan are located near waters that are too deep for conventional offshore wind development.

In the wind power industry, water depth is described in three distinct zones: shallow (less than 20 meters deep), transitional (between 20 and 50 meters) and deep (greater than 50 meters). Fixed monopile structures are economically suitable for projects sited in shallow and some transitional water depths. To reach deeper waters, developers can opt for either a jacket or tripod structure, both of which feature a wider footprint and smaller diameter tubulars. The Beatrice demonstration project off the coast of Britain was the first transitional water depth installation of a jacket type substructure for use with wind turbines. Two 5 MW RePower turbines were deployed on jackets and installed in a depth of 45 meters.

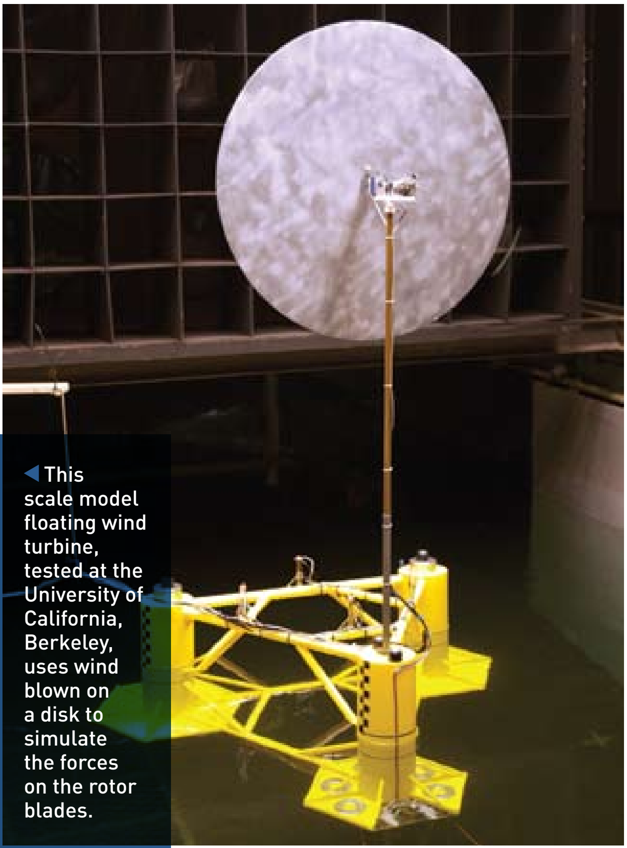
Experts argue that jacket foundations for wind turbines can be installed economically in depths of up to



Offshore wind turbines mounted on seabed foundations are limited to shallower waters, floating structures can be deployed at depths greater than 50 meters.

50 or 60 meters. Many coastal energy markets require solutions in even deeper water. The oil and gas industry faced a similar dilemma when hydrocarbons were found in very deep waters, and turned to floating platforms. Now, floating wind turbine technologies are emerging as the offshore wind industry learns the costs of near-shore development.

Currently half a dozen companies are working on commercial deep-water wind turbine technologies at various stages of development. Because offshore wind turbines inherently have a large mass in the nacelle and rotor at an elevation some 80 to 100 meters above the sea surface, stability of the floating platform is a challenge.



◀ This scale model floating wind turbine, tested at the University of California, Berkeley, uses wind blown on a disk to simulate the forces on the rotor blades.

Solutions to this challenge fall into three different stability criteria. The first category is gravity-based, with the center of gravity of the platform aimed at being as low as possible, well under the center of buoyancy. This calls for a very deep hull, similar to offshore spars. A second category is water-plane inertia based, where the floater surface area at the free surface is wide—that is, it has a large geometrical inertia. Traditional semi-submersible or column-stabilized units are examples from the offshore petroleum industry. Finally, some solutions are externally constrained for stability. The platform may be unstable when not moored, but is kept upright through large external mooring forces. Tension-leg platforms are moored to the seabed by stiff vertical tethers called tendons.

Each floating platform technology has a proven analogue and track record in the oil and gas industry. When considering a floating support structure for an offshore wind turbine, several logistical and economic considerations need to be assessed. For instance, in the case of a spar, while hull motions permit the use of existing commercial wind turbine technology, the necessary hull draft precludes using the spar in less than 120 meters of water. The spar also must be in a protected area for final upending and installation of the wind turbine. Locations in which such depth and weather protection criteria can be met are limited.

Semi-submersible designs also permit the use of existing and proven commercial wind turbine technology. The structure can be fully assembled in a sheltered harbor, quayside, and then wet-towed to its final installation site because the structure is inherently stable at both transit and operational drafts. What's more, the minimum draft requirement imposed is greatly reduced when compared to a spar.

Tension-leg platforms might conceivably use existing turbine technology, but the engineering and design of such a structure can be challenging. The difficulty resides in the natural frequency similarities and potential for structural coupling between the wind turbine and the tendons of a TLP mooring. The stability of a TLP is gained through the mooring and requires additional expensive stability aids such as buoyancy modules when the system is not moored. Further, the installation of TLP tendons typically requires significant seabed preparation, which may drive up the project costs. In addition, tension-leg platforms are typically limited to areas of deep-water free from significant tidal fluctuation and current.

Deploying wind turbines offshore creates the potential for innovative designs. For instance, wind turbines may have faster rotor speeds due to less stringent noise restrictions. In addition, some groups are investigating the use of downwind and vertical axis turbines due to their potential for reduced maintenance and higher fatigue resistance.

The financial risk involved with building these large-scale projects is deterring such innovations. Companies like StatoilHydro, the developer of the HyWind project, and Principle Power, which is working on the WindFloat concept, are partnered with existing commercial offshore wind turbine manufacturers and are designing their floating foundations to be compatible with many kinds of turbines. This reduces the technical and financial risks significantly, since the hulls are designed according to offshore oil and gas rules, leveraging the knowledge base of an industry with decades of experience in building floating structures.

The engineering requirements for the design of floating offshore wind turbines are extensive. Wind turbine design tools usually consist of an aerodynamic model (for flow around the blades) coupled with a structural code. Aero-elastic models used in the design of fixed turbines calculate all the necessary loading parameters, from turbine thrust and power generation, to blade and tower deflections. Common models are FLEX 5, developed by Stig Øye at the Technical University of Denmark, BLADED from Garrad Hassan & Partners Ltd., and ADAMS from MSC Software.

The design of floating structures usually involves hydrodynamics tools such as WAMIT Inc.'s software for studying wave interactions with vessels and platforms, or Principia's DIODORE, to predict the hydrodynamic quantities, such as added mass, damping and wave exciting forces, which are used as a kernel in the time domain simulations.

External forces, including the mooring system and viscous effects, require codes such as Orcina Ltd.'s OrcaFlex or TimeFloat, developed by Marine Innovation & Technology, which perform the Fourier transform of the frequency dependent hydrodynamic quantities. Analysis of the wind turbine and foundation separately is not sufficient in the case of a floating turbine because the interaction between the wave loads on the substructure and the dynamic loads due to wind turbine thrust forces on the tower and turbine cannot be neglected.

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There are currently no commercial numerical design tools on the market capable of calculating the complete response of a floating wind turbine and substructure fully coupled. The National Renewable Energy Laboratory has been leading a benchmarking exercise to compare various R&D tools since 2007. This effort shows promising results according to a paper at this year's European Wind Energy Conference. Some improvements still need to be addressed, specifically in the diffraction and radiation calculations of non-spar hulls, where Morison's equation assumptions are invalid. The complete design of a floating wind turbine using fully coupled tools is detailed in a paper to be presented by Christian Cermelli and co-authors at the Offshore Technology Conference in May.

▲ In a fjord southwest of Karmøy Island, Norway, the HyWind spar-type hull supports a 2.3 MW turbine. The hull displaces some 5,300 tons.

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In marine projects, design tools typically need to be validated against model tests in a wave tank or basin. Such work is performed frequently, and scaling laws are very well defined. In the case of an offshore structure, the ratio of inertial forces over gravitational forces (Froude number) is dominant, and Froude scaling is applied. This means a set of mathematical rules must be stringently applied to extrapolate results from model-scale testing in the laboratory environment to full-scale deployments in the field. For example, if λ is the scaling factor, then wave height scales according to λ, wave period according to √λ, and so on.

Unfortunately, in the case of a floating wind turbine, the wind loading on the turbine does not scale according to Froude's law. Extrapolating model-scale results to full-scale is therefore challenging. Modeling a wind turbine is possible, but the numerical tools must be used at model scale only.

A different approach replaces the model-scale wind turbine with a large disk. The disk area is calculated so that the thrust forces induced at a given wind speed is Froude scaled. Principle Power has followed this approach in testing the WindFloat at the University of California, Berkeley, towing tank.

Due to the precision of numerical tools, model-scale test campaigns and the mathematical existence of scaling laws, sub full-scale prototypes installed in the ocean do not add significant value to technology development or design. Measured motions in the field are difficult to correlate back to the numerical models due to the difficulty in measuring wind and wave conditions properly. In addition, nothing of significance is learned from sub full-scale testing from an installation and commissioning perspective, since the equipment used is at least an order of magnitude smaller in both size and complexity.

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In 2007, Blue-H Technologies BV, based in the Netherlands, was the first to install a floating wind turbine off the coast of Puglia in southern Italy. The technology is based on an offshore TLP structure where hull stability falls in the externally constrained category. Although this first platform was sub full-scale and later decommissioned, Blue-H is now developing a custom-made two-bladed turbine and has plans of deploying further prototype units.

The Norwegian firm StatoilHydro in 2009 installed a 2.3 MW Siemens turbine on the HyWind hull, a spar platform whose stability falls in the gravity-based category. The project cost was about 55 million euros. The hull, which was designed by Technip, a very well known and established engineering firm in the oil and gas industry, is about 100 meters deep and displaces some 5,300 tons.

The project's engineers successfully overcame some significant challenges. The hull was towed horizontally into a fjord where it was upended. Workers then mounted the tower, nacelle, and turbine on top of the hull using complex installation cranes in a floating-to-floating pick operation. The prototype is currently floating 10 kilometers southwest of Karmøy Island and is in the midst of a two-year test campaign.

Recently, the Portuguese utility EDP partnered with Principle Power to install a multi-megawatt full-scale floating wind turbine prototype off the coast of Portugal in 2011. The prototype, a semisubmersible fitted with water entrapment plates at the base of the columns, and with the turbine and tower affixed asymmetrically on one of the columns, is known as the WindFloat. The platform's three columns are spaced approximately 35 meters apart, to provide stability even when operating without ballast. This will permit the fully commissioned system to be wet-towed from the fabrication yard to offshore installation site.

The WindFloat system represents a sea change in offshore wind installation methodology, since its inherent stability permits most assembly and qualification activities to be performed quayside in a protected environment. Further, this methodology eliminates the need for specialized heavy lift offshore equipment and specialized operations such as a floating-to-floating pick.

The platform's innovative water entrapment plates increase the hydrodynamic added mass of the platform and add significant viscous damping, which reduces the structure's motions in waves.

The hull is also fitted with a closed-loop water ballast system, which moves water between columns, to compensate for changes in average wind velocity and direction. Thanks to this system, the mean position of the tower is almost exactly vertical, which will improve the turbine efficiency and protect the structure in extreme conditions.

The overall design efficiency and key components in the fabrication, installation, and commissioning of the WindFloat contribute to a system that should be no more expensive than current fixed installation methods for deeper water sites. ■

To Learn More

This list is a selection of sources that amplify the information in this article.

- "Integrated Dynamic Analysis of Floating Offshore Wind Turbines," B. Skaare, T.D. Hanson, F.G. Nielsen, R. Yttervik, A.M. Hansen, K. Thomsen, and T.J. Larsen; European Wind Energy Conference, Milan, Italy, 2007.

- "OC3-Benchmark Exercise of Aero-elastic Offshore Wind Turbine Codes," P. Passon, M. Kühn, S. Butterfield, J. Jonkman, T. Camp, and T.J. Larsen; Journal of Physics: Conference Series 75 (2007) 012071.

- "Offshore Code Comparison Collaboration within IEA Wind Task 23: Phase IV Results Regarding Floating Wind Turbine Modeling," J. Jonkman, T. Larsen, A. Hansen, T. Nygaard, K. Maus, M. Karimirad, Z. Gao, T. Moan, I. Fylling, J. Nichols, M. Kohlmeier, J. Pascual Vergara, D. Merino, W. Shi, and H. Park; European Wind Energy Conference, Warsaw, Poland, April 20-23, 2010.

- "Qualification of a Semi-Submersible Floating Foundation for Multi-Megawatt Wind Turbines," C. Cermelli, A. Aubault, D. Roddier, and T. McCoy; OTC-20674-PP, Offshore Technology Conference, Houston, Texas, May 3–6, 2010.