National Renewable Energy Laboratory
Innovation for Our Energy Future

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Engineering Challenges for Floating Offshore Wind Turbines

Conference Paper
NREL/CP-500-38776
September 2007

S. Butterfield, W. Musial, and J. Jonkman
National Renewable Energy Laboratory

P. Sclavounos
Massachusetts Institute of Technology

Presented at the 2005 Copenhagen Offshore Wind Conference
Copenhagen, Denmark
October 26–28, 2005

NREL is operated by Midwest Research Institute • Battelle   Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Engineering Challenges for Floating Offshore Wind Turbines

By
Sandy Butterfield
Walt Musial
Jason Jonkman
National Renewable Energy Laboratory
Golden, Colorado, USA

Prof. Paul Sclavounos
Libby Wayman
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

INTRODUCTION

The vision for large-scale offshore floating wind turbines was introduced by Professor William E. Heronemus at the University of Massachusetts in 1972 [1], but it was not until the mid 1990's, after the commercial wind industry was well established, that the topic was taken up again by the mainstream research community. Current fixed-bottom technology has seen limited deployment to water depths of 20 m. As the technology is advanced into deeper water, floating wind turbine platforms may be the most economical means for deploying offshore wind turbines at some sites. Worldwide, the offshore wind resource has been shown to be extremely abundant, with the U.S. energy potential ranked second only to China [3].

Technically, the long-term survivability of floating structures has already been successfully demonstrated by the marine and offshore oil industries over many decades. However, the economics that allowed the deployment of thousands of offshore oilrigs have yet to be demonstrated for floating wind turbine platforms. For deepwater wind turbines, a floating structure may replace driven monopoles or conventional concrete gravity bases that are commonly used as foundations for shallow water turbines. A floating structure must provide enough buoyancy to support the weight of the turbine and to restrain pitch, roll and heave motions within acceptable limits. The turbine design philosophy for floating may be impacted if platform dynamics require a more dynamically compliant machine but the platform costs are likely to dominate the cost tradeoffs. Therefore, it is assumed that the economics of deepwater wind turbines will be determined primarily by the additional costs of the floating structure and power distribution system, which are offset by higher offshore winds, close proximity to large load centers (e.g. shorter transmission runs), and greater public acceptance due to lower visual and environmental impacts. DOE cost of energy models indicate that if platform costs can be held near 25% of the total system capital cost then a cost goal of $0.05/kWh would be attainable [4]. The major objective of this paper is not to demonstrate the economic viability but rather to survey the technical challenges that must be overcome to reach this economic goal and to provide a framework from which the first-order economics can be assessed.

STRATEGY FOR ECONOMIC FLOATING WIND TURBINES

Floating platforms for wind turbines must be optimized to achieve the lowest life cycle cost of the entire system. Figure 1 shows the breakdown of total system costs for offshore turbines in shallow water from the wind turbine to the onshore utility connection, including the costs of operation and maintenance and decommissioning. Unlike onshore installations, the cost of offshore wind is not dominated by turbine costs, but by multiple balance-of-station (BOS) and operating expense (OPEX) factors. Clearly, to be effective in meeting cost goals all cost aspects must be addressed. When floating wind turbines are introduced, a large focus must be placed on limiting foundation costs, but at the same time intelligent system-engineering decisions must be made to assure that platform costs do not drive up the cost of other critical cost elements. More optimistically, floating platforms introduce a new design paradigm that may offer unique opportunities to reduce the weight and cost of companion systems.

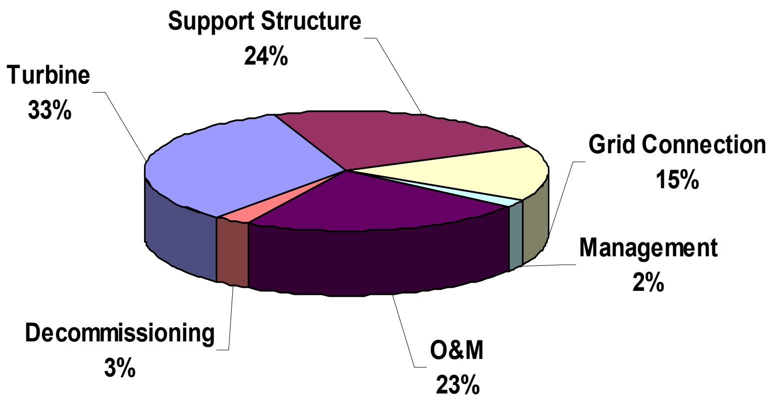


Figure 1 – Approximate Cost Breakdown for Offshore Wind Projects in Shallow Water
(Source CA-OWEE report 2001)

Water depth will play a key role in the economics of floating systems and will primarily decide the economic break point at which a particular floating configuration becomes more economical than its fixed counterpart. Floating systems may have unique advantages over bottom fixed structures depending on the topology, wave, sea ice, and seabed conditions. The cost/benefit of various engineering solutions is very different for shallow and deepwater applications.

When compared with the current costs for floating offshore oil and gas platforms, the $0.05/kWh offshore wind turbine cost goals may appear too ambitious. However, the differing requirements for an offshore floating wind platform and the opportunities to apply mass production economic principals will drive down costs considerably [5].

DESIRABLE FEATURES OF A FLOATING WIND TURBINE PLATFORM:

Many of the same issues that govern oil and gas platforms will also be present in the design of wind platforms but the importance of each variable will be weighted differently. There are a vast number of possible offshore wind turbine platform configuration permutations when one considers the variety of available moorings, tanks, and ballast options in the offshore industry. Unfortunately, a designer might find that most of the resulting topologies would have some undesirable aspects that would drive the system cost out of range for most wind applications. The optimum platform does not exist, of course, but there are many features that such a platform would embody that most designers could agree on. To narrow the range of options this study will compare several platform designs to features that an optimized platform should have. From this comparison we can begin to determine the key issues that limit each platform type and that will direct future study in this area.

FLOATING PLATFORM CLASSIFICATION

As mentioned earlier, floating platform configurations may vary widely. Typically, the overall architecture of a floating platform will be determined by a first-order static stability analysis, although there are many other critical factors that will determine the size and character of the final design. However, once the platform topology has been established, a crude economic feasibility analysis becomes possible. Therefore to focus the discussion, a classification system was developed that divides all platforms into three general categories based on the physical principle or strategy that is used to achieve static stability:

1) **Ballast**: Platforms that achieve stability by using ballast weights hung below a central buoyancy tank which creates a righting moment and high inertial resistance to pitch and roll and usually enough draft to offset heave motion. Spar-buoys like the one shown in Figure 2 apply this strategy to achieve stability [5].
2) **Mooring Lines**: Platforms that achieve stability through the use for mooring line tension. The tension leg platform (TLP), like the one shown in the center of Figure 2, relies on mooring line tension for righting stability [5].
3) **Buoyancy**: Platforms that achieve stability through the use distributed buoyancy, taking advantage of weighted water plane area for righting moment [6]. This is the principle used in a barge shown in Figure 2.

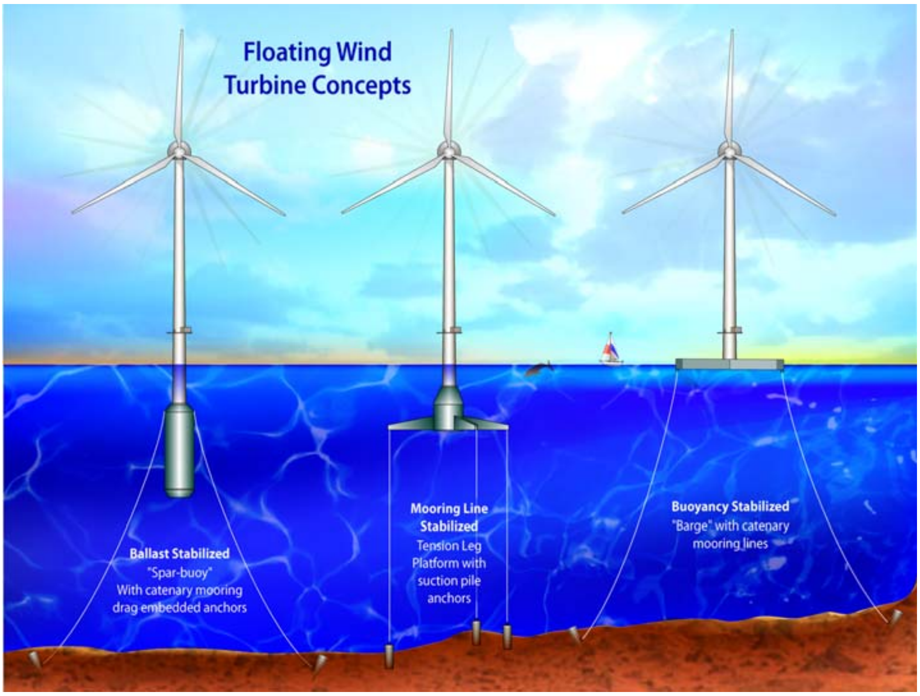
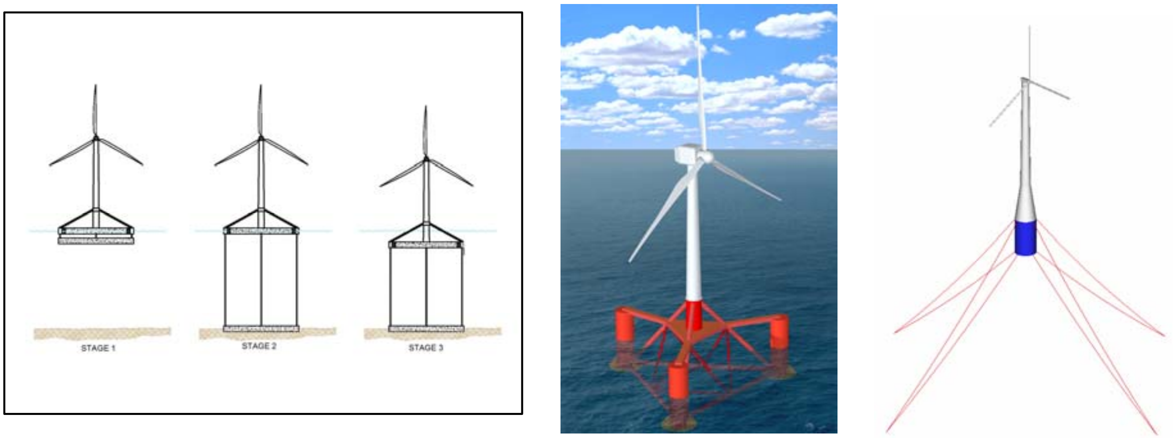


Figure 2 Typical Floating Platform Static Stability Concepts



Concept Marine Assoc. Semi-Submersible TLP [4]

Dutch Tri-floater [2]

MIT Double Taut Leg Buoy [9]

Figure 3 – Typical Floating Concepts

Each of these approaches for achieving stability can be thought of an idealized vessel with limited properties; some of these characteristics may be desirable and some may be undesirable for use on a floating wind turbine. For example, in the extreme case the idealized spar buoy will have a tank with zero water plane area suspending sufficient ballast below the waterline to offset the tower top moments. The mooring lines would only function to provide station-keeping. Similarly, the idealized TLP would be a weightless tank with zero water plane area, held only by the tension of the vertical tendons. Finally, the idealized barge would be weightless and moored only to prevent drifting. Its weighted water plane area would be sufficient to stabilize the platform under static load conditions.

Figure 4 is a construct that represents each of the idealized floating platform concepts with respect to one another. The points of this stability triangle represent each of idealized platforms described above.

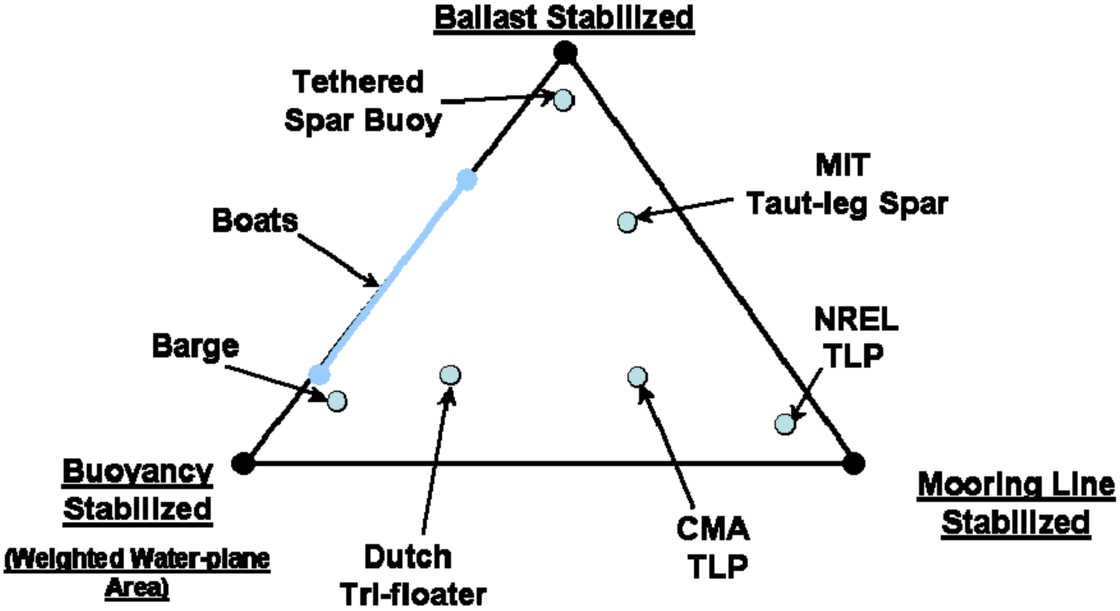


Figure 4 – Floating Platform Stability Triangle Showing Methods of Achieving Static Stability

In practice, all floating concepts are actually hybrid designs that gain static stability from all three methods, although generally relying on one primary source for stability. Physical hybrid floating platform designs will almost exclusively lie inside the triangle, between the primary points. Designers will seek the “optimum” platform from a unique balance of stability options that will achieve the best functionality and lowest cost. There may be no correct answer, only compromises that attempt to minimize the system cost by addressing each technical challenge.

Several real designs are plotted on the triangle for qualitative illustration of this method of platform classification. One design, the Dutch Tri-floater (shown in Figure 3) has distributed buoyancy tanks attached to the central tower through truss arms. This achieves stability primarily through weighted water plane area but weight of the steel tanks and truss structure will also provides significant mass to resist overturning moments. The catenary moorings provide some additional resistance to overturning, mainly due to the mass of the lengthy chain that extends out to a conservative suction pile mooring. In another concept, MIT designed a spar-buoy with a slender tank to achieve a low profile where it pierces the free surface (also shown in Figure 3). It gets increased stability from a two tiers of mooring lines sharing a single drag embedment anchor. A third platform designed by Concept Marine Associates (CMA) (also in Figure 3) has a TLP design that uses barge-like buoyancy compartments to achieve shallow draft stability for float-out. Once in position, a tank suspended from beneath the main deck is ballasted with water and gravel and lowered to the seabed to become a gravity-based anchor. Once the anchor is set, a winch system submerges the primary buoyancy tank by shortening the tendons, reacting against the anchor. This approach places the buoyancy tank below the major influence of wave loading. Ultimately, operational stability is achieved through mooring line tension, but the primary tank is designed for float-out stability through water plane area.

Each concept uses a combination of the three primary stability methods. The following section attempts to weigh the competing technical issues for the idealized points of the triangle. Tradeoffs among the three methods will yield widely varying results.

DESIGN CHALLENGES

The designer must tradeoff the pros and cons of each of these approaches in an attempt to reach the lowest cost system design. Table 1 gives a list of proposed design challenge parameters that would impact the performance and cost of a floating wind turbine system.

Table 1 – Design Challenge Tradeoffs for Stability Criteria

	Floating Platform Technical Challenges		
	Platform Stability Classifications		
Platform Design Challenge	**Buoyancy (Barge)**	**Mooring Line (TLP)**	**Ballast (Spar)**
Design Tools and Methods	-	+	-
Buoyancy Tank Cost/Complexity	-	+	-
Mooring Line System Cost/Complexity	-	+	-
Anchors Cost/Complexity	+	-	+
Load Out Cost/Complexity (potential)	+	-	
Onsite Installation Simplicity (potential)	+	-	+
Decommissioning & Maintainability	+	-	+
Corrosion Resistance	-	+	+
Depth Independence	+	-	-
Sensitivity to Bottom Condition	+	-	+
Minimum Footprint	-	+	-
Wave Sensitivity	-	+	+
Impact of Stability Class on Turbine Design			
Turbine Weight	+	-	-
Tower Top Motion	-	+	-
Controls Complexity	-	+	-
Maximum Healing Angle	-	+	-

Key: + = relative advantage
- **= relative disadvantage**
blank = neutral advantage

Each design challenge is evaluated for the three methods of achieving stability using a simple method of plus (+) and minus (–) symbols. The plus and minus symbols indicate ease with which each challenge might be overcome for each class.

As mentioned earlier the turbine design is impacted by the choice of platform. Therefore, it must be included in the table of challenge tradeoffs. The TLP is likely to provide the most stable platform and thus have the least impact on the turbine dynamics. A ballast-dominated design such as a buoy is likely to be heavier and therefore more expensive to build. The barge is likely to be subject to higher wave loading, which will increase the systems response (motions) to waves. Therefore, a turbine design that is tolerant of larger tower motions is needed. Turbines can be designed to tolerate larger motions but likely at a high cost.

RATIONAL FOR PLATFORM DESIGN CHALLENGE RATINGS:

Design Tools and Methods: The complexity of the task to develop accurate modeling tools will increase with the degree of flexibility and coupling of the turbine and platform. Usually this results in greater responses and motions to wave and wind loading. Predicting wave loads and dynamics for a stable platform such as the TLP will require new analytical tools but is likely to be less difficult than for platforms that are more subject to wave loading. Platforms, such as the barge, that have a large part of their structure near the free surface will have larger pitch, roll, and heave forces. A barge is likely to violate simple Morison's Equations assumption, which will be more complex to model and validate. Spar concepts will have smaller tower top motions relative to the barge but may still be subject to nonlinear wave forces requiring more advanced tools.

Additional offshore loads arise from impact of floating debris and ice and from marine growth buildup on the substructure. The analysis of offshore wind turbines must also account for the dynamic coupling between the translational (surge, sway, and heave) and rotational (roll, pitch, and yaw) platform motions and turbine motions, as well as the dynamic characterization of mooring lines for compliant floating systems.

Buoyancy Tank Cost/Complexity: All platform types require a system to provide buoyancy. A barge is likely to be the lowest cost per unit of displacement because the simple shape will employ equally simple fabrication techniques that are well established. However, since the barge depends primarily on water plane area, it would likely be a heavy structure. The spar-buoy is likely to be a simple rolled steel fabrication but more displacement is needed to counter the added weight of the ballast, resulting in an overall high material cost for the system. The TLP tank is likely to have the lowest displacement requirements and the lowest cost, but more complexity is required in the tank structure to support the loads from the mooring lines.

Mooring Line System Cost/Complexity: The cost of the mooring lines is highly dependent on water depth. A barge and spar-buoy are likely to have catenary mooring lines that are attached to drag embedded anchors. In such a system the cost of the lines and chain will be driven by long lengths needed to minimize vertical loading on the anchors. A TLP will have short lines since they extend vertically, but they must carry a much higher load to assure constant tension between the anchors and buoyancy tank.

Anchor Cost/Complexity: Drag embedded horizontally loaded anchors associated with a barge or buoy would have lower material cost and complexity than high capacity vertical load anchors. Catenary moorings are loaded horizontally and are not subjected to the full loads experienced by the platform. TLPs require vertical or taut leg mooring systems employing high capacity anchors that must offset the buoyancy forces acting on the tank plus a reserve to prevent the lines from going slack under severe conditions. This is the primary design challenge for concepts relying on mooring lines for stability [5].

Float Out Cost/Complexity and Weather Window Tolerance: Any platform that is stable during float-out with a fully assembled turbine will avoid the high cost of special purpose ships to carry and place the turbines on site. A self-stable platform can be towed by low-cost tugboats or buoy tenders. This characteristic may reduce life cycle costs when major turbine retrofits, long term maintenance or decommissioning is needed.

Weather window tolerance is the ability of an offshore turbine to be floated out and installed in a broad range of weather conditions. Weather conditions frequently cause delays in installation process costing standby fees and idle installation crews. A platform that can be installed in higher sea states, higher wind conditions with less special-purpose vessels will reduce the cost of installation. A system that can be towed-out, fully assembled, in more demanding sea states will reduce installation costs as well as long term maintenance costs if the platform has to be towed back into port for overhaul.

Onshore assembly and commissioning of the turbine, tower and platform is the path to efficient high volume, low cost production. Unlike oil and gas platforms, wind turbines will be deployed in quantities of 100 or more which will permit the development of tooling and mass production technique to lower cost. Of all the strategies this will impact the long-term costs most by taking advantage of assembly line tooling where material and components are brought the factory instead of the final site for assembly. Higher quality and safer work conditions can be sustained with less impact from poor weather and sea conditions. This is a major advantage of the barge. Certainly special purpose floatation could be designed to stabilize a TLP or other platform during float-out but not without adding cost and complexity to deployment.

Onsite Installation Simplicity: The cost of onsite construction is driven by the charter fees of special purpose craft and cost of crew which is all multiplied by the complexity of the assembly process and weather tolerance of the assembly process. A heavy lift of a nacelle to mate with a moving platform could prove difficult and expensive. For this reason at sea assembly must be minimized. The best situation is likely to be a self-contained anchor deployment system on a stable barge. It might be economical to assemble a spar-buoy system with turbine in place and tow it out de-ballasted with the turbine leaning over and resting on the tug. This would minimize draft in port and allow tank ballast to be added at sea for final vertical orientation. This strategy would eliminate some of the large vessel equipment. Similarly, a hydrodynamically stable TLP could be designed [7] to float-out with an unballasted gravity anchor, which can be deployed on site without special equipment.

Decommissioning and Maintainability: Platforms that are stable with a low draft can be towed into port for long-term maintenance or decommissioning. The ease at which this can be accomplished will lower maintenance cost during critical overhaul cycles. Systems that are more difficult to un-tether and float back to shore, such as the TLP or a spar-buoy, may be more costly for large maintenance operations. Another aspect is the relative burden of maintenance required for the platform itself. Simple systems may require less maintenance. Finally, accessibility has been demonstrated to be a key factor in sustaining high availability. Platforms that facilitate access during poor weather will lower the overall system cost by increasing energy capture and lowering O&M.

Corrosion and Ice Resistance: Platforms that have much of their structure near the free surface will be subject to higher corrosion and ice flow loading. This is a disadvantage for substructures, such as the barge, that depend on water plane area to achieve stability. This problem can be addressed by using non-corrosive materials such as concrete, corrosion resistant coatings, and cathodic protection, however, addressing this issue will add cost to the system.

Water Depth Independence: The ability to install a single platform design over a broad range of depths increases the number of sites suitable for that design. Each platform type has a minimum depth that it can operate in. Platforms that depend on water plane area can operate in shallow or deep water sites. TLPs and spars require depths of at least 50-m for a 5-MW turbine [7]. A shallow draft self-stable platform can also be towed out of a shallow port to either deep or shallow water sites. A barge meets these characteristics while TLPs and spar-buoys are likely to require greater channel depths during float–out and deployment. In deeper waters the costs are driven more by anchor line lengths which impact barges and buoys more than TLPs.

Sensitivity to Bottom Soil Conditions: Geotechnical surveys are expensive and time consuming. If an anchor system requires certain minimum soil conditions or design modifications to suit the soil conditions, then site-specific engineering is needed for each site. Any anchor system that meets a broad range of soil conditions will require less geotechnical work and less site-specific anchor design. Drag imbedded vertical load anchors are likely to suit a broader range of soil conditions than suction piles because they loaded more lightly and their failure consequences are less catastrophic than for a vertical load anchor on a TLP.

Minimum Footprint: Environmental impact is likely to affect cost. Large spread mooring systems impact more bottom area, reducing the space between turbines and increasing the obstacles that may impact other uses of the sea. This issue may be critical for project permitted in environmentally sensitive regions.

Wave Sensitivity: Extreme waves are the design drivers for most offshore structures. Some platforms might be more tolerant of higher sea states. A platform that is tolerant of high sea states during extreme weather conditions can be placed at a broader range of sites. Generally, submerged platforms can more easily avoid extreme waves relative to platforms at the surface.

IMPACT OF STABILITY CLASS ON TURBINE DESIGN RATINGS:

It is common for the offshore turbine designers to focus on the support structure, but the extra motion allowed by floating platforms will significantly affect the turbine designs as well. More active dynamics will be experienced by all the floating concepts resulting in greater tower top motions and coupling between the support structure and rotor. For this reason it is important to include the impact of platform motion with respect to stability classification in overall system design, as shown in Table 1. The following are four of the major issues that one might consider in the initial trade off.

Turbine Weight: The weight of the nacelle/rotor assembly (NRA) will directly affect the size and cost of the buoyancy tank required to support the total weight of the system. Thus, any reductions in tower-top weight will result in further reductions in total system weight. This is strong incentive to reduce the weight aloft. This can be done in many ways, and including some methods were rejected for land-based systems because of acoustic emissions or aesthetics. For all designs, higher rotor tip speeds will result in NRA weight reductions. This is realized by several physical advantages. Higher rotational speeds allow smaller blade planform and lower blade weight for the same energy output. Higher speeds mean lower input torque and lower gear ratios, and hence smaller shafts and gearboxes. Current trends in offshore drive train designs are towards direct drive generators which can be made smaller for higher rotational speeds. Direct-drive generators are expected to be more reliable than modular gear driven, systems but present wound rotor generators are heavier. Permanent magnet generator designs promise to offer further weight reductions and improved efficiency for future designs. The heaviest component above the water is by far the tower. Lower thrust loads and alternative lightweight materials may also help lower tower weight. The weight reductions may also be realized in the platform itself where, for example, lightweight aggregates can provide concrete options 40% below standard mixtures.

Tower Top Motion: The degree of platform motion will have a proportional impact on the NRA design requirements and hence system cost. The turbine design will have to be more robust to accommodate high heel angles, increased nacelle displacements, heave motion, and angular accelerations resulting from pitch and roll motions. A barge design might experience larger rotational motions from wave loading, which will induce dynamic loads in the rotor, tower, and blades. Flexible rotor designs might accommodate these dynamics more easily than current ridged rotor designs. Downwind rotors might accommodate large deflections more readily than upwind rotors, which have smaller tower clearances. While platforms that allow higher nacelle motion may benefit more from these turbine innovations, generally all floating turbine systems could realize a greater potential cost reduction from flexible designs when compared to fixed bottom systems.

Controls Complexity: Controls are playing an increasingly important roll in the overall stability of wind turbine systems. Controls are already used in onshore turbines to damp undesirable structural resonances and reduce dynamic response to turbulence in the wind. In floating platforms it is conceivable that controls would be used to limit the response of the entire turbine/platform system to stochastic wave loading. For example, pitch motions (fore/aft direction) can easily be limited by an intelligent collective pitch control strategy. Similar techniques have already been used to dampen tower motions in onshore turbines. A greater challenge will be in damping roll motions, which are translations of the rotor in the plane of rotation (side-to-side), but researchers are also working on control methods to limit these responses. Some platform choices might introduce dynamics that are more difficult to control than others. Thus, it is important to consider the benefits and challenges posed by this issue.

Maximum Healing Angle: Healing angle - the displacement angle of the tower during extreme loading - can disturb lubrication distribution in gearboxes, alter bearing loading, and create abnormal component forces and dynamic loads. Some onshore wind turbines have been designed to operate at extremely high shaft tilt angles for passive load alleviation, but some offshore platforms might require heal angle specifications that are both dynamically acting and much higher than any land-based application to date. The questions are can these systems be designed to economically include these additional requirements, and what additional dynamics are introduced?. Spar buoys, for example, might experience high static heal angles that require special mechanical design considerations when making configuration choices.

ANALYTICAL TOOL DEVELOPMENT

One of the immediate challenges common to all support structure designs is the ability to predict loads and resulting dynamic responses of the coupled wind turbine and platform system to combined stochastic wave and wind loading. In the offshore environment, additional load sources impart new and difficult challenges for wind turbine analysts. Figure 5 and 6 illustrate the range of different loading sources and additional degrees of freedom needed to model floating platforms.

Wave induced forcing is the most apparent new source of loading. Hydrodynamic effects are included within comprehensive analysis tools by incorporating a suitable combination of wave loading models in regular and irregular waves. Time domain wave loading theories, including free surface memory effects, are used to relate simulated ambient wave elevation records to loads on the platform. Wave loads result from the integration of the dynamic pressure of the water over the wetted surface of the platform and include inertia (added mass) and linear drag (radiation), buoyancy (restoring), incident wave scattering (diffraction), current and nonlinear viscous drag effects.

Analysts must have a tool that is able to simulate all these conditions but even if the tool is very capable it must be applied in a manner that accurately captures the lifecycle loads. Design standards specify the load cases that must be run, but they rely heavily on the skill of the analyst to accurately simulate all the possible turbine operating states in proper combination with all the possible environmental conditions [8]. New methods for predicting life cycle loads for dynamically active systems in the presence of multiple nonlinear stochastic load sources need to be developed.

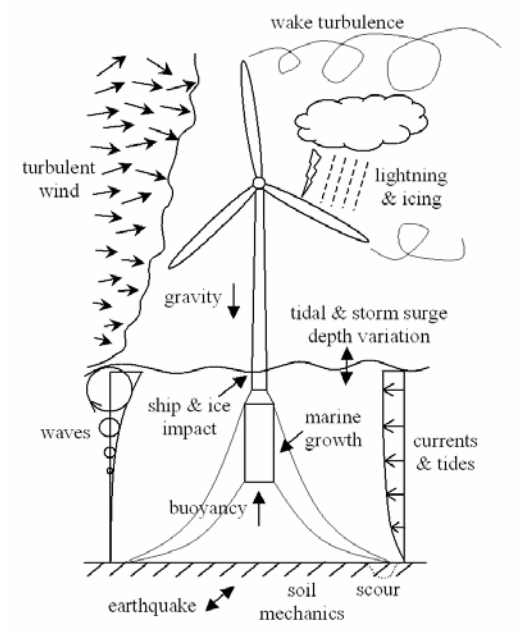


Figure 5: Offshore Turbine Loading Sources

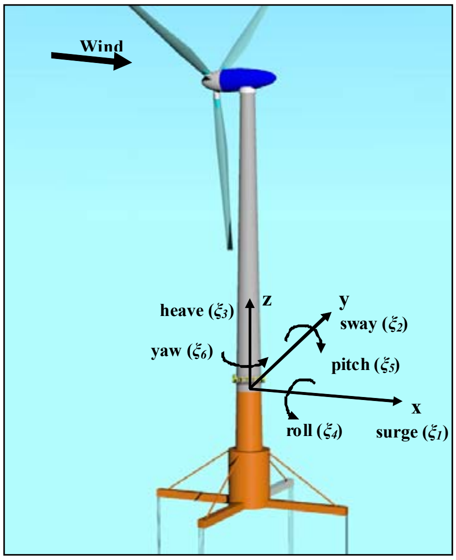


Figure 6: Support Platform Degrees-of-Freedom

One example of a technical challenge the analyst must overcome is predicting the lifecycle fatigue load spectrum. The offshore oil industry applies extrapolation techniques to only the wave loading, but for wind turbine there two significant load spectrums that are acting simultaneously; wind and waves. Because of the nonlinearities associated with the aerodynamics and hydrodynamics, the simulations are typically run in the time domain. This implies that 20 years of simulations must be run to capture the full range and duration of all the stochastic loading from wind and waves. Even if this were possible multiple realizations would have to be run to capture the range of statistical possibilities. So the analyst must intelligently choose "representative" load cases and extrapolate the results to lifecycle load spectra. Extrapolating to the extreme load possible in presence of two different dominant stochastic load environments is not well-developed technical capability. Only recently has research begun on developing extreme load extrapolation techniques.

CONCLUSIONS

Floating platforms for wind turbines have been proposed for many years but only recently has the technology matured enough to seriously consider overcoming the technical challenges required to design successful machines. The offshore oil and gas industry has proven that the technical challenges can be overcome but the economics of implementing this industry's solution would prohibit any deployment of machines in a competitive wind energy market. The challenge is a primarily economic one. These economic challenges present technical challenges. This paper has outlined these challenges and suggested goals that lead to economical floating systems.

This paper provides a framework for classification of floating wind turbine platforms on the basis of static stability criteria that can be used as a practical method to perform first-order economic analysis on a wide range of platform architectures. Floating systems offer the opportunity to perform most of the assembly process onshore in production facilities that can maximize the advantage of series production. Through high production floating systems that are lower cost than fixed bottom systems, which must be constructed at sea, may be possible. These systems could be deployed in a wide range of site conditions including high wind sites located further offshore in deep water, ultimately leading to the lowest cost offshore turbines.

REFERENCES

1. Heronemus, W. E. "Pollution-Free Energy From Offshore Winds", 8th Annual Conference and Exposition Marine Technology Society, Washington D.C., September 11-13, 1972.
2. Studie narr haalbaarheid van en randvoorwaarden voor drijvende offshore windturbines. ECN, MARIN, Lagerwey the Windmaster, TNO, TUD, MSC, Dec. 2002.
3. Siegfriedsen, Lehnhoff, & Prehn, aerodyn engineering, GmbH – Presented at Offshore Wind Energy in the Mediterranean and other European Seas Conference, April 10-12, 2003, Naples, Italy
4. Musial, W.D.; Butterfield, C.P. "Future for Offshore Wind Energy in the United States" NREL/CP-500-36313 - EnergyOcean Proceedings, Palm Beach, FL, June 2004.
5. Musial, W.D.; Butterfield, C.P.; Boone, A. "Feasibility of Floating Platform Systems for Wind Turbines", NREL/CP-500-34874, 23rd ASME Wind Energy Symposium Proceedings, Reno, Nevada, January 2004.
6. Newman, J.N, *Marine Hydrodynamics*, The MIT Press, Cambridge Massachusetts, 1977, ISBN 0-262-14026-8
7. Draft Final Report of "Semi-Submersible Platform and Anchor Foundation System for Wind Turbine Support", NREL Subcontract No. YAM-4-33200-10
8. Committee Draft, IEC 61400-3, IEC Web Page - www.iec.ch
9. Lee, K. H. "Responses of Floating Wind Turbines to Wind and Wave Excitation", Master of Science Thesis, Massachusetts Institute of Technology, 2005

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* September 2007	**2. REPORT TYPE** Conference paper	**3. DATES COVERED** *(From - To)* October 26-28, 2005

4. TITLE AND SUBTITLE
Engineering Challenges for Floating Offshore Wind Turbines

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
S. Butterfield, W. Musial, and J. Jonkman

5d. PROJECT NUMBER
NREL/CP-500-38776

5e. TASK NUMBER
WER5.3301

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-500-38776

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
The major objective of this paper is to survey the technical challenges that must be overcome to develop deepwater offshore wind energy technologies and to provide a framework from which the first-order economics can be assessed.

15. SUBJECT TERMS
floating offshore wind turbine; technical challenges; economics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18