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Feasibility of Floating Platform Systems for Wind Turbines

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W. Musial, S. Butterfield, and A. Boone

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1617 Cole Boulevard
Golden, Colorado 80401-3393

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FEASIBILITY OF FLOATING PLATFORM SYSTEMS FOR WIND TURBINES[1]

By
Walt Musial
Sandy Butterfield
Andrew Boone
National Renewable Energy Laboratory
Golden, CO 80401
walter_musial@nrel.gov
sandy_butterfield@nrel.gov

ABSTRACT

This paper provides a general technical description of several types of floating platforms for wind turbines. Platform topologies are classified into multiple- or single-turbine floaters and by mooring method. Platforms using catenary mooring systems are contrasted to vertical mooring systems and the advantages and disadvantages are discussed. Specific anchor types are described in detail. A rough cost comparison is performed for two different platform architectures using a generic 5-MW wind turbine. One platform is a Dutch study of a tri-floater platform using a catenary mooring system, and the other is a mono-column tension-leg platform developed at the National Renewable Energy Laboratory. Cost estimates showed that single unit production cost is \$7.1 M for the Dutch tri-floater, and \$6.5 M for the NREL TLP concept. However, value engineering, multiple unit series production, and platform/turbine system optimization can lower the unit platform costs to \$4.26 M and \$2.88 M, respectively, with significant potential to reduce cost further with system optimization. These foundation costs are within the range necessary to bring the cost of energy down to the DOE target range of \$0.05/kWh for large-scale deployment of offshore floating wind turbines.

INTRODUCTION

Although the vision for large-scale offshore floating wind turbines was introduced by Professor William E. Heronemus at the University of Massachusetts in 1972 [1], 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. A recent Dutch report [2] presents a complete bibliography and a summary of the research to date, and is the basis for some of the later cost studies.

Current fixed-bottom technology has seen limited deployment to water depths of 30-m thus far. Although this technology may be extended to deeper water, eventually floating wind turbine platforms may be the most economical means for deploying wind turbines in the coastal waters beyond the view shed of densely populated urban load centers. Worldwide, the deep-water wind resource has been shown to be extremely abundant, with the U.S. potential ranked second only to China [3].

Technically, the feasibility of deepwater wind turbines is not questioned as 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 will replace pile-driven monopoles or conventional concrete bases that are commonly used as foundations for shallow water and land-based turbines. The 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 capital costs for the wind turbine itself will not be significantly higher than current marinized turbine costs in shallow water. Therefore, 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 and close proximity to large load centers (e.g. shorter transmission runs). Integrated cost of energy models indicate that if platform costs can be held near 25% of the total system capital cost that DOE cost goals of \$0.05/kWh are attainable. Thus, the major objective of this paper is to demonstrate, with a simple static cost model, that platform cost can be brought into this economic range.

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Although the characteristics of proven offshore floating platforms used by the oil and gas industries are similar to the concepts being considered for floating wind turbine platforms, it is their differences that will allow the necessary cost reductions.

- Oil platforms must provide additional safety margin to provide permanent residences for personnel. Wind platforms do not.
- Oil platforms must provide additional safety margin and stability for spill prevention. This is not a concern with wind platforms.
- Wind platforms will be deployed in water depths up to 600 ft (182.4-m). Oil platforms are deployed in depths from 1500 ft (456-m) to 8000 ft (2432-m).
- Submerging wind platforms minimizes the structure exposed to wave loading. Oil platforms maximize above-water deck/payload area.
- Wind platforms will be mass-produced and will benefit from a steep learning curve.

PLATFORM TOPOLOGIES

Multiple Turbine Floaters

One multiple-turbine concept is a single pontoon type floater with several turbine towers on it to share anchors costs and provide wave stability [4] as shown in Figure 1. Another multiple-turbine concept is to place an array of smaller turbines on a single tower and platform [5, 6]. In his analysis of the first concept, Halfpenny determined the cost would be very high and it was questionable whether the large structure could withstand extreme wave loading. Because turbine spacing is poorly optimized, both multiple-turbine concepts require the floating structure to either yaw with wind direction changes or compromise energy production when the wind shifts off the prevailing direction. Systems consisting of multiple turbines on a single floater may prove to be more expensive than single-turbine floaters because of additional support structure required to connect several rotors or towers together. However, for very large systems (>20-MW per structure) it may be possible to lower overall system weight with multiple turbines due to cubic mass scaling laws [7]. Multi-turbine concepts are not considered further in this paper. Table 1 lists the description, status, advantages, and disadvantages for both multiple- and single-turbine floater concepts.

Figure 1 - Multiple-turbine floater. [6]

Single-Turbine Floaters

Several types of single turbine floating platforms for wind turbines have been analyzed and summarized [2]. This paper examines an abridged selection of possible platform topologies to provide context for the analysis. This was narrowed down to just two types for the purpose of demonstrating platform economics.

Single-turbine floating structures can be classified by the type of mooring system they use, because the mooring method dictates much of the fundamental platform architecture. The most commonly used mooring systems for anchoring ships and floating oil production units are catenary moorings, taut-leg moorings, and vertical tension legs. Catenary moorings and taut-leg moorings are represented in Figure 2. A vertical tension leg is considered to be a subset of taut-leg moorings. The biggest advantages of floating platforms with catenary moorings are the relatively low cost of the anchors, and the potential to be deployed in shallower water. The biggest problem is that the vertical tension of the anchor line is generally insufficient to maintain platform stability against overturning, especially for a wind turbine where the weight and horizontal forces act so far

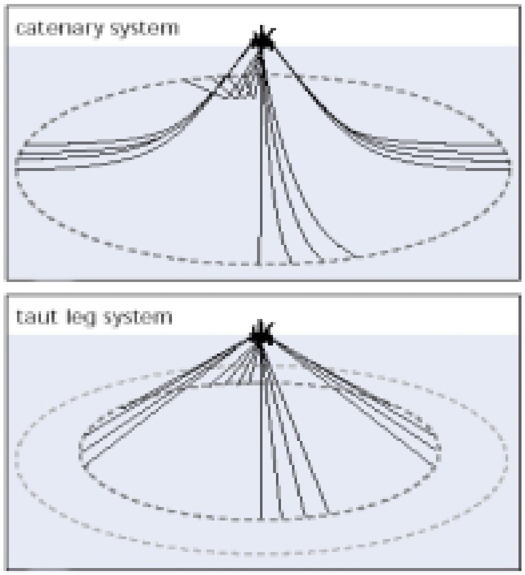

Figure 2 – Catenary and taut-leg mooring systems. [11]

above the center of buoyancy. Consequently, significant ballast must be added below the center of buoyancy, or the buoyancy must be widely distributed to provide stability. In the absence of significant vertical mooring forces, catenary moored platforms present a significant portion of the platform structure above the water line, subjecting them to higher wave loading. Thus, by their nature the catenary mooring type platforms also subject the wind turbine to larger base motion in all directions, increasing the complexity of the system integration and possibly introducing some additional turbine cost.

Taut-leg mooring systems become advantageous over catenary systems as water depth increases, because they have a smaller footprint and less mooring line is needed. If the taut legs, shown in Figure 2, are installed in a vertical orientation, the footprint becomes even smaller requiring even less mooring line, but high vertical anchors forces will require more complex and costly anchors with limited anchoring options. Systems using these vertical mooring arrangements have the advantage of being able to submerge the largest portion of the structure below the surface to minimize wave action, while maintaining a very stable platform. Ultimately, it may be a trade-off between the added complexity introduced by platform dynamics and the associated turbine cost, and the added complexity and costs of the anchor system that determines the best option.

Types of Catenary Mooring Systems

Wind researchers are examining several concepts used successfully by the offshore industry as a possible means for deployment of floating wind turbines. Spar buoys, shown in Figure 3, have been used in the offshore oil industry for many years. They consist of a single long cylindrical tank and achieve hydrodynamic stability by moving the center-of-mass as low as possible, placing ballast beneath the buoyancy tank. This elongated shape also serves to minimize heave motion due to wave action. A spar-buoy has the simplest shape of any floating platform, but because the center of mass of a horizontal-axis wind turbine is quite high, a massive structure would be necessary to support a wind turbine.

The tri-floater concept, which is the subject of the cost comparison described later, floats on three cylindrical buoyant columns that support the turbine tower using a tripod structure of steel beams. Other similar concepts include the "pillbox" design. This is a catenary moored cylindrical tank with a large diameter and a relatively short axis. The turbine is attached to the center of the tank above the waterline.

Figure 3 – Spar-buoy. [9]

This concept was rejected by the Dutch study [2] because the tank size required for hydrodynamic stability was cost prohibitive. The spar-buoy, the tri-floater, and the pillbox concepts achieve hydrodynamic without relying on their anchoring systems, which are mainly required for station keeping. However, these platforms can subject the wind turbine to dynamic motions caused by wind and wave loads.

Types of Vertical Moored Systems

With vertically moored systems, the structure is submerged by vertical or taut angled tendons anchored to the seabed. These anchoring systems provide the most stable type of floating platform and may result in the lowest near term risk option, because conventional offshore wind turbines could be used with some confidence. One specific design used by the oil and gas industry for deep-water exploration is the tension-leg platform (TLP) (shown in Figure 4). Excellent platform stability can be achieved with multiple tendons (tension legs) spread out on either side of the tower base. Reserve buoyancy is provided in the submerged vessels to prevent the tendons from going slack under extreme conditions. Vertical anchoring systems allow the largest portion of the structure to be submerged below the water level to minimize wave loading. TLP anchors need to withstand much larger mooring line forces than what is required for a catenary-mooring anchor. In this report, researchers at the National Renewable Energy Laboratory (NREL) developed a cost model for a mono-column TLP for a floating wind turbine. Table 2 gives the advantages and disadvantages for catenary and vertical mooring systems.

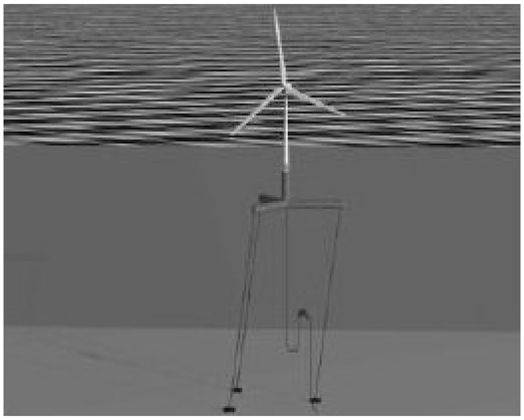

Figure 4 – Tension-leg platform [8]

PLATFORM ANCHORING SYSTEMS

General Anchoring Principles

The load capacity of any anchor system depends on the bottom soil conditions. The shear strength of the soil is the primary mechanism for resisting the forces applied. The weight of the soil is also a major factor. The deeper the anchor can be embedded, the greater the quantity of affected soil, and hence, the greater the holding capacity. These factors vary so widely that most anchors for permanent installations are specifically designed for the bottom conditions present at the site.

The direction of applied force also influences the holding capacity of an anchor. If the force is applied parallel to the bottom, an anchor can be very effective without deep embedment because as resisting forces are applied it digs deeper into the seabed. This is the principal advantage used in a catenary mooring system. A typical catenary mooring system uses heavy chain that forms a catenary shape from the point of attachment to the seafloor where mean horizontal forces of the platform are reacted. Catenary moored anchors have predominately horizontal mooring forces and require less precision in their placement. Therefore, installation is less expensive. Platforms using catenary mooring systems experience greater motions in every direction compared to taut-leg or vertical tension-leg systems.

With the exception of dead weight anchors, vertical load anchors depend on deep embedment to affect a large wedge of soil between the anchor and the seabed floor (soil surface). Deep embedment is the key to maximize pullout load. Therefore, vertically loaded anchors are more expensive to install. Based on these anchoring principles, the challenge is to find a relatively inexpensive anchoring system with a high vertical load capacity that is easy to install.

A TLP used by the offshore oil industry is shown in Figure 5. TLPs use taut vertical legs (tendons) for anchoring. Vertical tendons allow the platform to move horizontally to the surface of the water (surge and sway), partially absorbing wind and wave loads. Vertical tendons for very deep applications use steel pipe, which offers very stiff connections to the anchor, and the hollow center gives the tendon neutral buoyancy. Attaching both ends becomes very expensive due to the joints needed to terminate them. Usually multiple tendons are needed thus creating a need for a complex tension equalization mechanism.

Figure 5 – Vertical Mooring System [17]

Costs for the anchoring system depend on the material cost of the anchor and on the installation. Additional costs are the mooring lines, which can be made of chain, cable, or pipe. The different types of seafloor anchors are described below.

Gravity-Base Anchor

A gravity-base anchor relies on dead weight to supply vertical or horizontal forces. The load carrying capacity is equal to the difference between its weight and its buoyancy. The raw material is inexpensive but massive amounts of it are needed to achieve the desired capacity. Gravity-base anchors can be used in TLPs.

Drag-Embedded Anchor

Drag-embedded anchors are suitable for applications where anchor movement (creep) over time may not be critical. They are dropped to the seabed and dragged to achieve deep embedment. The weight of the chain attached to the shank causes line tension to drive the fluke deeper [10]. It is one of the lowest cost anchor types and may be suited for catenary moored systems where precise placement is not needed and horizontal mooring forces exist. A class of drag embedded anchors has been developed called vertical-load anchors (VLAs), shown in Figure 6. These anchors are designed to carry high vertical loads and may be more suitable for anchoring wind turbine platforms.

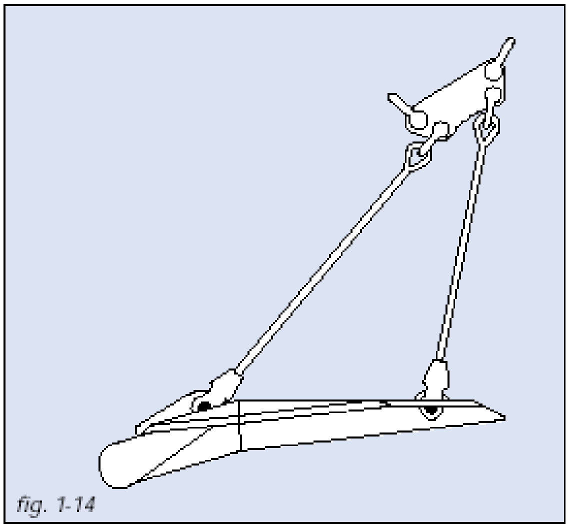

Figure 6 – Side-view of Vertical Load Anchor
Source Vryhof Anchor Manual 2000 [11]

Driven Pile Anchor

Driven pile anchors are the most commonly used anchors for offshore oil production units. Some large driven piles (and the hammer used to drive them) are shown in Figure 7. Many years of experience in the oil and gas industry has proven that piles are very reliable and achieve high load capacity. Piles will not creep, they are permanent, and they are precisely located. However, installation cost can be high. Driven piles are installed using a large vibratory or impact hammer to drive the pile into the seafloor. They are well suited to take vertical loading.

Figure 7 – Driven piles [12]

Suction Anchor

Suction anchors, shown in Figure 8, are a commonly used alternative to the driven-pile embedment anchor. Suction anchors use a long pipe that is open at the bottom end and closed off at the top. The closed end is outfitted with pump fittings so that when the pipe is dropped vertically to the seabed, water can be evacuated and the pipe sucked into the bottom soil. The anchor line is attached to a pad eye near the midpoint of the pipe allowing tension to be applied to the pipe in the transverse direction. This approach places the tension line well down into the soil allowing a large wedge of soil to support the line load. This is most effective for catenary systems but is much more effective for vertical loading than drag embedded anchors.

Figure 8 – Suction anchors. [13]

Driven Anchor Plate

Another new approach is the embedded anchor plate shown in Figure 9. It uses some of the same principles as the suction anchor but less material and lower cost. One key advantage is that when tension loads are applied to the plate, it rotates in the soil, allowing it to bear against a much larger wedge of soil. It can be precisely located, can sustain high vertical loads, and is not likely to creep. The installation process can use a suction anchor to achieve embedment, or it can be jetted, vibrated, or impacted into place.

Figure 9 – Driven anchor plate. [14]

Torpedo Embedded Anchor

The torpedo embedded anchor is a pile that is dropped to the seabed and its own kinetic energy drives it into the bottom. Some combination of torpedo with a driven plate tip, which can rotate when tension is applied, might be the least expensive approach for offshore wind turbines using vertical mooring systems. A variant of this approach has been used onshore for many years, and a research and development effort has recently been initiated by the offshore oil production industry to develop the technology for anchoring floating oil platforms.

Drilled and Grouted Pile

All of the previous examples assume that the soil conditions allow the anchor to be driven into the seabed. If rock is encountered, the most effective way to attach an anchor is to drill into the rock and grout a pile into the hole. The pile is similar in size and shape to a driven pile. Drilled and grouted piles are more reliable and can achieve higher vertical loads than driven piles, but are more expensive because they require heavy installation equipment.

PLATFORM COST ANALYSIS

The primary purpose of this study is to provide a first-order cost analysis of typical floating platform concepts to evaluate the cost of energy at various offshore sites. The capital costs for two different platforms were considered. First, a cost study performed in the Netherlands for a tri-floater concept is examined in this report for baseline comparisons. The tri-floater concept was developed by ECN, MARIN, Lagerwey, TUD, and TNO [2] and is shown in Figure 10. The Dutch study gives the best available data found for a floating wind turbine structure and is therefore considered a valid point of reference.

Figure 10 – Dutch Tri-floater Concept [2]

This analysis was compared to a simple TLP model developed at NREL. The NREL system uses a mono-column TLP as a design point for its analysis. This concept was developed at NREL independently, derived from similar TLP designs used by the oil and gas industry [15]. By coincidence, the 5-MW wind turbine used in the Dutch report has identical power output and similar load assumptions as turbine used to evaluate the TLP concept developed at NREL. The mono-column configuration was chosen because its simple geometry was easy to analyze and gather data for quick cost projections. Table 3 details the assumptions used for the Dutch tri-floater concept and the NREL TLP concept.

Description of Dutch Tri-floater Concept

The platform construction encompasses three buoyancy tanks that are 8 meters (m) (26.32-ft) in diameter and 24 m (79 ft) tall with 12 m (39.48 ft) of the tank submerged. The tanks are arranged in an equilateral triangle and spaced 68 m (223.7 ft) apart. They are connected by structural steel beams and braces and the turbine tower is supported at the center. Because a catenary mooring system was used, some of the structure is above the surface of the water and is subjected to full wave loading effects. The catenary mooring system uses six suction pile anchors with chain/cable moorings preloaded at 300 kN (67,446 lb) to restrain platform motion. Platform motion behaviors in pitch, roll, and heave were analyzed and accounted for in the Dutch concept. For a more complete description, see reference [2].

Description of NREL TLP Concept

The mono-column TLP used in the NREL analysis uses a single cylindrical buoyancy tank that is 16 m (52.64 ft) in diameter and 10 m (32.9 ft) tall with the cylinder axis positioned vertically and co-axial with the tower axis, as shown in Figure 11 (not to scale). The tank top surface is submerged 15 m (49.35 ft) below the mean water level. The cylinder walls are fabricated from .0254-m thick (1-in) rolled steel. The location and size of precise reinforcements are not considered, but the tank thickness adequately represents the volume of steel required for a

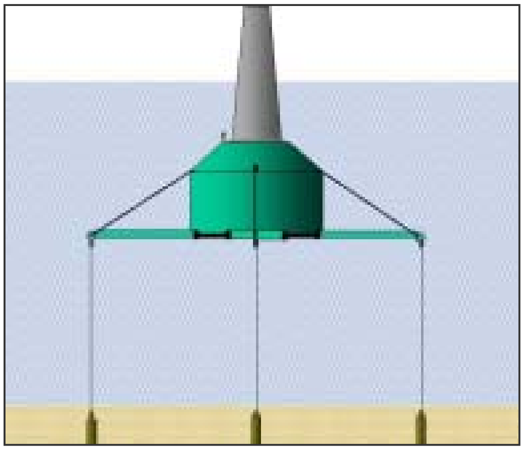

Figure 11 – NREL TLP concept

tank of this size. The tank was sized using a simple static analysis with a margin of safety of 2.0 on the required buoyancy to prevent the tendons from going slack under the extreme tower base moment of 187,000 kN-m. However, wave loading was not analyzed, and for the purposes of this cost study is assumed to be adequately compensated by the added buoyancy. The tank weight is 1755.8 kN (394,703 lb).

Three radial arms extend perpendicular from the tank walls with 120-degree spacing at the bottom of the tank. The arms are 22-m (72.38-ft) long and .91-m (3.0-ft) diameter cylindrical steel tubes that are .0254 m thick (1.0-in). The arms attach to the tank with pinned connections and are restrained by cables that extend from the end of the arms to the top of the tank to form simple triangular truss members. As a first approximation, the arms were sized to resist Euler buckling with a safety factor of four. The three arms weigh 459.4 kN (103,273 lb.). The arm length was chosen, for a fixed tank diameter of 16 m (52.64 ft), as the point where the system weight reached a minimum. As the arms increase in length, the buoyancy requirements are reduced, allowing the center tank to become smaller and lighter. At a tendon-to-tendon spacing of 60 m (197 ft), further increases in arm length added weight faster to the system than was being eliminated from the main tank.

At the end of each arm, tubular steel vertical tendons connect the platform to the seafloor. The tendons are assumed to be neutrally buoyant and weigh approximately 1601 kN (360,000 lb). The weight and cost of the tendons is assumed to be proportional to the water depth. For this study, six suction pile anchors are assumed in a water depth of 182.4 m (600-ft). Each anchor must carry a vertical tension force of 4740 kN (1,065,647 lb). The cost model could be improved by considering the relationship of anchor and tendon costs with tendon force requirements. Further increases in tendon-to-tendon spacing would result in reductions in tendon force, which would lower the cost of anchors and tendons. This influence has not yet been incorporated into the model. As mentioned, wave loading is not accounted for specifically and, therefore, any advantages that the TLP design may have over a catenary moored platform due to lower wave interactions are ignored. However, this influence could be important.

Although the TLP is inherently more stable than a catenary mooring type platform, the system dynamics are still very important. For this study, dynamics were not considered but would need to be considered if a more rigorous analysis were undertaken. Although the results of such an analysis could change the design, it is assumed that dynamic tuning of the platform to dodge wave harmonics would not appreciably change the production costs.

COST COMPARISONS

Table 4 compares the cost of the Dutch tri-floater concept with the NREL TLP concept. These costs are comparable largely because they were both performed on platforms designed for 5-MW turbines. But several cautions should be noted.

The cost figures in the third column provide a break down of the tri-floater costs in U.S. dollars taken directly from reference 2. These costs were converted from EURO given in the original report at a rate of $1.02/1.00 EURO; the exchange rate in December 2002 when the report was published. The Dutch report used conservative assumptions (according to conversations with the authors) that were unlikely to be challenged resulting in a $7.1 M single unit platform cost.

A brief discussion in the Dutch report indicates that cost reductions of approximately $1 M could be realized if the manufacturing location were changed to Asia. In addition, they estimate that 20% to 40% further reductions can be realized with series production based on 100 units and value engineering efforts, giving the estimated minimum cost of the tri-floater at $4.26M as presented in Table 4. This cost was derived from the detailed costs for the single unit with the above reductions applied.

The NREL TLP costs are rough approximations but are based on reliable cost per unit weight metrics for steel fabrication. Tank, tendon, and arm costs assumed specific costs of $1 to $2 per pound for large fabricated steel. The conservative estimate for the NREL concept was $6.5 M and the low cost estimate was $2.88 M. The high estimate assumes that steel costs are set at $2/lb and anchoring costs are set at the high end of the estimates received for suction pile anchors. The low cost estimate of $2.88 M assumes $1/lb steel production costs, more typical for volume production, and the use of vertical load anchors or some other lower cost anchoring system that could be developed.

Interestingly, the greatest differences between the Dutch tri-floater concept and the NREL TLP concept are in the cost of the steel support structure and buoyancy tanks. This difference appears to be primarily a result of a more massive structure needed to support the weight of the buoyancy tanks, ballast, and steel bracing above the surface. In the NREL TLP concept, the large platform components are all submerged. To determine the precise differences, however, a more detailed study must be completed.

A similar cost metric that was used for estimating the steel costs has not yet been established for anchor costs, although establishing a cost per vertical force requirement should be possible for a given anchor type and water depth. Anchor costs were approximated in the NREL study by surveying several commercial anchor manufacturers to get budgetary pricing information for a 8896-kN (2,000,000-lb) vertical anchor force. Prices covered a wide range, from as low as $20,000 to as high as $500,000 per anchor. For the purposes of this study, the anchor costs were assumed to range from $100,000 to $300,000 each with an additional installation cost of $50,000 to $200,000 each. It may be inferred from the previous discussion that a high degree of cost uncertainty lies in the anchor costs and further work is required to make estimates that can be fully backed up with commercial cost numbers. However, it is clear that anchors will play a large role in determining the final platform cost, and that a wide range of anchoring options exists.

The final cost category includes a range of miscellaneous items that are necessary for the deployment of offshore floating platforms. These items include mooring reinforcements, paint, cathodic protection, miscellaneous items, and turbine installation costs. The more comprehensive Dutch study detailed these items. The NREL study includes these same numbers from the Dutch report directly, because although the NREL model does not account for these items, it recognized that these costs are significant and should be included.

SYSTEM OPTIMIZATION

The Dutch study and the NREL TLP cost model show project costs for 5-MW turbine floating platform technology at $4.26 M and $2.88 M, respectively, in volume production. However, both of these studies are based on conservative, conventional technologies for which convenient cost information could be obtained. They do not provide a full system optimization. Historically, the maturation process of land-based wind systems had the consequence of categorically eliminating many potential innovations because of poor technical performance, high cost, high acoustic output, or objectionable visual appeal. The investigation of offshore wind energy is a new paradigm that will require old perceptions to be re-examined. Design concepts that were abandoned for land-based turbines may be well suited for offshore turbines. In addition, mature technologies from the marine and offshore oil industries will be introduced under a unique set of wind power plant specifications. Further system cost reductions will be possible with the specific application of new technology innovations. The following highlights some of the areas that might be explored.

Offshore systems may benefit from a variety of materials that are not applicable to or have been rejected for land-based systems. The primary buoyancy tank used to support the tank in the NREL model is made from steel. This enabled the derivation of a simple cost model based on consistent and easy to predict steel fabrication costs of roughly $1/lb. However, steel corrodes easily and must be painted at very high costs (see table 4). Alternatively, lightweight aggregates have already been used to produce high strength concrete buoyancy tanks for offshore oil TLPs, such as the Conoco-Phillips' Heidriun TLP. Concrete tanks could lead to substantial cost reductions based on the lower cost of the raw materials, better corrosion resistance, and lower maintenance costs.

Wind turbines have always attempted to minimize the weight of the nacelle and supporting structure as a means for controlling capital costs. Light-weight materials may play a greater role in the development of floating structures, as turbine weight reductions will subtract from the cost of the supporting structure and buoyancy tank. Composites may also find broader applications in untraditional areas such as the tower, hub, mainshaft, and bedplate. Further optimizations to minimize system mass may lead to large turbine clusters on a single floater and a re-evaluation of the best total plant size.

The rotational speed of land-based turbines is constrained by regulations governing noise emissions. Limited tip speeds of 76 m/s (170 mph) dictate larger blade planforms and off-optimum power production. If unconstrained, rotor speed could be optimized for increased energy production and lower extreme loads. This would have the positive effect of driving system costs down.

Land-based wind turbines are ostensibly restricted from running downwind because of perceptions about low frequency noise caused by tower shadow. Offshore systems will not have this restriction. This could lead to lighter weight rotors, less costly yaw drives, and reduced turbine loads.

Offshore systems may be able to control yaw through passive weather-vaning of the turbine or platform. This could lead to lower cost systems.

Offshore winds have not yet been fully characterized but probable lower wind shears will enable shorter tower heights. Because tower height is proportional to the base moment and the size of the buoyancy tanks required, shorter towers will lead to substantial cost savings. It is conceivable that towers need only be tall enough for the blade tips to clear the extreme wave when operating.

SUMMARY AND CONCLUSIONS

This report presented a general technical description of several types of floating platforms. Platform topologies were classified as multiple- and single-turbine floaters and by anchoring method. Platforms using catenary mooring anchors were contrasted to vertical mooring systems and the advantages and disadvantages were discussed. Specific anchor types were described in detail. A rough cost comparison was performed for two different platform architectures using a 5-MW wind turbine. One platform was based on a Dutch study of a tri-floater platform, and the other was a mono-column tension-leg platform developed at NREL. Cost estimates showed that single unit production cost is $7.1 M for the Dutch tri-floater and $6.5 M for the NREL TLP concept. However, value engineering, multiple unit series production, and platform/turbine system optimization can lower the unit platform costs to $4.26 M and $2.88 M, respectively, with significant potential to reduce cost further with system optimization. These foundation costs are within the range necessary to bring the cost of energy down to the DOE target range of $0.05/kWh for large-scale deployment of offshore floating wind turbines.

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Table 1 - Advantages and Disadvantages of Multiple- and Single-Turbine Platforms

	Advantages	Disadvantages
Multiple-Turbine Floaters	1. Wave stability 2. Shared anchors 3. Mass optimization possibilities	1. High cost support structure 2. Wave loading 3. Complex yaw control
Single-Turbine Floaters	1. Simplicity 2. Modularity for manufacture 3. Lower structural requirements 4. Standard yaw control options	1. Individual anchor costs

Table 2 – Advantages and Disadvantage of Principal Mooring Systems

	Advantages	Disadvantages
Vertical Anchor Mooring (Tension-Leg Platforms, taut-leg moorings)	• Inherent platform stability • Minimal wave loading • Simplified dynamics	• Expensive anchors • May not work in water depths less than 50 m.
Catenary Mooring Systems	• Low-cost anchors • May be deployed in shallow water.	• Ballast required for stability • Large amount of structure at surface • Complex dynamics, platform motion.

Table 3 - Comparison of Two Floating Platform Options

	Dutch Tri-floater Concept	NREL TLP Concept
Platform type	Semi-submerged tri-floater with spread moorings	Mono-column Tension leg platform
Power output	5 MW	5 MW
Rotor diameter	115 m	NA
Turbine location above waterline	83 m	85 m
Tower base diameter	7.5 m	7 m
Tower top diameter	4.5 m	NA
Mass of tower, turbine & rotor	6995 kN	8000 kN
Height of tower	65 m	100 m
COG location of tower above base	31.1 m	NA
Height of tank (submerged)	12 m x 3 tanks	10m
Diameter of tank	8 m x 3 tanks	16m
Tank displacement	2713 m^3	1989.5 m^3
Tendon spacing	68 m (tank centers)	60 m
Allowable heel (static + dynamic)	10 degrees	NA
Allowable lateral acceleration	3 m/s^2 at base of tower	NA
	5 m/s^2 at turbine	NA
Thrust in operational condition	1000 kN	1700 kN
Drag in survival condition	400 kN (at 50m above base)	NA
Ultimate moment at base	200,000 kNm	187,000-kNm

Table 4 - Cost Comparison of Two Floating Wind Turbine Platform Concepts *

* Both concepts assume conventional turbine configurations

	Dutch Tri-Floater Concept [2]			NREL TLP Concept		
Item	Weight (1000 lbs)	Specific Cost (U.S.D/lb)	Cost (million U.S.$)	Weight (1000 lb)	Specific Cost (U.S.$/lb)	Cost (million U.S.$)
FLOATING STRUCTURE						
Buoyant tanks	1068.5	1.14	1.22	394.7	1.00 to 2.00	.39 to .79
Braces	866.9	1.46	1.27	115.9	1.00 to 2.00	.12 to .23
Upper hull deck	345	1.37	0.47	NA	NA	NA
Support column	179.2	1.6	0.29	NA	NA	NA
Upper tank/turbine connection	NA	NA	NA	100	2	0.2
Arms	NA	NA	NA	103.3	1.00 to 2.00	.10 to .21
Platform Structure Subtotal 1			**1.94 to 3.24**			**.81 to 1.43**
MOORING SYSTEM						
Mooring chain	1120	0.91	1.02			
Mooring wire	302.4	0.91	0.28			
Anchors	448	1.37	0.61			.60 to 1.80
Vertical tendons (600-ft depth)				360	1.00 to 2.00	.36 to .72
Installation of suction anchors and platform			0.61			.30 to 1.20
Mooring System Subtotal 2			**1.51 to 2.52**			**1.26 to 3.72**
ANCILLARY ITEMS						
Mooring reinforcement	112	1.37	0.15			0.15
Paint	56	11.41	0.64			0.64
Cathodic protection	56	4.56	0.26			0.26
Miscellaneous	112	1.83	0.2			0.2
Installation of wind turbine			0.1			0.1
Ancillary Subtotal 3			**.81 to 1.35**			**.81 to 1.35**
TOTAL COST $M			**4.26 to 7.11**			**2.88 to 6.50**

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13. ABSTRACT *(Maximum 200 words)*

This paper provides a general technical description of several types of floating platforms for wind turbines. Platform topologies are classified into multiple- or single-turbine floaters and by mooring method. Platforms using catenary mooring systems are contrasted to vertical mooring systems and the advantages and disadvantages are discussed. Specific anchor types are described in detail. A rough cost comparison is performed for two different platform architectures using a generic 5-MW wind turbine. One platform is a Dutch study of a tri-floater platform using a catenary mooring system, and the other is a mono-column tension-leg platform developed at the National Renewable Energy Laboratory. Cost estimates showed that single unit production cost is $7.1 M for the Dutch tri-floater, and $6.5 M for the NREL TLP concept. However, value engineering, multiple unit series production, and platform/turbine system optimization can lower the unit platform costs to $4.26 M and $2.88 M, respectively, with significant potential to reduce cost further with system optimization. These foundation costs are within the range necessary to bring the cost of energy down to the DOE target range of $0.05/kWh for large-scale deployment of offshore floating wind turbines.

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