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A study of rotor and platform design trade-offs for large-scale floating vertical axis wind turbines

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Abstract. Vertical axis wind turbines are receiving significant attention for offshore siting. In general, offshore wind offers proximity to large populations centers, a vast & more consistent wind resource, and a scale-up opportunity, to name a few beneficial characteristics. On the other hand, offshore wind suffers from high levelized cost of energy (LCOE) and in particular high balance of system (BoS) costs owing to accessibility challenges and limited project experience. To address these challenges associated with offshore wind, Sandia National Laboratories is researching large-scale (MW class) offshore floating vertical axis wind turbines (VAWTs). The motivation for this work is that floating VAWTs are a potential transformative technology solution to reduce offshore wind LCOE in deep-water locations. This paper explores performance and cost trade-offs within the design space for floating VAWTs between the configurations for the rotor and platform.

1. Introduction

There are many challenges that must be addressed and overcome to realize cost-effective deep-water floating offshore wind systems. As a potential solution, this work is focused on assessing both the technical and economic feasibility of a deep-water floating VAWT system. The paper documents current findings including system-level design studies of the rotor, platform & mooring, and drivetrain and preliminary LCOE impacts analysis. The benefit of a floating VAWT is envisioned through system-level improvements and BoS cost reductions, which are addressed in this project through design studies that feed into a LCOE analysis. Several of the inherent advantages of a deep-water floating VAWT system are illustrated in Figure 1. VAWTs offer the potential to reduce offshore project costs in several areas across the project life-cycle as noted in Figure 2.

Similar and recent floating VAWT projects have been undertaken [1,2], which provide important insights into performance and costs. The Sandia project builds upon prior VAWT experience at Sandia National Laboratories, as noted in [3]. Recent work that lays the foundation for the current design studies includes VAWT design code development [4], a design study of rotor structural dynamic performance and the impact of floater type on system dynamics [5], an investigation of flutter (aero-elastic instability) potential in large-scale VAWTs [6], and an initial platform design study for floating VAWTs [7]. The present study builds upon these works to explore performance and cost trade-offs between the rotor and platform.

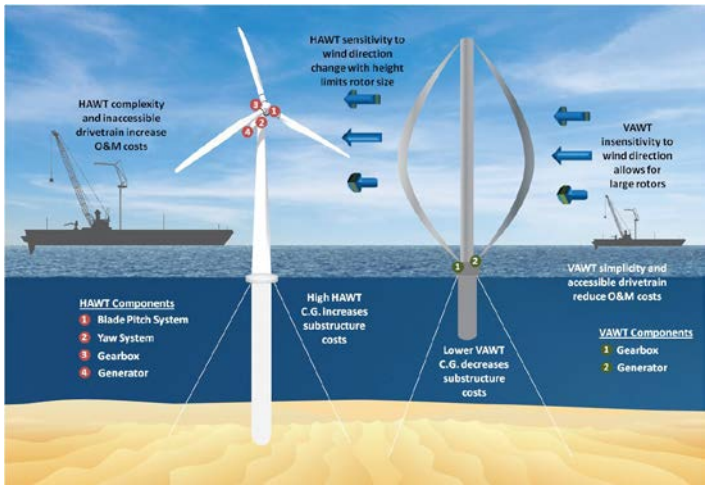

Figure 1. Comparison of HAWT and VAWT machines for deep-water offshore deployment

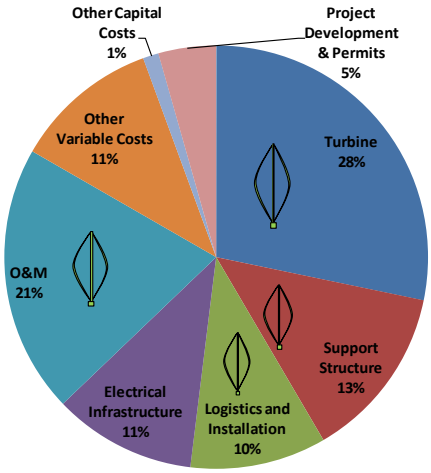

Figure 2. Estimated life-Cycle cost breakdown for an offshore wind project, and areas VAWTs improve

2. VAWT System Design and Analysis Results

The optimal floating VAWT configuration is not known, including the optimal configurations for the major components being the rotor, the platform & mooring, and the drive-train. Therefore, in this study, a range of options for the configurations of the major components were considered in order to explore and better understand the design space of a floating VAWT system. The results of this study, as described in this section, include design studies for the rotor (structural and aerodynamics), platform & mooring, and drivetrain. A key focus of this section, and this work in general, is on the relationships among the design of the major components (e.g. rotor-platform design trade-offs) and opportunities to reduce LCOE.

2.1 Rotor Design Studies

As a starting point, in order to reduce the parameter space of the turbine design, a rotor design study was performed with various 5MW design configurations. The design variables included the rotor architecture (Darrieus or V-shaped rotor configuration), number of blades (2 or 3 blades), tip chord length (small or large chord), material choice (glass or carbon), tapering scheme (uniform or tapered root), and rotor curvature (only for the V-VAWT). A depiction of the four principal configurations is shown in Figure 3.

The analysis included aerodynamic performance of the rotors, stability of modes of vibration, static loadings at parked and operating conditions, and rotor cost modeling, all as a means to characterize the suitability of the VAWT aerodynamic and structural designs for the design space as defined above. A few results are highlighted. The vertical center of gravity (CG) location of the topside (rotor/tower) for all configurations analyzed is shown in Figure 4. CG is an important quantity as, for example, lowering the CG should lead to smaller underwater structure. The rotor material costs for the various VAWT designs are shown in Figure 5, which illustrates cost and mass trade-offs for glass versus carbon rotors. In both figures, “Mass” refers to the topside mass of the rotor.

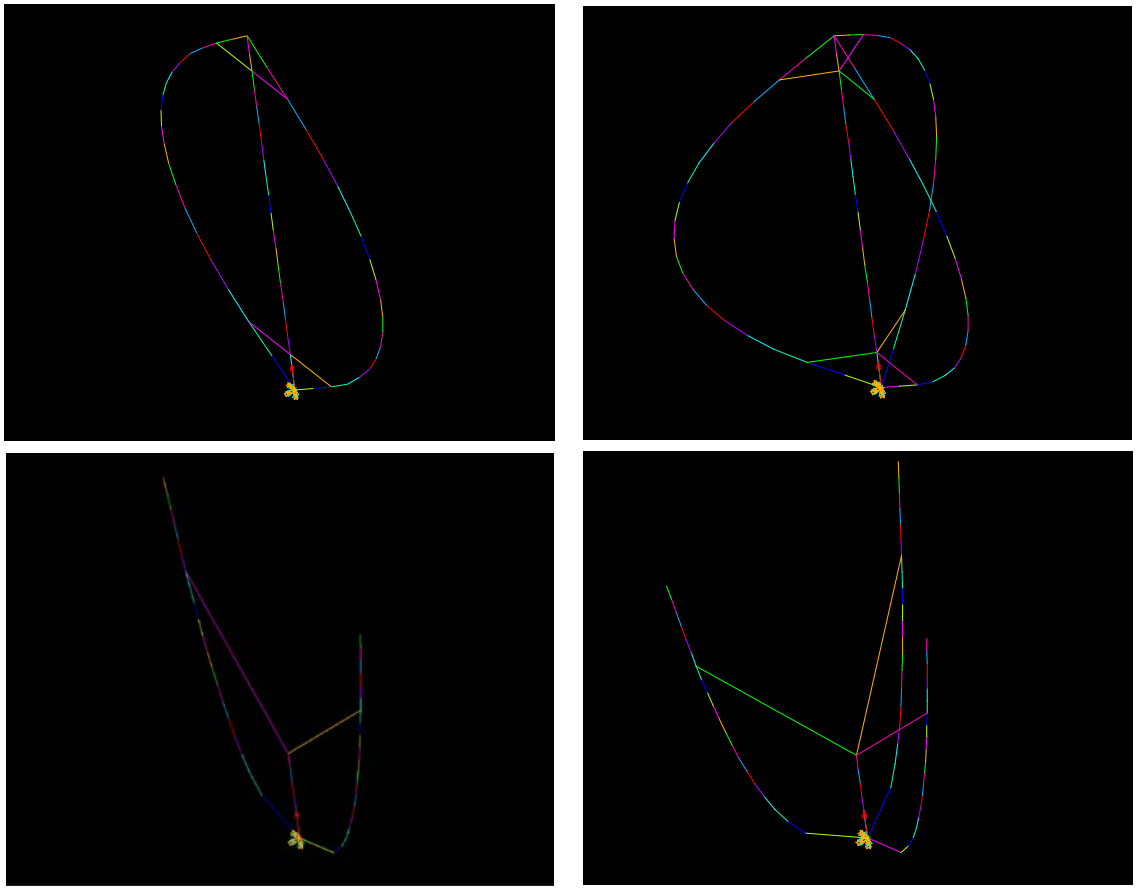

Figure 3. Finite element models of 2-bladed Darrieus (top left), 3-bladed Darrieus (top right), 2-bladed V-VAWT (bottom left), and 3-bladed V-VAWT (bottom right)

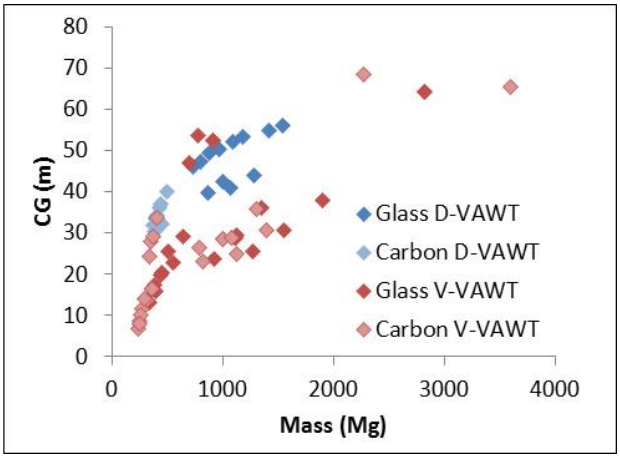

Figure 4. Rotor CG measured from water surface versus topside mass

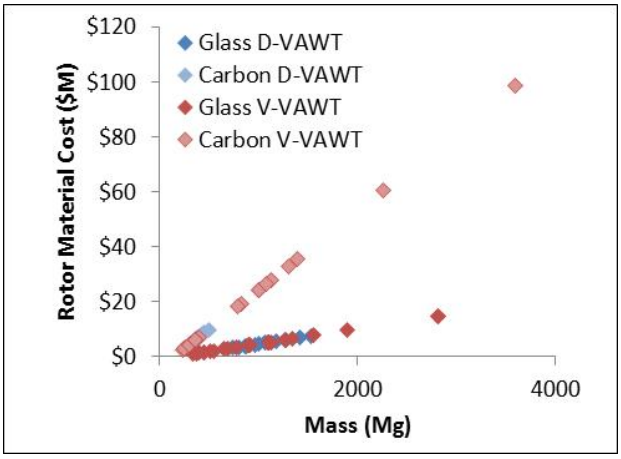

Figure 5. Rotor material costs for all designs versus topside mass

For the aerodynamic analysis, twelve Darrieus and twelve V-VAWT rotor designs were analyzed, each design incorporating a unique combination of blade chord at maximum radius (2m or 3m), number of blades (2 or 3 blades), and choice of blade tapering (un-tapered, single-tapered, or double-tapered) as introduced above.

The general trend observed in the aerodynamic performance was that maximum rotor aerodynamic efficiency (power coefficient) increases with rotor solidity. Solidity is increased by the addition of blade taper (in the present design study), by increasing the number of blades for a fixed blade chord, or by increasing the blade chord for a fixed number of blades. Increasing the solidity, however, comes at the price of lower maximum RPM as the lower RPM leads to higher torque, which increases the cost of the drive train.

As one example, Figure 6 shows the power curves for Darrieus designs having double-tapered blades, with varying number of blades and blade chord. The solidity of the two-bladed, large-chord design (2b-lc-dt) is the same as that of the three-bladed, small chord design (3b-sc-dt), and the power curves for those two designs match prior to stall.

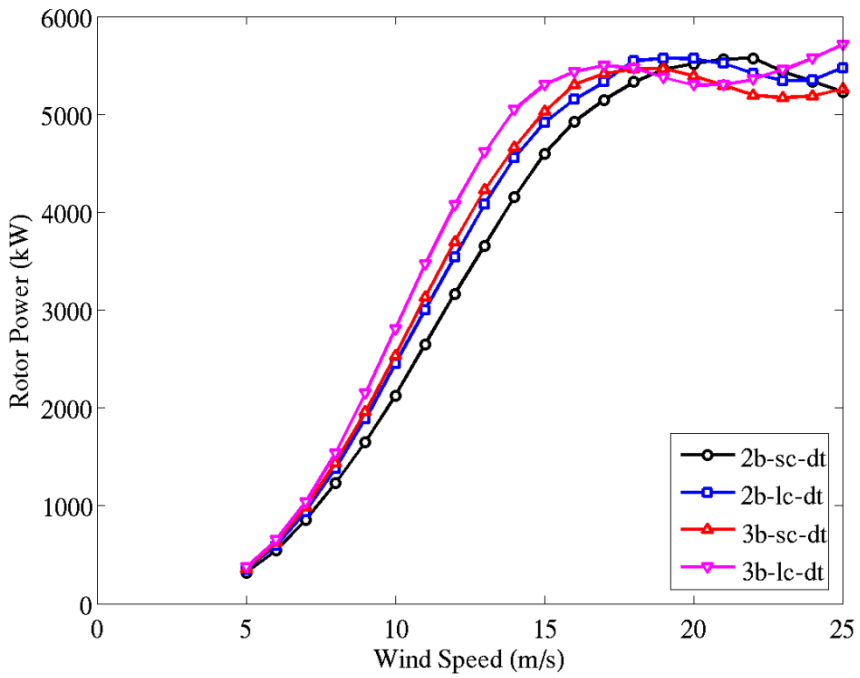

Figure 6. Power curves for Darrieus rotors, double-tapered designs

2.2 Platform Design Studies

This section presents results of the initial platform and mooring design studies for the Sandia floating VAWT system ([7]). The initial platform design studies included a comparison of spar and semi-submersible floating support structures. Proven floater types with publicly available specifications ([8], [9]) were selected in this study to provide a basis for scaling these concepts to the design requirements resulting from the rotor specifications (Section 2.1). A visual comparison of the scaled platforms is shown in Figure 7 for three different design points. Again, the design points were taken to represent the range of topsides (with varying mass & inertial properties, varying aerodynamic loads, and other design inputs) from the rotor design studies as summarized in Section 2.1.

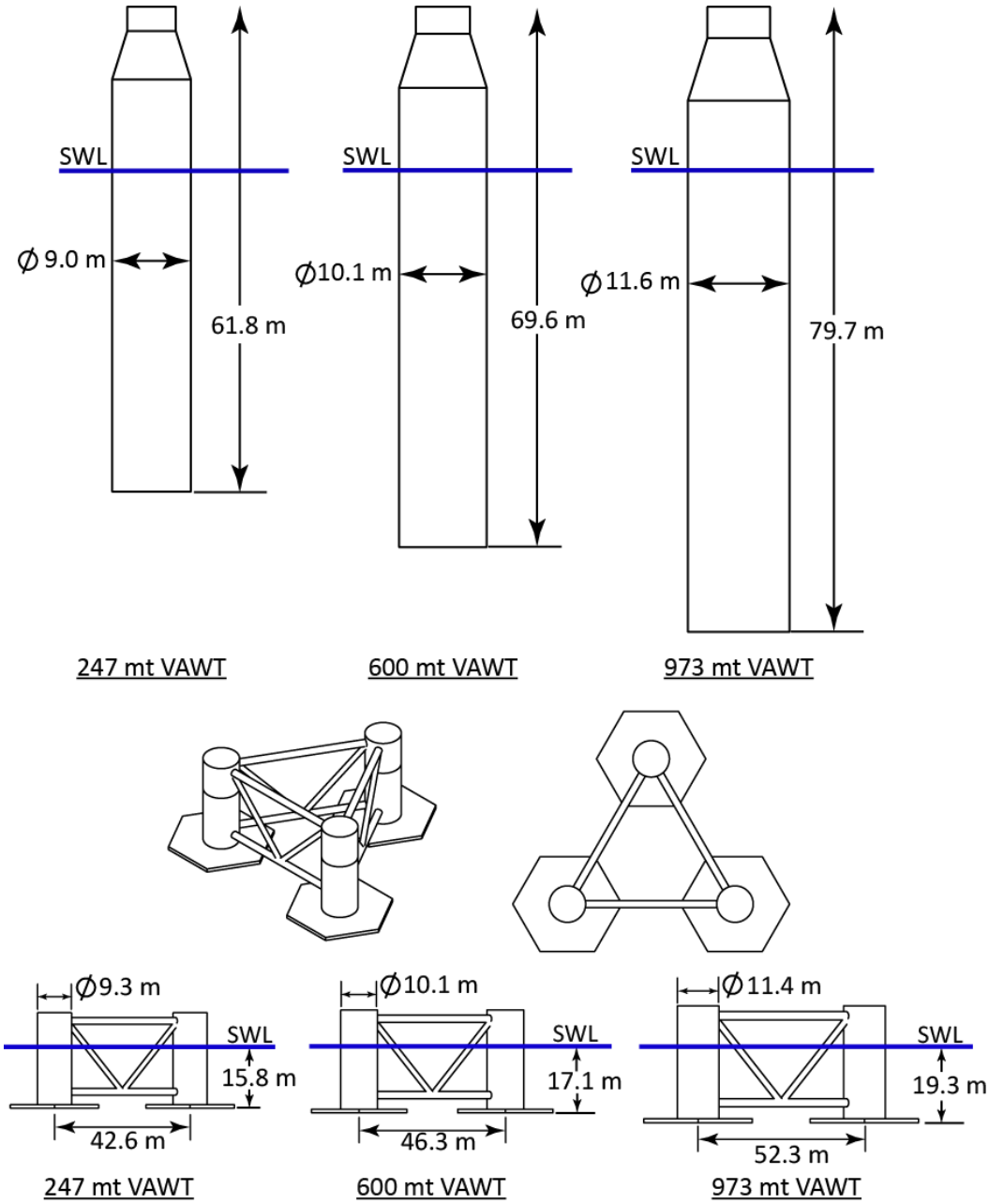

Figure 7. Spar and semi-submersible size comparison over the design range of the rotor

The design criteria for sizing the platforms were to limit the pitch angle to 5 degrees and obtain a pitch period between 30 and 40 seconds. Depending on the specific design parameters of the VAWT topside being investigated, the platform was Froude scaled until a design constraint was reached. In some cases for the lighter topsides, it was impossible to satisfy both criteria simultaneously as decreasing the platform steel mass lowered both the pitch angle and the pitch period. It was chosen to maintain the pitch angle and let the pitch period continue to fall, to demonstrate the trend as shown in the regions where the pitch period drops below 30 seconds and the 5 degree pitch angle is maintained.

Results of the platform design are presented below in Figure 8 (for the spar) and in Figure 9 (for the semi-submersible). Note that these results are for the entire range of VAWT rotor topsides defined

above in Section 2.1. From these plots, a few observations can be made regarding platform sizing trends. Most notable is the direct dependence of platform steel mass on topside mass as lighter topsides require smaller floaters and, vice versa, heavier topsides require larger floaters. Further, for the largest topsides, the controlling parameter is limiting the pitch period (to a value <40 seconds). However, as the topside mass decreases, the controlling parameter begins to shift towards keeping the mean pitch angle to a value of <5 degrees. As the topside decreases in mass, the pitch period decreases while maintaining a constant pitch angle. For the lightest topsides, a more robust optimization method is required to fully realize the platform scaling possibilities as simple Froude scaling can't satisfy both design criteria simultaneously.

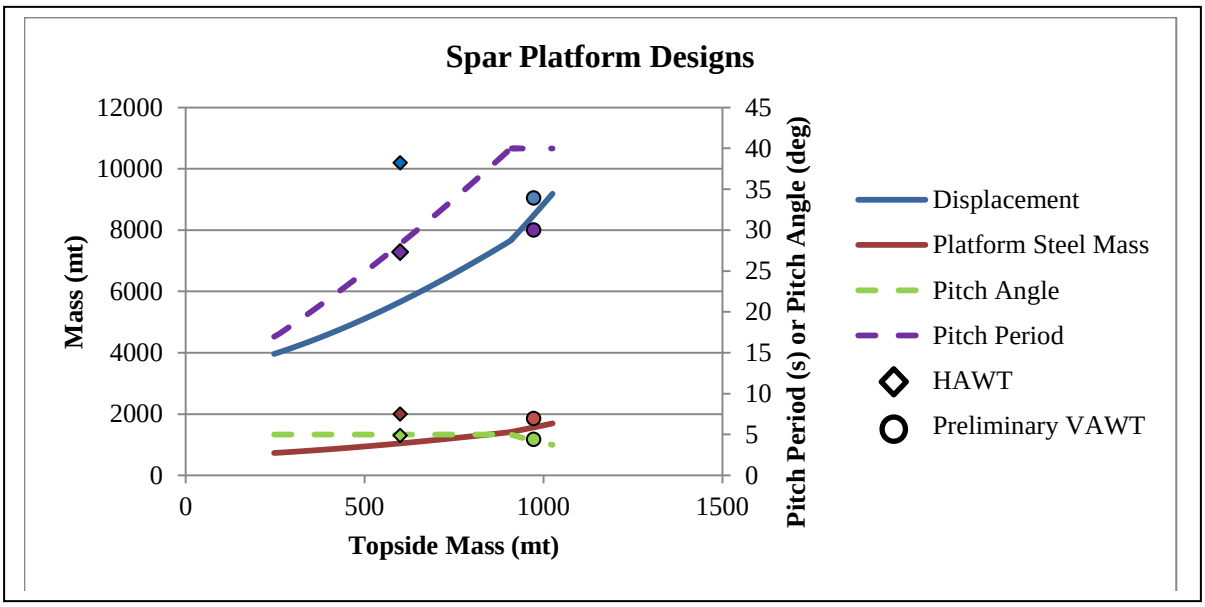

Figure 8. Spar-buoy platform design results

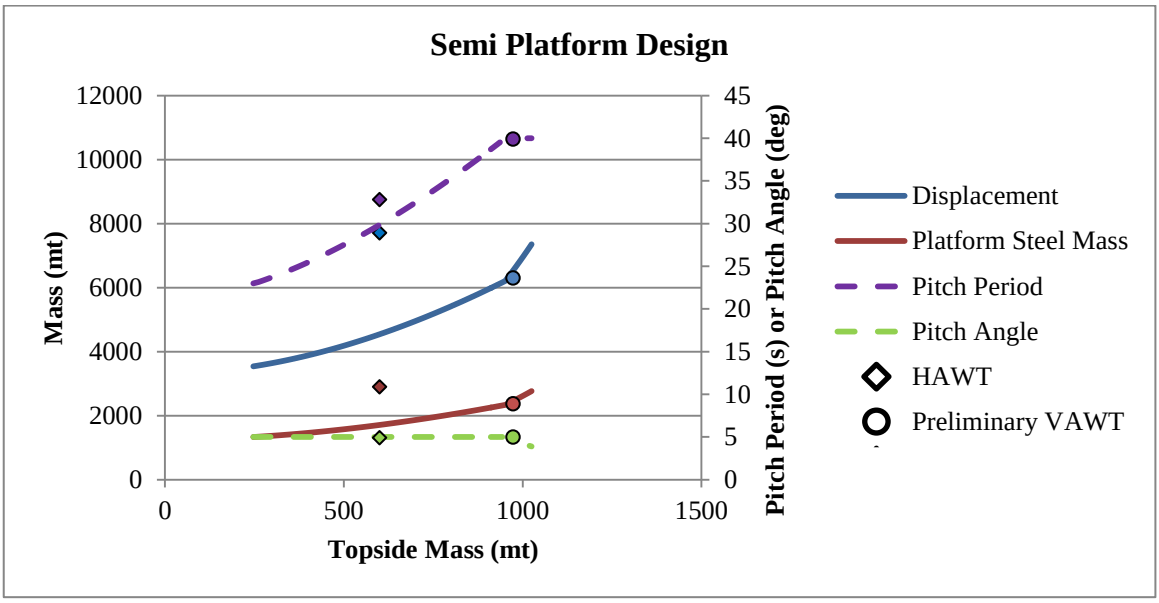

Figure 9. Semi-submersible platform design results

Results for one of the preliminary VAWT designs (from the high end of the topside mass range) are shown with circular marks and a HAWT design (based on the NREL 5MW reference turbine [10]) is shown as diamond marks on each graph. Additionally, the platform size for the HAWT (with mass of 600-mt) was designed to have the same performance as the VAWT design in an effort to provide a similar basis for comparison. As noted in [7] the HAWT topside has a higher CG, larger aerodynamic load and higher center of pressure than the VAWT, thus, the size of the platform must increase to provide a similar level of performance. This is shown in the figures above by comparing the diamond markers for the HAWT design with the design curves for the VAWT design at 600-mt topside mass.

This information is provided in tabular form in Table 1, where one can compare the steel material requirements for (a) two different floater types (spar and semi-submersible) and (b) two different topside turbine types (HAWT and VAWT). The advantage of the VAWT over the HAWT in steel mass savings is evident from the table. For the case of equal topside mass of 600 mt for the HAWT and VAWT, 48% and 41% reduction in steel mass is found for the VAWT topside for the spar and semi-submersible, respectively. For the case of higher VAWT topside mass of 973 mt (a 62% increase in topside mass over the 600 mt topside) the reductions in steel mass for the VAWT topside are 25% and 18% for the spar and semi-submersible, respectively, over the 600 mt HAWT topside.

Table 1. Comparison of platform steel mass for two platform/floater types and two topside types of equal power rating (5MW)

	HAWT		VAWT (with equal mass of 600 mt)		VAWT (with mass of 973 mt)	
	Spar-buoy	Semi-Sub	Spar-buoy	Semi-Sub	Spar-buoy	Semi-Sub
Topside Mass (mt)	600	600	600	600	973	973
Platform Steel Mass (mt)	2,000	2,900	1045	1708	1,500	2,370
Percent mass reduction versus HAWT	--	--	48%	41%	25%	18%

2.3 Drivetrain Impacts Analysis

In addition to rotor and platform considerations, the drivetrain has significant implications with respect to system-level design trade-offs for a floating VAWT, as discussed in this section. Further, there is a fundamental difference when considering a VAWT and HAWT of equal power rating in that the drivetrain must be designed for the larger torque and lower RPM associated with the VAWT rotor. This is expected to result in higher drivetrain costs per MW. Choosing VAWT rotors with higher RPM is preferred to reduce drivetrain costs, yet this requires a lower solidity rotor, as noted above. Although beneficial to drivetrain sizing, the lower solidity and higher RPM rotor design is more challenging from a structural point of view, and a compromise in the design is needed.

Some additional points can be made regarding other aspects of the drivetrain design for a floating VAWT system. By locating the drivetrain at the turbine base, the CG of the rotor system is significantly lowered – the CG of the rotor is reduced by 10's of meters for the rotor plus drivetrain

assembly for the range of topsides in Section 2.1. This is a significant reduction and advantage for the floating VAWT with respect to the sizing and cost of the floating platform, as evidenced in the preceding section. In addition, another advantage is that the placement of the drivetrain results in reduced costs with respect to (a) assembly & installation, (b) inspection, and (c) maintenance costs of the drivetrain components due to improved accessibility (See Figure 1).

3. Cost Implications at the Floating VAWT System Level

In this section, cost implications are discussed. Some issues we seek to better understand are (1) trade-offs in rotor and platform options (better to have a light costly rotor with small cheap platform or a heavy cheap rotor with big costly platform, (2) high or low desired RPM (which impacts numerous design variables including annual energy production (AEP), drivetrain sizing, loads, resonance, aero stability, etc), and (3) operations & maintenance (O&M) costs as they relate to selection and design of the major components.

The LCOE impacts analysis is performed considering the following cost structure with the cost of an offshore wind farm considered to be decomposed into three main categories (as detailed in Figure 10): (1) balance of system (BoS) costs, (2) turbine capital costs, and (3) O&M costs. BoS costs can be further decomposed to include: transportation, installation, electrical interconnection, and other costs. Turbine capital cost can be further decomposed into: rotor cost, drive-train cost, support structure cost, control & monitoring system costs, and marinization cost.

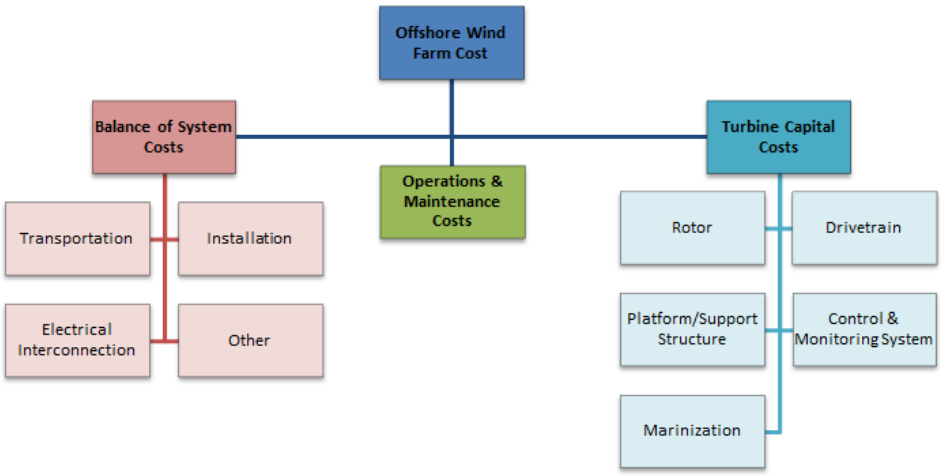

Figure 10. Offshore wind farm cost categories and sub components

Figure 11 summarizes preliminary system-level design and cost studies for a set of rotors having the lowest LCOE. These include four Darrieus rotors and one V-VAWT rotor. The first two Darrieus rotors, one with 2-blades and one with 3-blades, are carbon designs with large chords. The carbon designs are light-weight but more costly rotors; however, the platform costs are lower. The third and fourth Darrieus rotors, again one with 2-blades and one with 3 blades, are glass designs having small chords. These glass Darrieus rotors have higher associated topside mass, but lower rotor costs in comparison to the carbon Darrieus rotors. However, the platform costs for the glass rotors are higher due to the higher topside mass. A general trend showing higher AEP with lower RPM can also be observed.

Specific values for the capital costs of the major components have not been provided here in order to emphasize the relative order of costs and their associated cost trade-offs. In particular, a few key

points on capital costs include: (1) the drivetrain costs vary but not significantly for each rotor, (2) the rotor and platform costs vary significantly for the carbon versus glass rotors; however, the sum of the rotor and platform costs are similar for each of the four Darrieus designs, and (3) the V-VAWT was found to have high rotor mass and high rotor costs in comparison to the Darrieus designs, although the aerodynamic performance was in-line with the Darrieus rotors.

VAWT ROTOR CONFIGURATION DESCRIPTION	Carbon 3 blades Large chord	Carbon 2 blades Large chord	Glass 3 blades Small chord	Glass 2 blades Small chord	Carbon 2 blades Large chord
Normalized Turbine AEP (MW-hr)	1.0	0.92	0.94	0.85	0.95
Rotor Speed (RPM)	6.30	7.20	7.20	8.25	7.40
Drive-train Cost	+	+	+	+	+
Rotor Cost	++	++	+	+	++++
Platform & Mooring Cost	+	+	++	++	++

Figure 11. Summary of Preliminary System-level Design and Cost Trade-offs

4. Concluding Remarks and Future Work

In conclusion, a few key points should be emphasized:

(1) The Darrieus rotor is a VAWT rotor configuration proven with field experience and offering structural advantages and aerodynamic efficiency similar to a HAWT. However, there is still room for enhancement of the Darrieus rotor when designing VAWTs at large-scale and for floating offshore systems. This has been explored in this work through a rotor design study, which included a study of rotor configuration, number of blades, chord size, and blade tapering schemes. For example, tapering of blade chord toward the root ends leads to higher AEP versus non-tapered blades.

(2) RPM is a key design variable impacting virtually all aspects of the design and impacting all of the major components. RPM is an important parameter for energy capture, aerodynamic loads, drivetrain sizing, platform dynamic loads, and structural dynamic resonance.

(3) As anticipated, lower CG and lower overturning moments for a VAWT resulted in significantly less steel material a HAWT of equivalent power rating. This indicates strong potential for LCOE reduction through platform cost reductions, and is a major advantage for VAWTs over HAWTs in deep-water offshore.

In future work, we will refine the designs for the major components and their cost estimates, with the goal to quantify LCOE with reasonable uncertainty for a floating VAWT system. The refinements to the design and cost analysis will include: (1) for the rotor; inclusion of additional costs such as manufacturing, (2) for the platform & mooring; we will consider additional floater types and re-visit practical design requirements such as freeboard height, (3) for the drivetrain; sizing of both direct drive and geared options will be considered along with costing, (4) for operations and maintenance costs; we will calculate these costs including unique VAWT characteristics such as improved drivetrain accessibility at the water line, and (5) for BoS costs; will be computed for a floating VAWT system including important costs such as installation, assembly, and electrical infrastructure.

5. References

[1] Paulsen, U., Borg, M., Madsen, et. al, "Outcomes of the DeepWind conceptual design" Energy Procedia 10.1016/j.egypro.2015.11.437, 2015

[2] Borg, M., Collu, M., "A comparison on the dynamics of a floating vertical axis wind turbine on three different floating support structures," Energy Procedia 53, Proceedings of EERA DeepWind'2014, 11th Deep Sea Offshore Wind R&D Conference, 2014, pages 268-279.

[3] Sutherland, H.J., Berg, D.E., and Ashwill, T.D., "A Retrospective of VAWT Technology," Sandia National Laboratories Technical Report, SAND2012-0304, January 2012.

[4] Owens, B.C., Hurtado, J.E., Paquette, J., Griffith, D.T., and Barone, M., "Aeroelastic Modeling of Large Offshore Vertical-axis Wind Turbines: Development of the Offshore Wind Energy Simulation Toolkit," 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 8–11, 2013, Boston, MA, USA, AIAA-2013-1552.

[5] Owens, B.C., Griffith, D.T., and Hurtado, J.E., "Modal Dynamics and Stability of Large Multi-megawatt Deepwater Offshore Vertical-axis Wind Turbines: Initial Support Structure and Rotor Design Impact Studies," 32nd ASME Wind Energy Symposium, National Harbor, MD, USA, January 2014.

[6] Owens, B.C., and Griffith, D.T., "Aeroelastic Stability Investigations of Large-scale Vertical Axis Wind Turbines," Journal of Physics Conference Series, Science of Making Torque from Wind Conference, June 18–20, 2014, Lyngby, Denmark.

[7] Fowler, M., Bull, D., and Goupee, A, "A Comparison of Platform Options for Deep-water Floating Offshore Vertical Axis Wind Turbines: An Initial Study," Sandia National Laboratories Technical Report, SAND2014-16800, August 2014.

[8] Jonkman, J. M., 2010, "Definition of the floating system for Phase IV of OC3," NREL Technical Report No. TP-500-47535.

[9] Roddier, D., Cermelli, C., Aubault, A. and Weinstein, A., 2010, "WindFloat: A Floating Foundation for Offshore Wind Turbines," *Journal of Renewable and Sustainable Energy* 2 033104.

[10] Jonkman, J. M., Butterfield, S., Musial, W., and Scott, G., 2009, "Definition of a 5-MW Reference Wind Turbine for Offshore System Development," National Renewable Energy Laboratory, Technical Report NREL/TP-500-38060.