Baseline Design of a Hurricane-Resilient Wind Turbine

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Abstract

Under U.S. Department of Energy-sponsored research Funding Opportunity Announcement 415, the National Renewable Energy Laboratory (NREL) led a team of research groups to produce a complete design of a large wind turbine system to be deployable in the Western Gulf of Mexico region. As such, the turbine and its support structure would be subjected to hurricane loading conditions. Among the goals of this research was the exploration of advanced and innovative configurations that would help decrease the design's levelized cost of energy (LCOE), and the expansion of the basic International Electrotechnical Commission's (IEC's) [1] design load cases (DLCs) to include hurricane environmental conditions. The wind turbine chosen was a three-bladed, downwind, direct-drive, 10-MW rated machine. The rotor blade was optimized based on an IEC load suite analysis. The drivetrain and nacelle components were scaled up from a smaller sized turbine using industry best practices. The tubular steel tower was sized starting from ultimate loads at tower top derived from the rotor optimization analysis. The substructure used is a new battered and raked jacket structure. The complete system has also been modeled within an aero-servo-hydro-elastic tool, and future papers will discuss results of the dynamic response analysis for select DLCs. Although resource limitations prevented multiple design iterations, the results are valuable for predicting the LCOE of large offshore wind turbines deployed in subtropical U.S. waters, as well as for demonstrating the impact of design innovations on LCOE.

Main Environmental and Structural Parameters

Turbine rating [MW]/water depth [m]	10 MW (IEC Class IB)/25		
Hub height [m]/deck height (flange level) [m]	135/20.7 (clears 1,000-yr wave crest – [2])		
Design Environmental Parameters from [3]	DLC 1.6 **10-yr RP Event**	DLC 6.1 **100-yr RP Event**	Robustness Check **500-yr RP Event**
Wind speed (1-hr mean,10 m MSL) [m/s]	30.7	39.5	52.1
Max wave height and period- H_{max} [m] / T [s]	10.1/11.3	17.2/13.7	21/14.8
Surge [m]/Current [m/s]	1.1/1.52	2.3/2.1	2.45/2.44

Soil stratigraphy (Typical of proximity to South Padre Island; source: Keystone Engineering)	Penetration Range [m]	Description
	0-25	Very soft to very stiff clay
	25-35	Medium dense to dense fine sand
	35-50	Very stiff clay
	50-60	Medium dense to dense silty fine sand
	60-75	Very stiff to hard clay

Rotor Design

Wetzel Engineering Inc. performed a design optimization that considered the following:

- Downwind rotor to try and relax stiffness requirements and lighten the blades
- Airfoils: WEI-FB (maximum chord, inboard) and DU-NACA (outboard) 64%–21% t/c
- LCOE and maximum root-bending moment as main drivers
- IEC DLCs including EOG, ECD, and hurricane survival cases
- Carbon-reinforced spar cap and thick airfoils
- Analysis of approximately 4 million blade configurations
- Blade length, platform, and tip-speed as design variables.

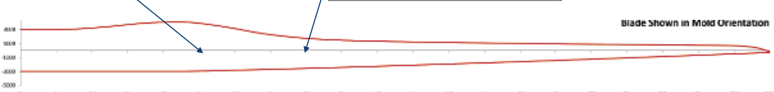
The final design was constrained by:

- Maximum tip-deflection of 15% (no tower clearance issues)
- Composite layers' utilization <1
- Modal requirements (resonance avoidance versus rotor forcing 1P, 3P,…)

Parameter	Value
Blade length [m]	105
Max chord [m]	7
Optimal tip-speed-ratio	10
Rated wind speed [m/s]	11.2
AEP [MWhr]	49,241
Cp max	0.473
Blade mass [tonnes]	64

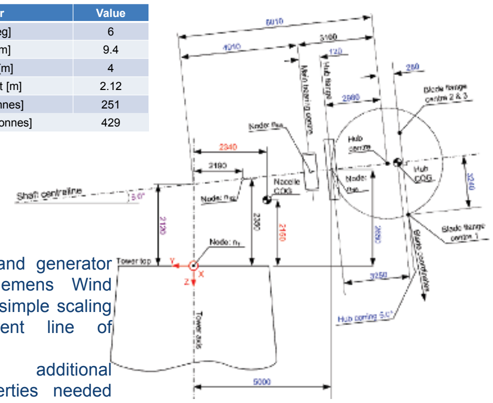
Materials: 2,3,4AX fiberglass, balsa and PVC, UD Carbon spar

First and Second Eigenfrequencies:
- ~0.6 and 1.6 Hz flatwise
- ~0.98 and 3.46 Hz edgewise



Nacelle Design

Parameter	Value
Shaft tilt [deg]	6
Overhang [m]	9.4
Hub radius [m]	4
Tower-to-shaft [m]	2.12
Hub mass [tonnes]	251
Nacelle mass [tonnes]	429



- Hub, drivetrain, and generator designed by Siemens Wind Power based on simple scaling laws and current line of products
- NREL derived additional aeroelastic properties needed for FAST simulations
- Basic torque and pitch controller devised by NREL.

Optimized Support Structure

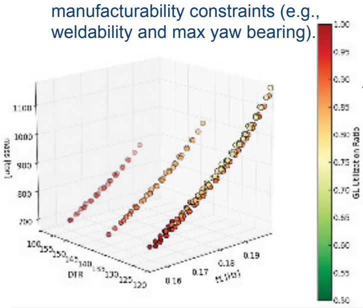
Optimized Tower

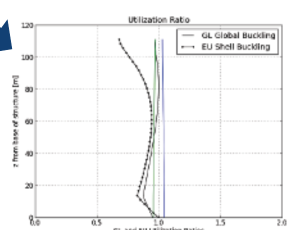
The tower mass was minimized while:

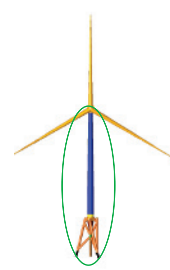
- Maximizing ULS utilization (GL and Eurocode standards [4-5]) under prescribed turbine loads (from rotor analysis)
- Targeting a prescribed system (soft-stiff) first natural frequency
- Including structural and manufacturability constraints (e.g., weldability and max yaw bearing).

Main Design Parameter	Value
RNA (rotor-nacelle-assembly) mass [tonnes]	865
RNA CM(center of mass) x offset [m] (downwind)	**5.87**
Max rotor thrust (yaw-bearing force) [kN] DLC 1.6/DLC 6.1	1.9E3/ 4.3E2
Design wind speed [m/s] DLC 1.6/DLC 6.1	33/70
Substructure equivalent lateral/axial spring constant [kN/m]*	5.80E4/ 6.46E6
Substructure equivalent rotational spring constant [kNm/rad]*	4.4E7
Steel density [kg/m3]**	8,792
Target first eigenfrequency [Hz]	0.14*

[*] From Keystone Engineering
[**] Accounts for secondary steel, flanges, hardware, appurtenances, and coatings.







Design (Unfactored) Loads At Tower Base	Value for DLC 1.6	Value for DLC 6.1
Tower base shear [kN]	2,360	2,610
Tower base bending moment [kN m]	283,660	166,600

[*]From tower optimization

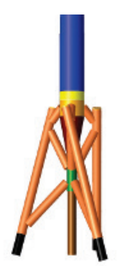
Parameter	Value
Tower base OD [m]	6.96
Tower top OD [m]	4.5
Diameter-to-thickness ratio (OD/t)	163.5
Tower length [m]	111.2
Tower constant OD segment length [m]	13.35
Tower mass [tonnes]	656
First system eigenfrequency [Hz]	~0.16

The downwind location of the RNA CM adds ~15% to the tower mass compared to an upwind configuration. This is due to additional loading that augments the thrust-driven bending moment.

Optimized Substructure

The substructure was optimized by:

- Verifying members against code checks (ISO[6]) under prescribed turbine, tower, and hydrodynamic loads
- Targeting first eigenfrequency (0.14–0.17Hz)
- Ensuring designated deck height
- Ensuring proper pile penetration
- Minimizing overall steel mass.



Parameter	Value
Pile OD/t [m]	2.4/.04
Pile embedment [m]	61
Pile mass (3 piles+caisson) [tonnes]	604
Batter	3.5
Leg OD/t [m]	2.5/0.018
Brace OD/t [m]	2.4/0.025
Caisson OD/t [m]	2.4/0.03
Jacket mass [tonnes]*	602
TP mass [tonnes]	83
Total mass [tonnes]**	745

[*]Does not include secondary steel
[**]Including secondary steel

Conclusions and Future Work

- This paper introduced the results of a conceptual design study focusing on a baseline, hurricane-resilient, offshore wind turbine. More details will be provided in future technical reports and papers including LCOE estimates.
- API RP2 MET (interim bulletin) [3] was used to extend the IEC DLCs to hurricane events
- Several innovations were selected (e.g., downwind system and innovative substructure)
- The downwind location of the nacelle CM contributed to ~15% penalty in tower mass compared to an upwind configuration, due to the resulting additional overturning moment.
- A full optimization of the entire support system can produce considerable savings in overall system mass than independent tower and substructure designs [7], but this is left to future research.

References

[1] International Electrotechnical Commission (IEC). (2009). *IEC 61400-3 Ed. 1.0: Design Requirements for Offshore Wind Turbines.*
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[5] EN 1993-1-6 (2007): *Eurocode 3: Design of steel structures - Part 1-6: Strength and stability of shell structures.*
[6] International Organization for Standardization (ISO). (2008). *ISO 19902:2007 -Petroleum and natural gas industries – Fixed Steel Offshore Structures.*
[7] Damiani, R.; Song, H. (2013). *A Jacket Sizing Tool for Offshore Wind Turbines within the Systems Engineering Initiative*; Offshore Technology Conference, Houston, Texas, April 30–May 4, 2013.

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