The Design Challenges of Large, Deep-Water, Vertical-Axis Wind Turbine Rotors

Josh Paquette

Sandia National Laboratories

Overview

- **Sandia VAWT Experience**
- **VAWT Potential for Deep-Water Offshore Wind**
- **Sandia Offshore Technology Development Project**
  - VAWT Airfoils
  - Aerodynamic Modeling
  - Aeroelastic Modeling
- **Scaling to Large Machines**
  - Design Options
  - Mass Properties of 5MW Darrieus Glass Rotors
  - Structural Dynamics Concerns
  - Parked Loads

Sandia VAWT Experience

Previous SNL VAWT Research

- **Early 1970's to mid 1990's**
- **Started with Savonius rotors, Moved Quickly to Full-Darrieus Rotors**
- **Succession of Designs: Leading to the Very Successful 17-m, 100 kW Full-Darrieus VAWT**
  - Successful Commercialization
    - Several US Manufactures
    - FloWind
      - **Over 500 VAWTs Deployed: Primarily in Altamont Pass**
      - **170 19-m Turbines in their Fleet**
- **Culminated with Design of the 34-m Research VAWT Test Bed**
  - Commercialization
    - The Point Design
    - FloWind EHD Turbine

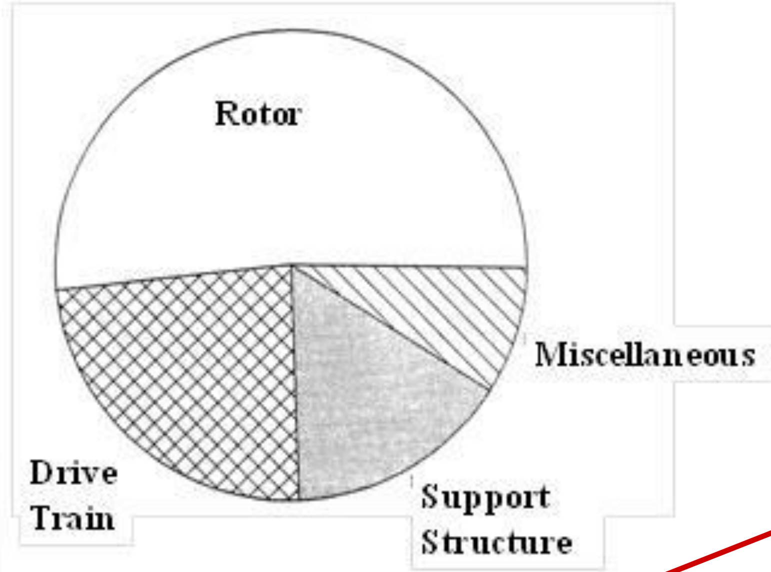
34-m VAWT Test Bed

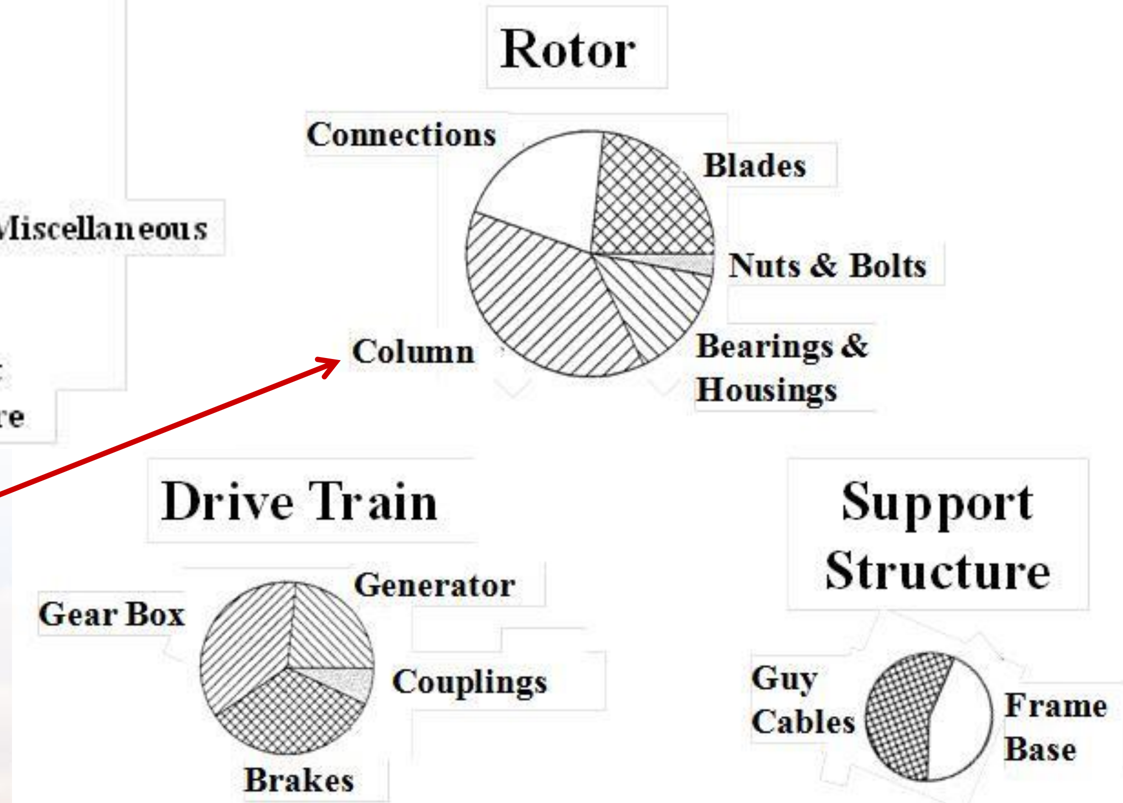
- **Located in Bushland, TX**
  - Dedicated: May, 1988
  - Decommissioned: Spring, 1998
- **Rotor: 34-m Dia, 50-m Height**
- **Performance:**
  - Variable Speed: 25 to 38 rpm
  - Rated Power: 500 kW
- **Heavily Instrumented**

  72 Strain, 25 Environmental,

  22 Performance, 29 Electrical
- **Large Database, Many Publications**

Economic Analysis

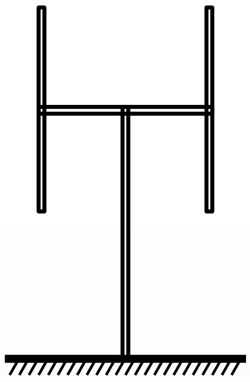


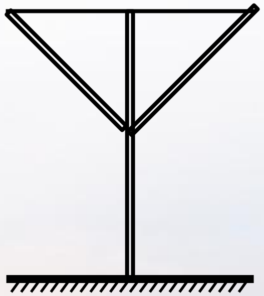


Tower was the Largest Cost Element of the Rotor

Cantilever Designs

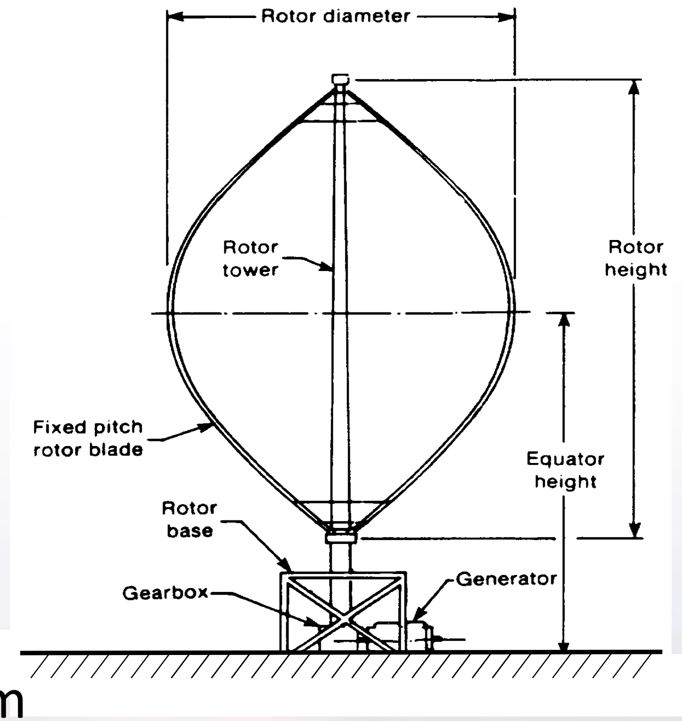
- **"H" Rotor**
  - No Reefing Capabilities
  - High Performance Penalty
    - Blade-to-Cross-Arm
    - Tip Losses
  - Aerodynamics Brakes in the Cross Arm
- **"Y", "V" or Sunflower Rotor**
  - Blade Tip Stabilization: Aerodynamic Losses
  - Foldable Design
    - High Wind Survival
    - Hinged Blades: Maintenance Problem
- **Molded Composite Blades**





VAWT Technology

- **Long Blades**
  - Twice as Long as Equivalent HAWT Blade
  - Innovative Materials & Manufacturing Techniques
- **Active Aerodynamic Control**
  - Passive Power Control: SNF Airfoils
  - Aerodynamic Brakes
- **Large Footprint: Guy System**
  - Cantilever Designs
- **Torque Ripple**
  - Compliant Drive Train
- **Power Train**
  - May or May Not Self Start: Starting System Required
  - Right-Angle Transmission



Considerations for Off-Shore Applications

- **Aerodynamics**
  - SNL NLF Airfoils, Summer Airfoils
  - Better Structural Characteristics: “Thick Airfoil” Series
  - Eliminate and/or Fair Struts and Joints
- **Blade Materials**
  - Composite Materials
  - Molded Composite Structure
    - High Bend-in-Place Stresses
    - Tailored Chord Distribution
- **Drive Train and Power Components**
  - Variable Speed with Regenerative Braking
  - Brake System
  - Direct-Drive
  - Vertically Mounted Generators

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Sandia Wind Site

WindMesa.com Site

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A Retrospective of VAWT Technology

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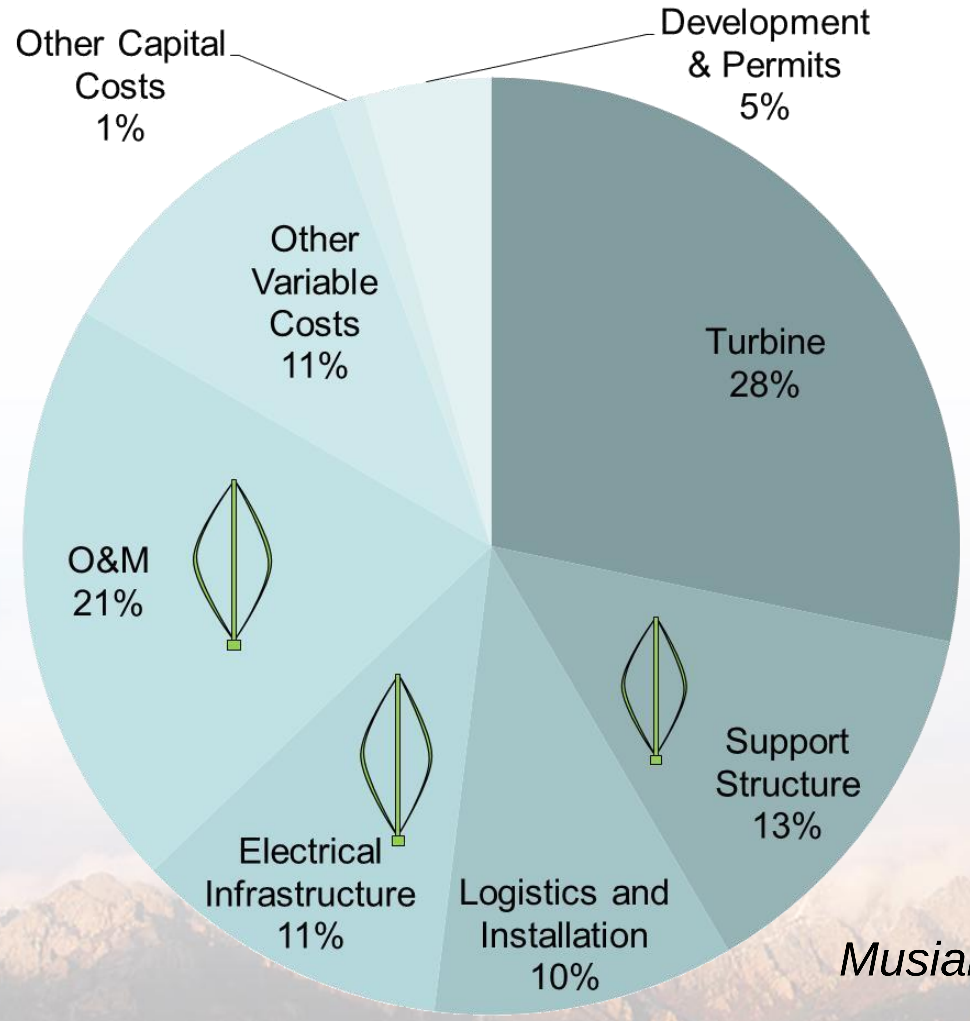
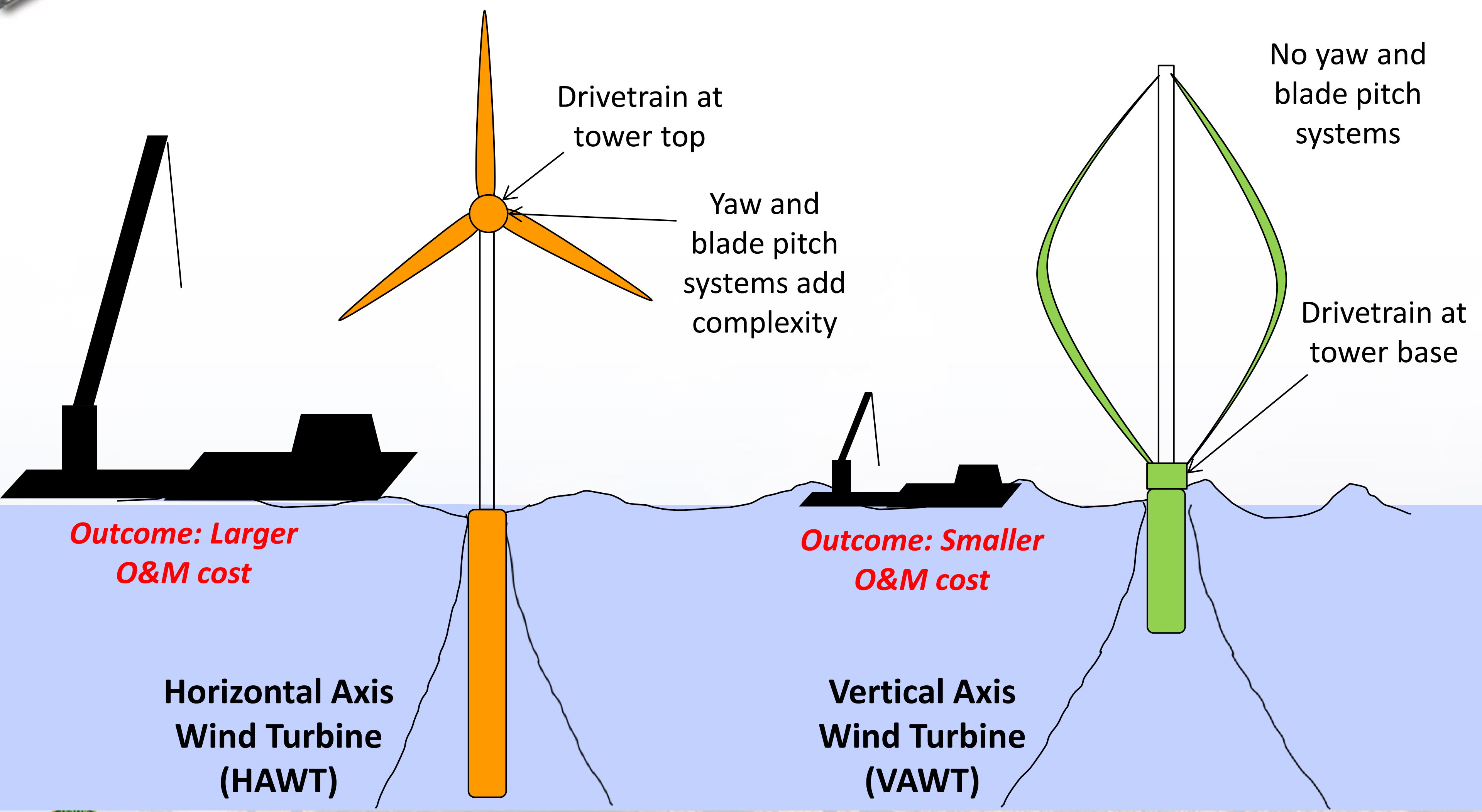
VAWT Potential for Deep-Water Offshore Wind

Offshore Wind Project Cost Breakdown

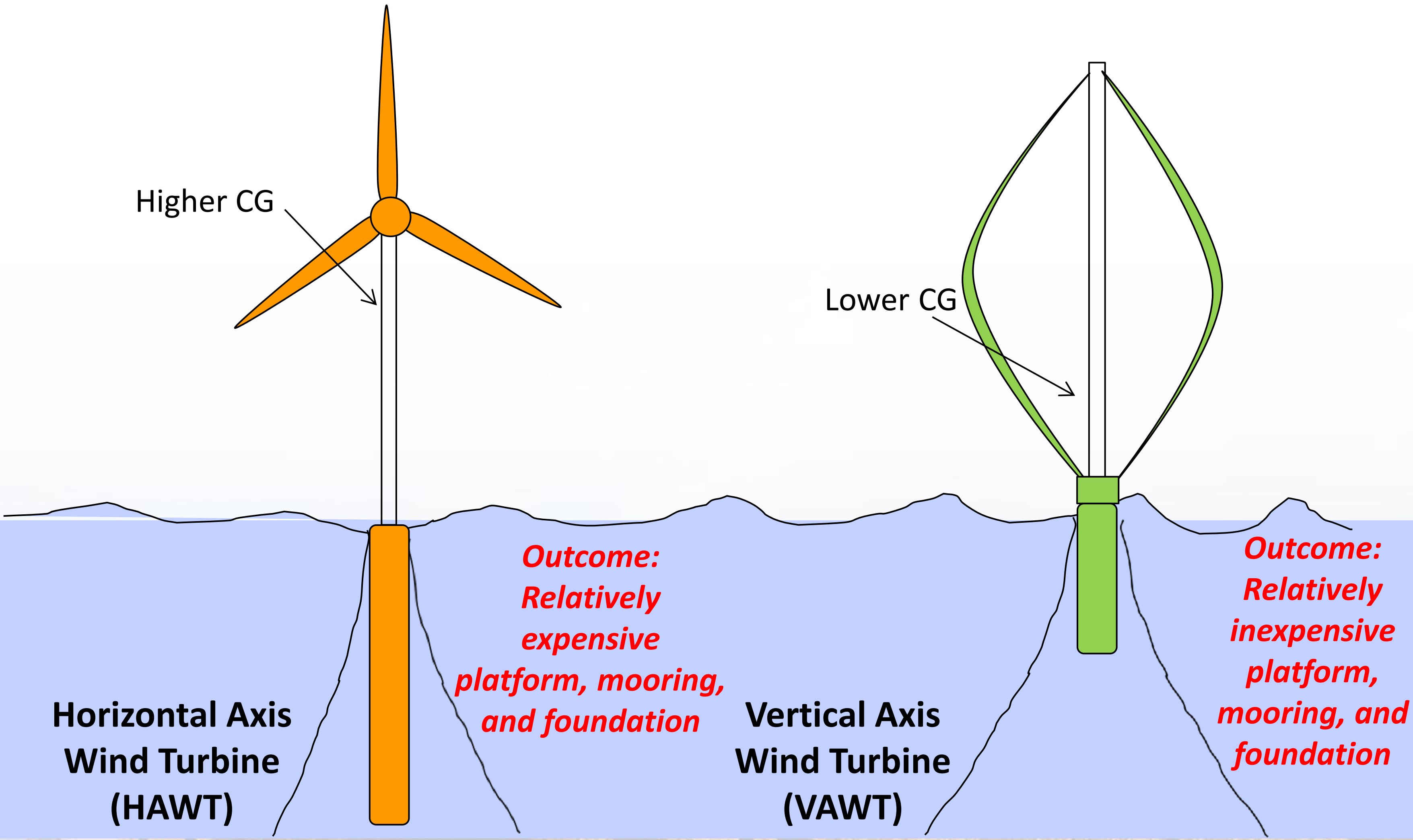


Musial & Ram 2010

Offshore Design Challenge:
O&M Costs > 25% of the Total Project Cost

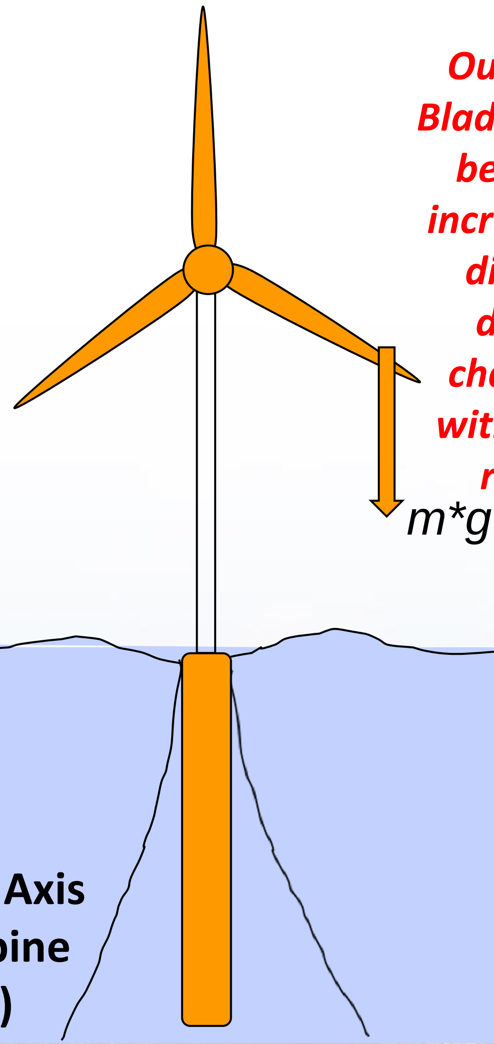


Offshore Design Challenge:
Foundation Costs > 20% of Total Project Cost



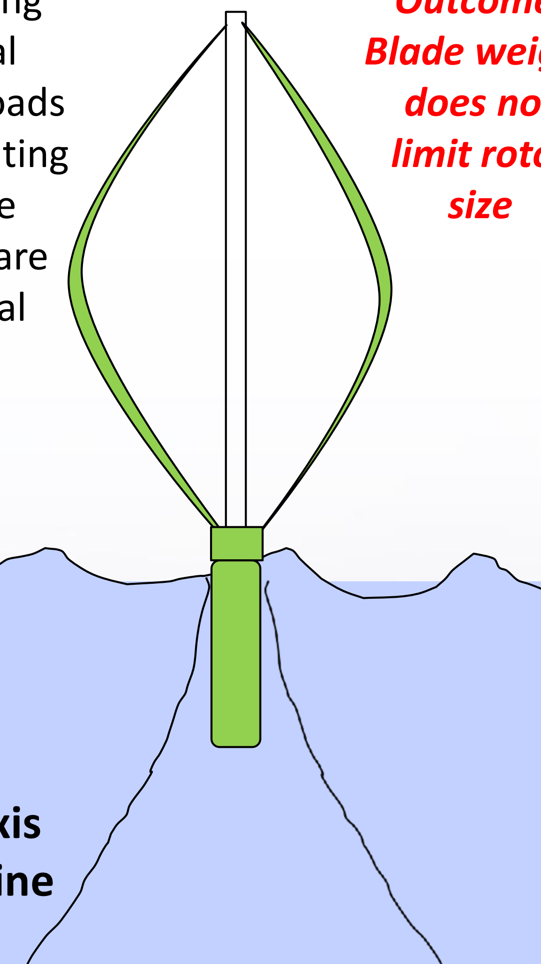
Offshore Design Challenge:
Increased Supporting Infrastructure Cost Demand Larger Rotors

Operating cyclical gravity loads and resulting fatigue impact increase with rotor size



Outcome: Blade weight becomes increasingly difficult design challenge with larger rotors

Operating cyclical gravity loads and resulting fatigue impact are minimal

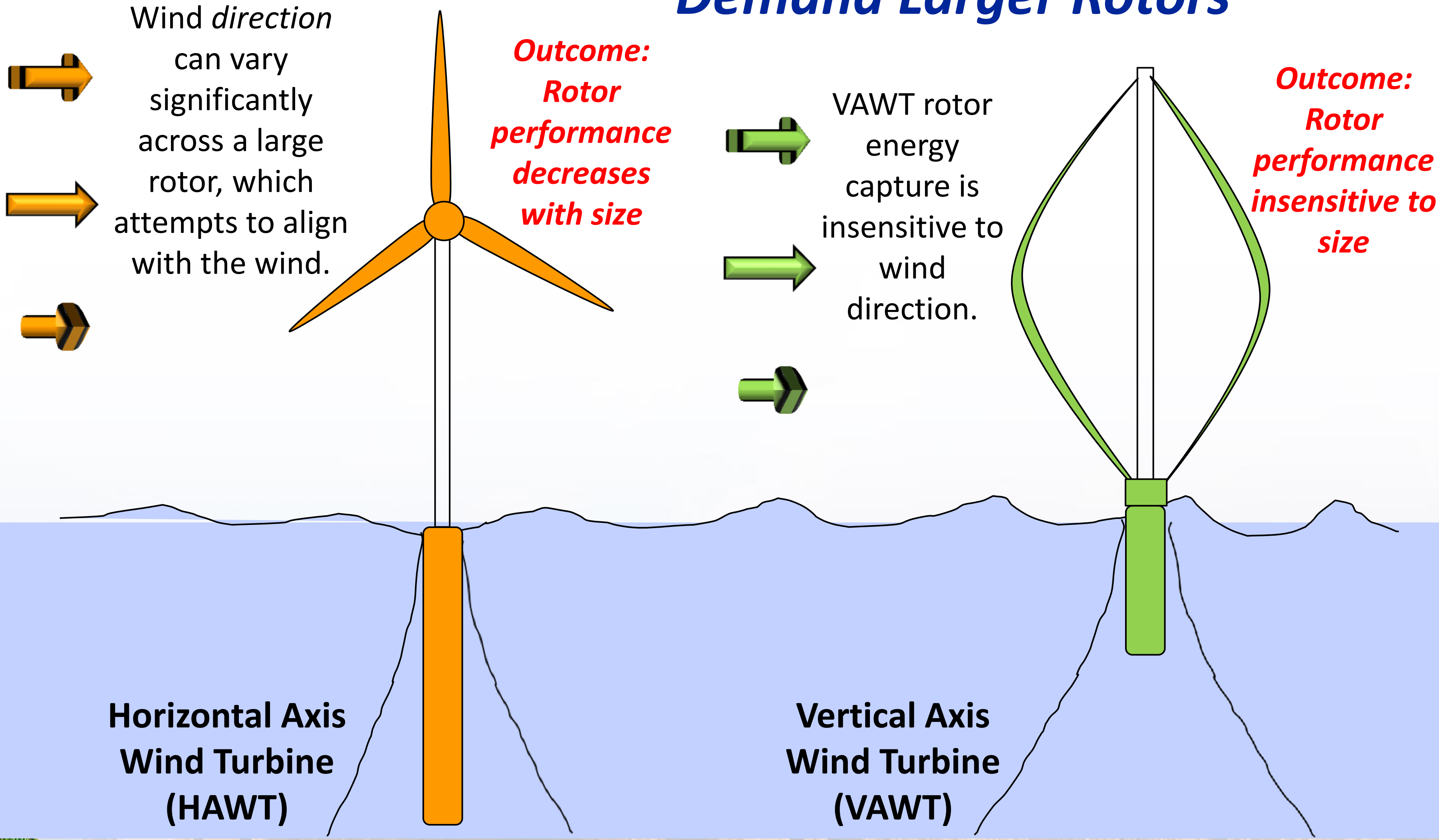


Outcome: Blade weight does not limit rotor size

Horizontal Axis Wind Turbine (HAWT)

Vertical Axis Wind Turbine (VAWT)

Offshore Design Challenge:
Increased Supporting Infrastructure Cost Demand Larger Rotors



Sandia Offshore Technology Development Project

Offshore VAWT Rotor Project Goal

Demonstrate the feasibility of the Vertical-Axis Wind Turbine (VAWT) architecture for very large-scale deployment in the offshore environment.

The most critical barrier to offshore wind, high Cost of Energy (COE), is specifically targeted with the overall goal of achieving a 20% reduction in COE through application of VAWT rotor technology.

Partners

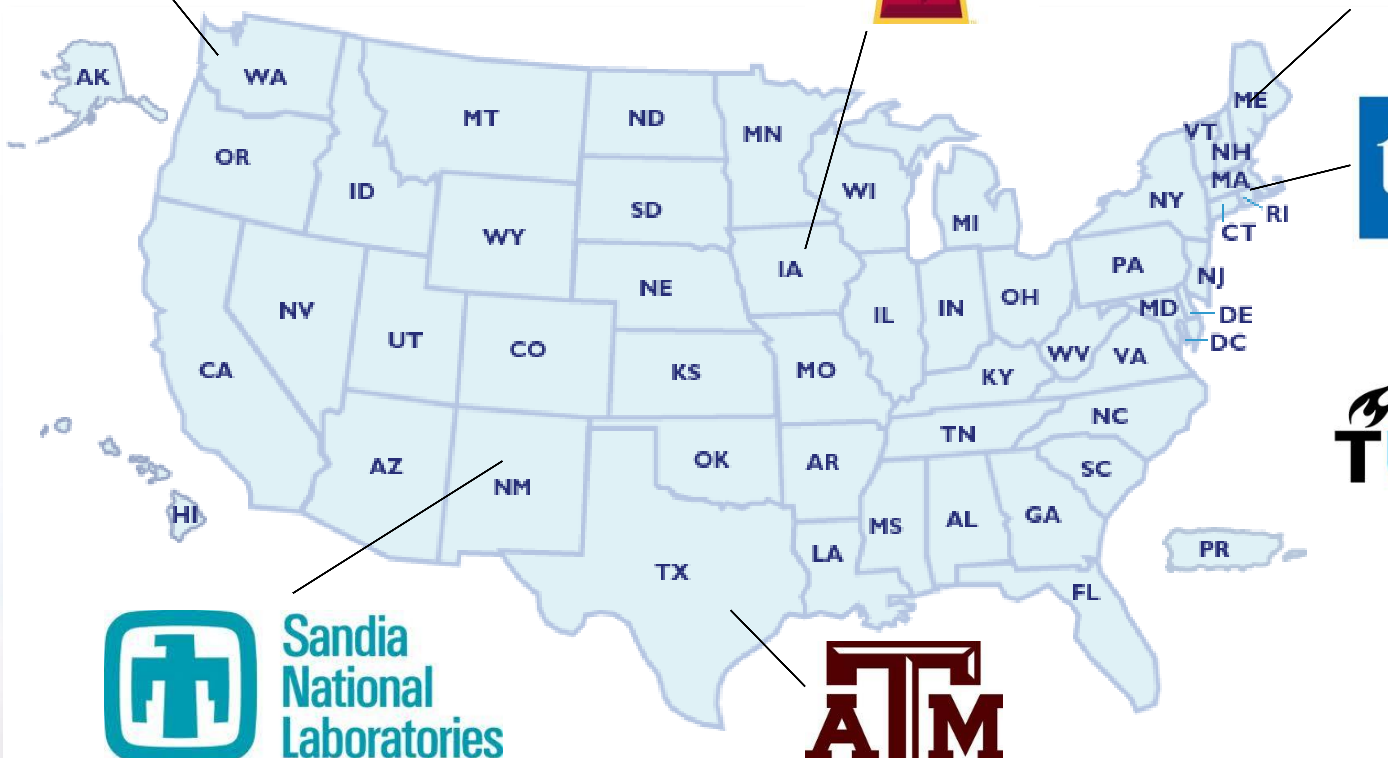
DNV

STATE

1865 THE UNIVERSITY OF MAINE

tpi

TU Delft



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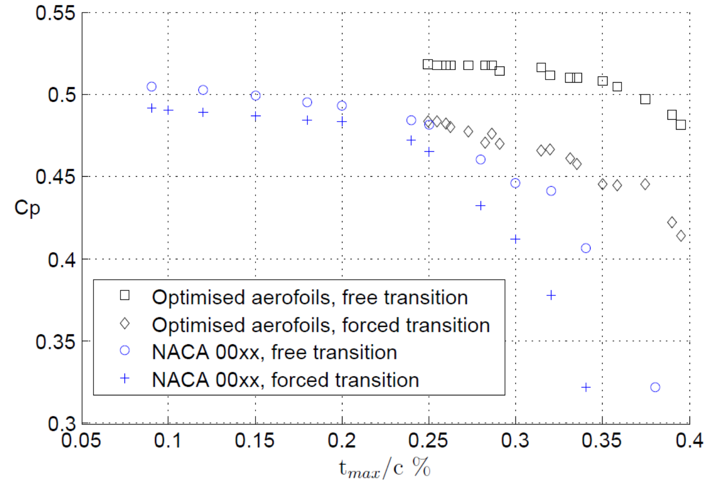
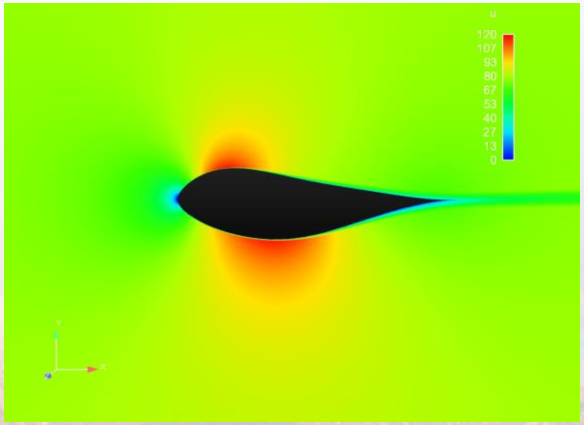
VAWT Specific Airfoils
(TU Delft)

- **Key idea: Aerodynamic optimum for a VAWT airfoil is lift curve slope / drag, not lift / drag**
  - Consequence of the inherently unsteady nature of VAWT aerodynamics
  - Leads to thicker optimal foils
  - Thicker foils give stiffer blades
- **TU Delft has designed a new family of thick VAWT airfoils**
- **SNL is assessing the performance under soiled conditions using CFD**
- **Goal: incorporation into SNL VAWT rotor designs**

Sectional power coefficient

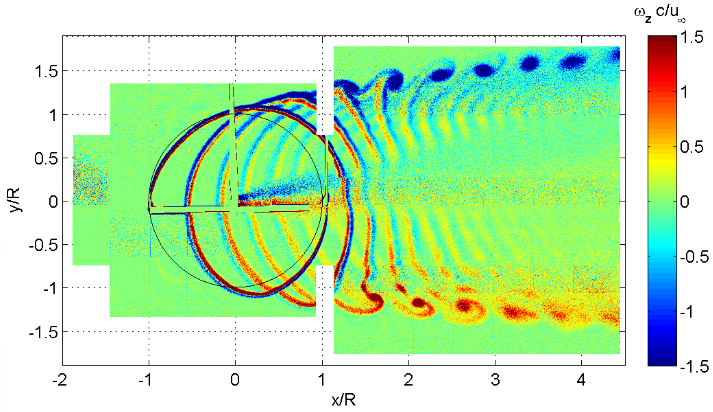




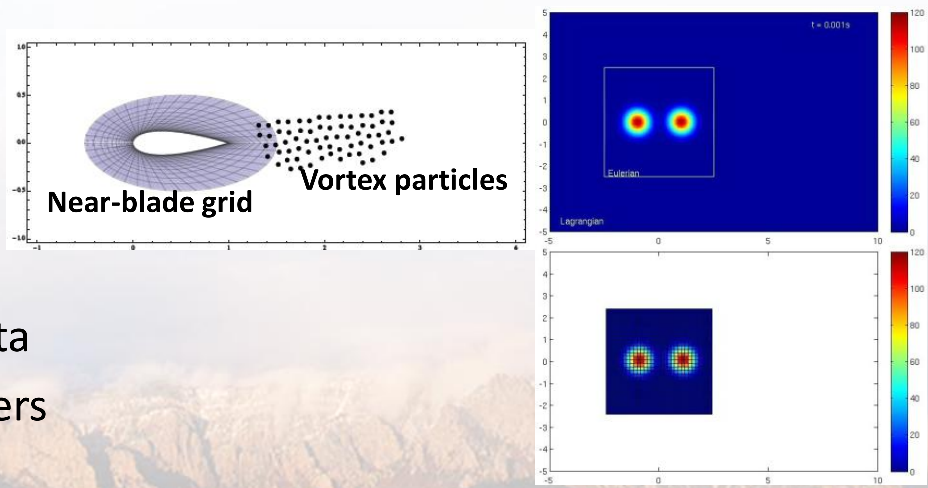
VAWT Aerodynamic Modeling (TU Delft)

- **Goal: Develop a highly accurate, but efficient, code for VAWT aerodynamics**
- **Approach: Hybrid Eulerian/Lagrangian Method**
  - The flow in the near-blade region is calculated using conventional CFD
  - The flow in the wake is calculated using a vortex particle method
- **Accomplishments**
  - 2D version of the code is complete and is undergoing testing
- **Future Work**
  - Extension to 3D
  - Validation against VAWT experimental data
  - Efficiency improvements on GPU computers

PIV measurements of a VAWT wake

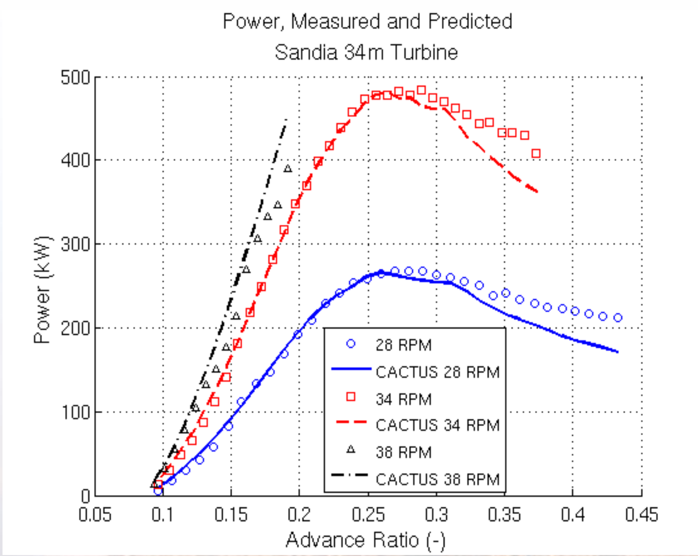


Modeling Approach

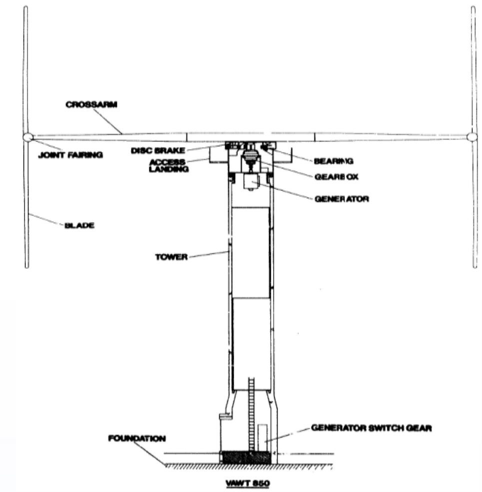


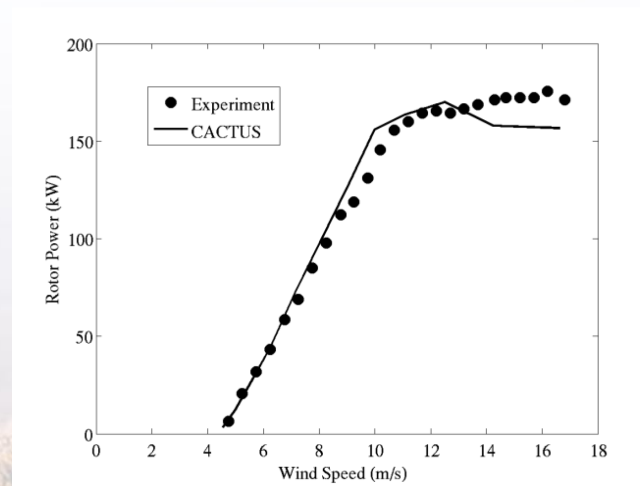
Aerodynamic Modeling: CACTUS

SNL/DOE 34 m Darrieus Testbed



UK VAWT 850 H-VAWT





Murray, J. and Barone, M. "The development of CACTUS: a wind and marine turbine performance simulation code, ASME Wind Energy Symposium, Orlando, FL, January 2011.

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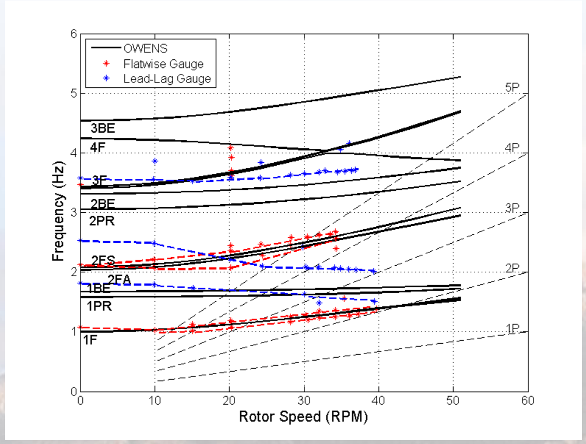
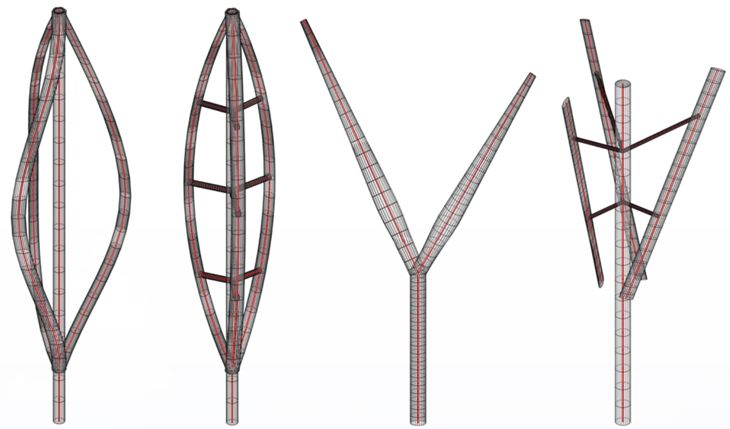
Offshore Wind Energy Simulation Toolkit for Vertical-axis Wind Turbines (VAWTs)

- **Features:**
  - Considers VAWTs of arbitrary configuration
  - Enables modal and transient analysis capabilities
    - Resonance / stability
    - Turbulent winds, start up, shut down, etc.
  - Enables couplings/interfaces to:
    - *Arbitrary aerodynamics modules*
    - *Arbitrary hydrodynamics/mooring modules*
    - *Floating platform motions*
    - *Generator and drivetrain dynamics*
    - *Turbine control algorithms*
  - Accounts for passive aeroelastic couplings
  - Open-source, batch capability
- **Validation (SNL 34-meter VAWT)**

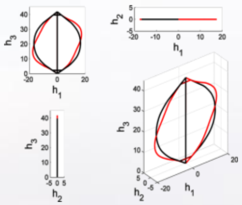
Campbell diagram:

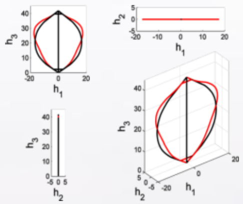


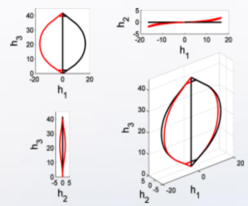
Arbitrary VAWT Geometries:

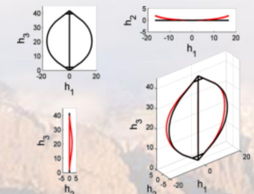


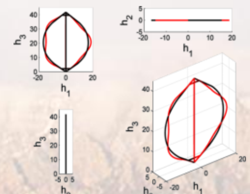
SNL 34-m parked mode shapes:

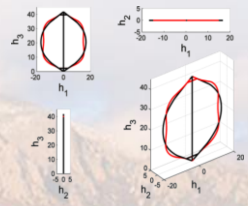

1st Antisymmetric Flatwise


1st Symmetric Flatwise


1st Propeller


1st Blade Edgewise (Butterfly)


2nd Antisymmetric Flatwise


2nd Symmetric Flatwise

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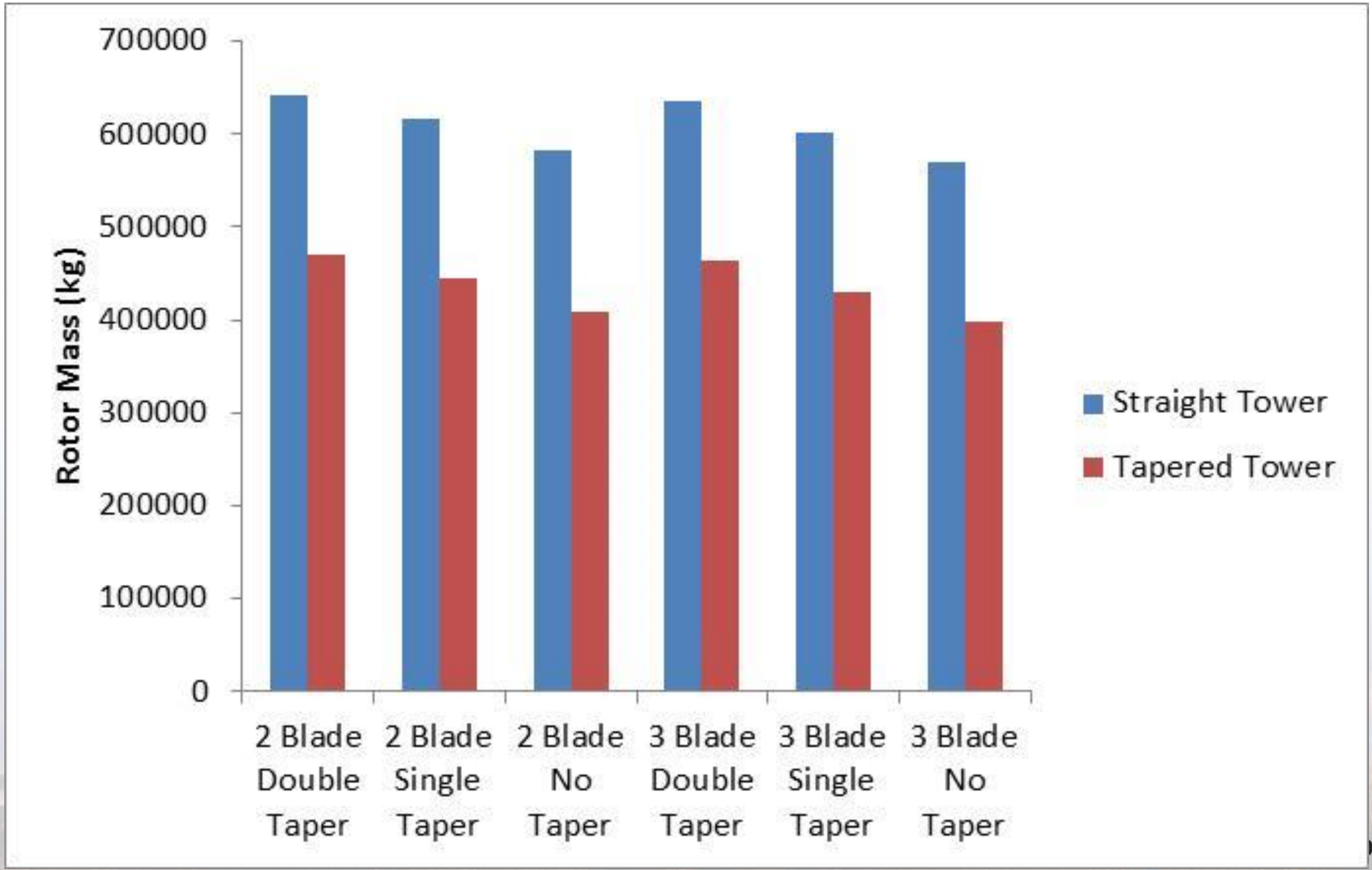
Scaling to Large Machines

Design Options

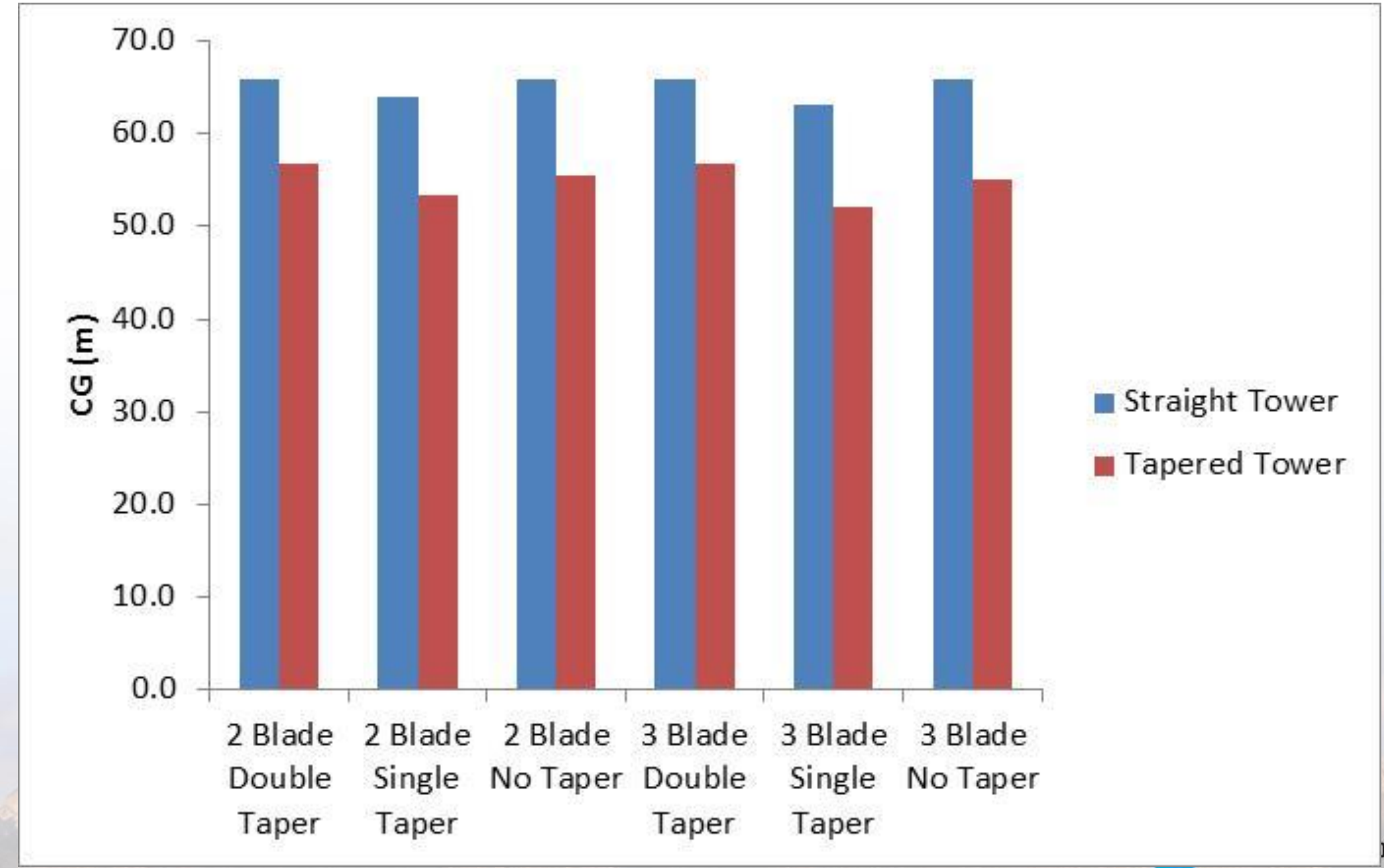
- **2-Bladed vs. 3-Bladed**
  - Generally, 2 bladed should be lighter
  - 3 bladed rotor is balanced and reduces torque ripple
- **Double Tapered vs. Single Tapered vs. Non-Tapered (constant chord)**
  - Aerodynamically Optimal vs. Low CG vs. Ease of Manufacturing
- **Straight vs. Tapered Tower**
- **Glass vs. Carbon**
  - Cost vs. Weight
- **Darrieus vs. V-Shaped**
  - Structurally and Aerodynamically Efficient vs. Low Rotor Weight

5MW Scaling of Glass Darrieus:

Effect of Design Options on Rotor Mass

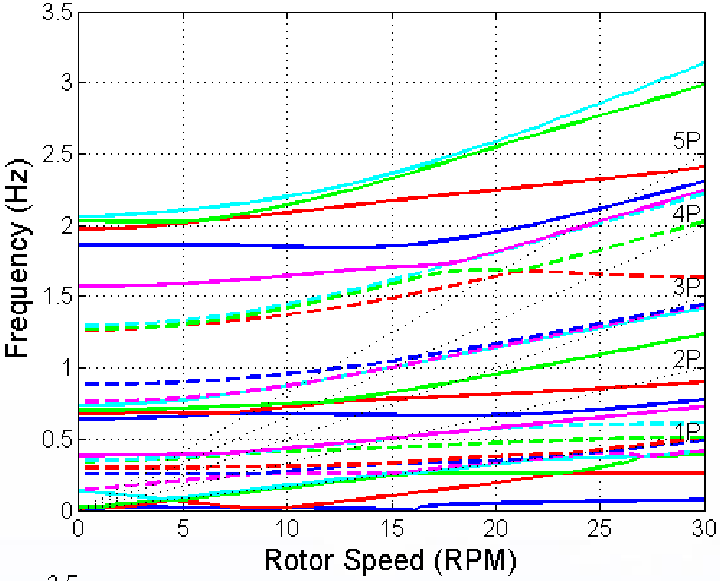


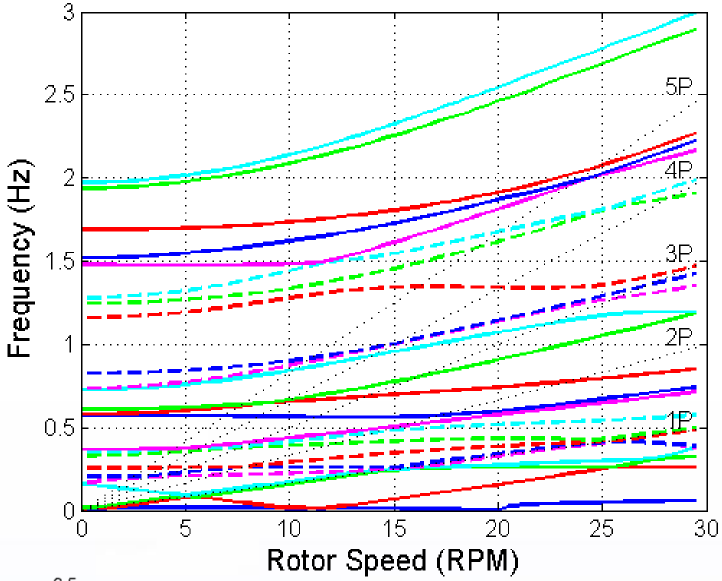
5MW Scaling of Glass Darrieus:
Effect of Design Options on Rotor CG



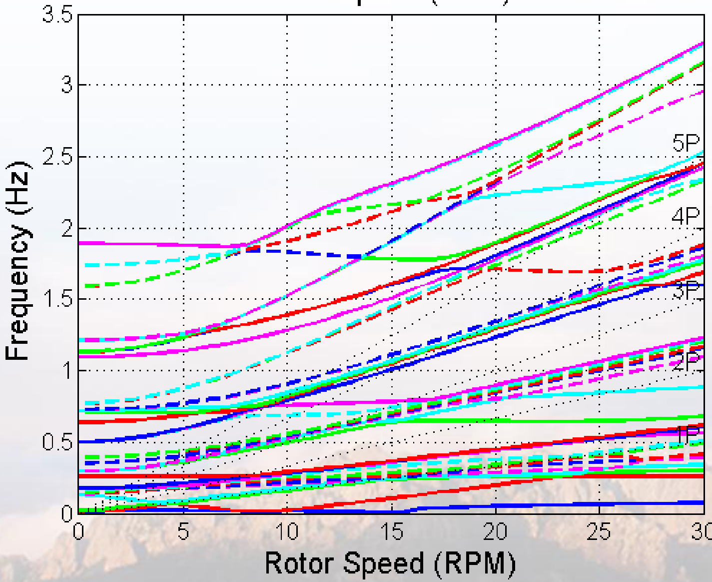
Double Tapered Blades

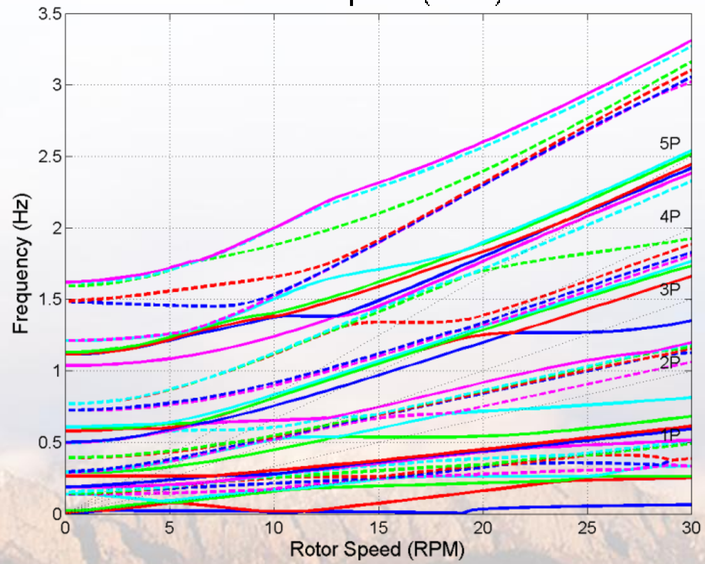
2-Bladed





3-Bladed





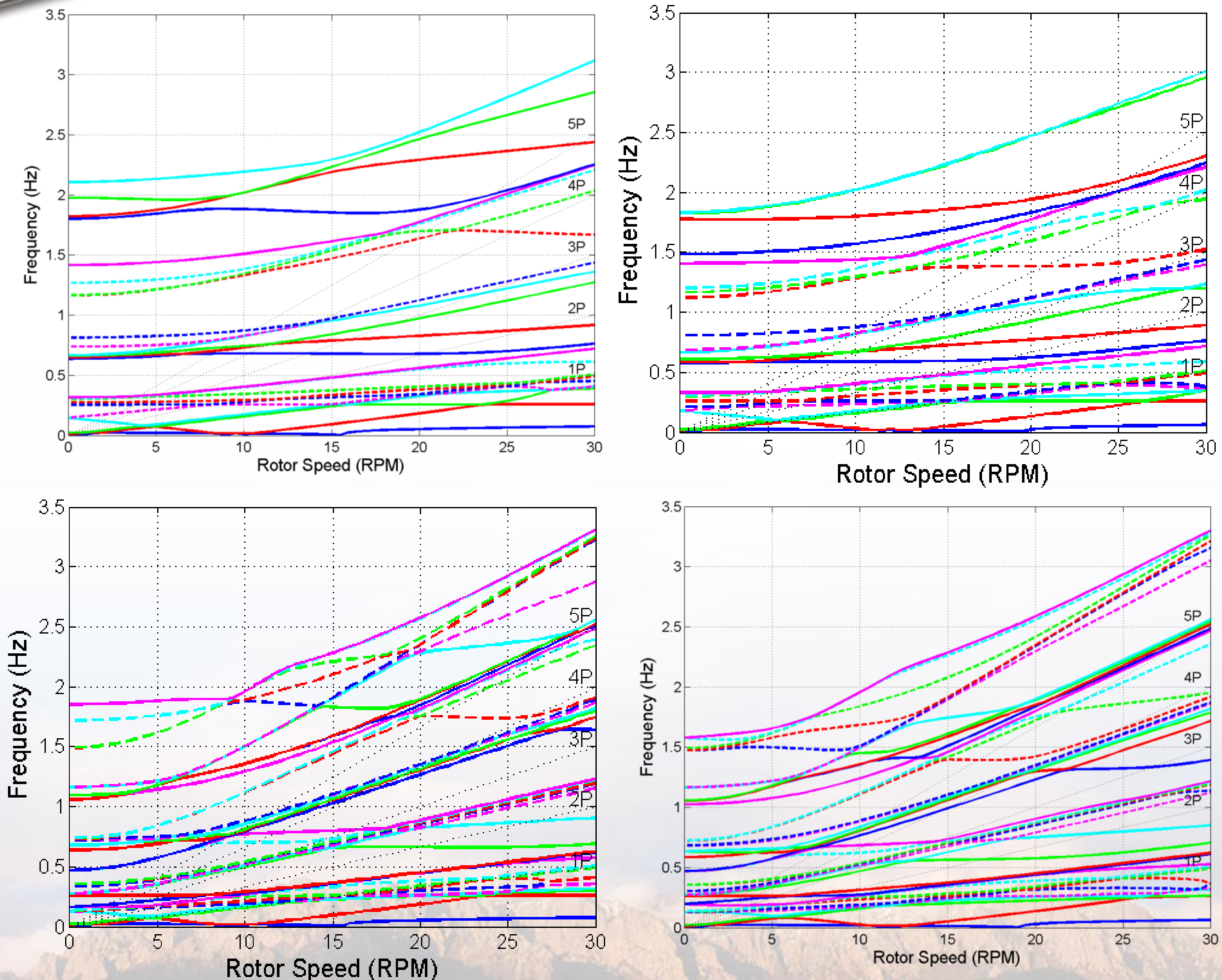
Straight Tower

Tapered Tower

Single Tapered Blades

2-Bladed

3-Bladed



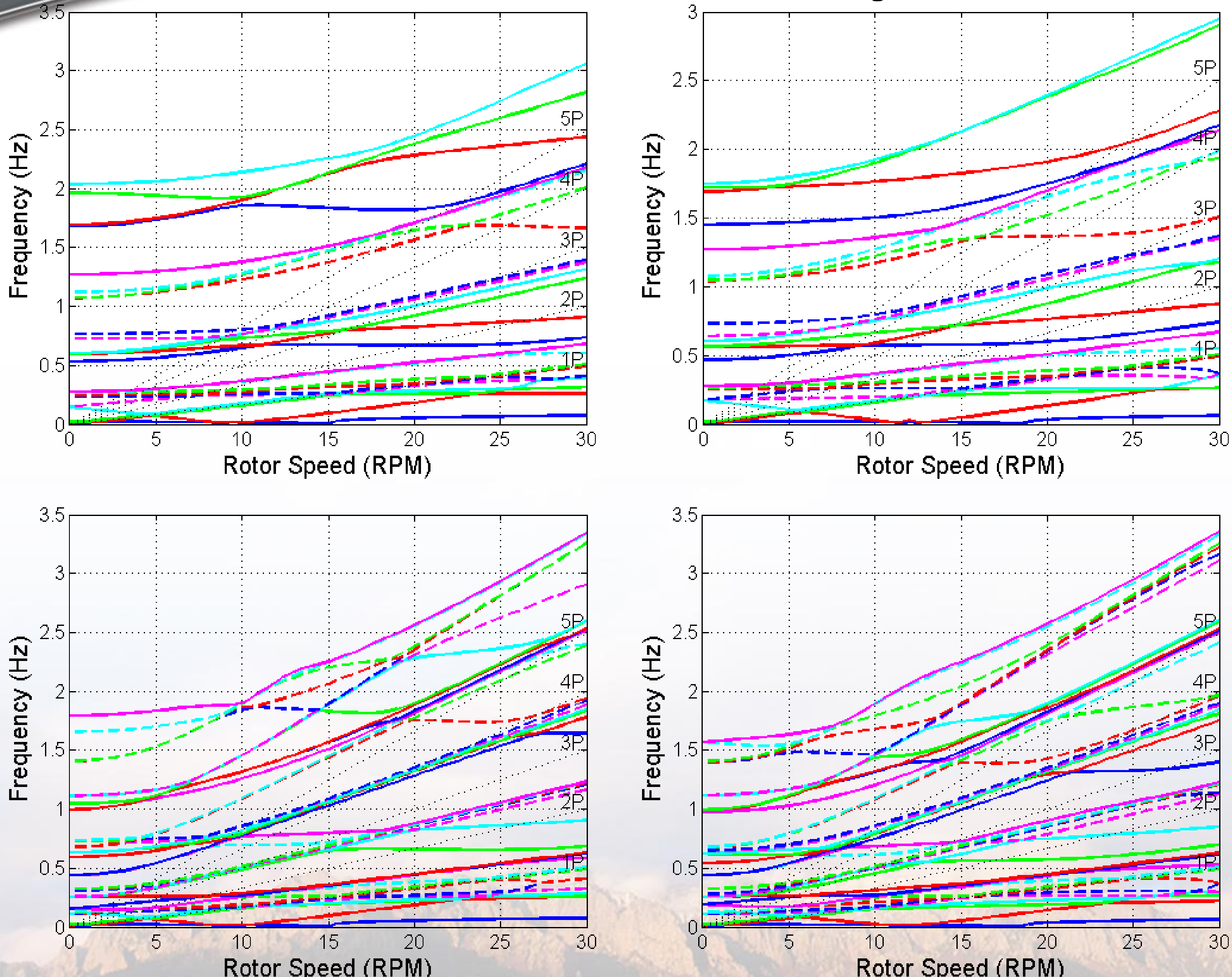
Straight Tower

Tapered Tower

Non-Tapered Blades

2-Bladed

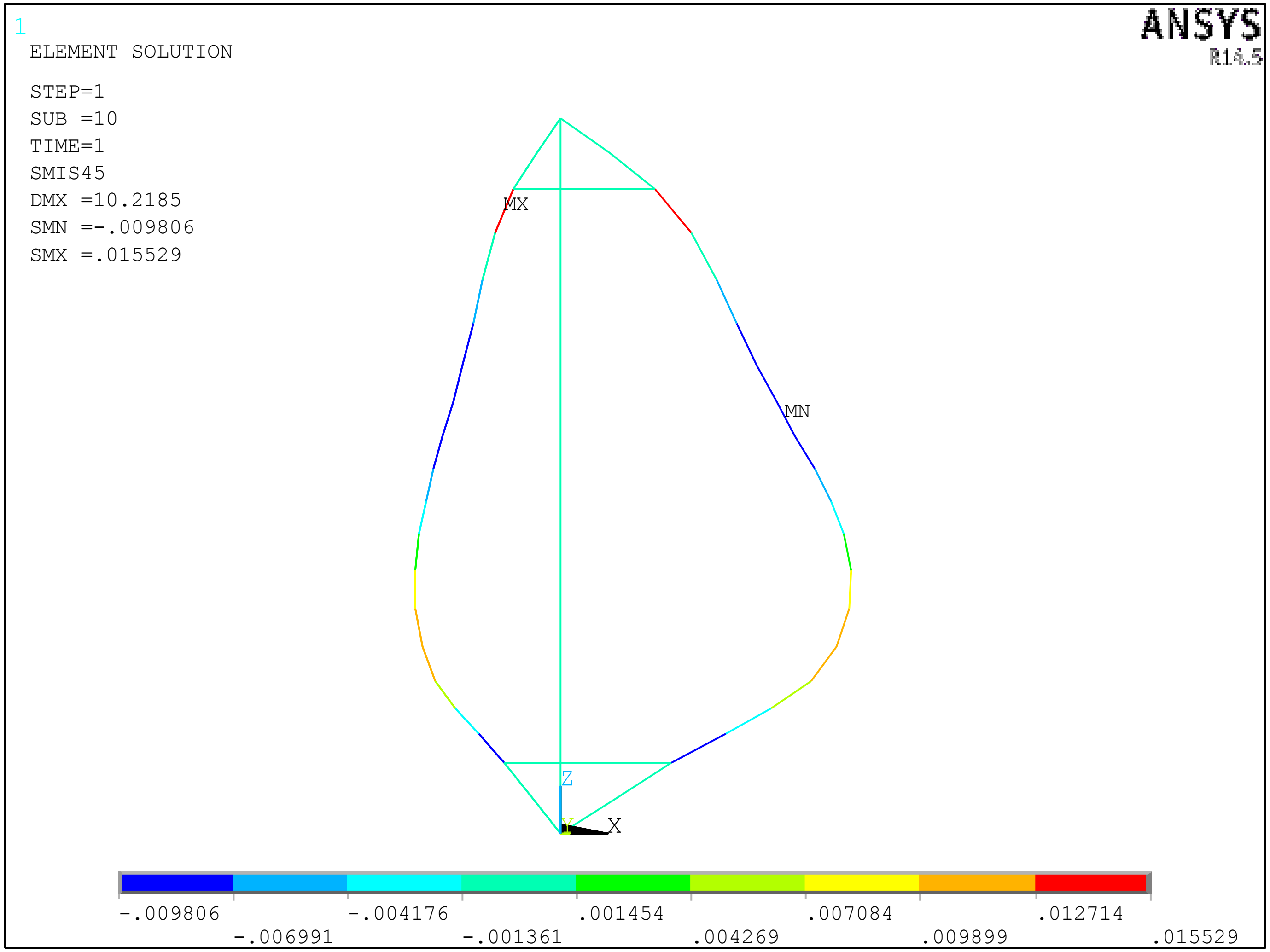
3-Bladed



Straight Tower

Tapered Tower

Other Concerns: Parked Loads



Surface Strains for Parked, 3-Bladed, Glass, Single-Tapered 5MW Darrieus Rotor