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Advances in Floating Offshore Vertical-Axis Wind Turbine Design

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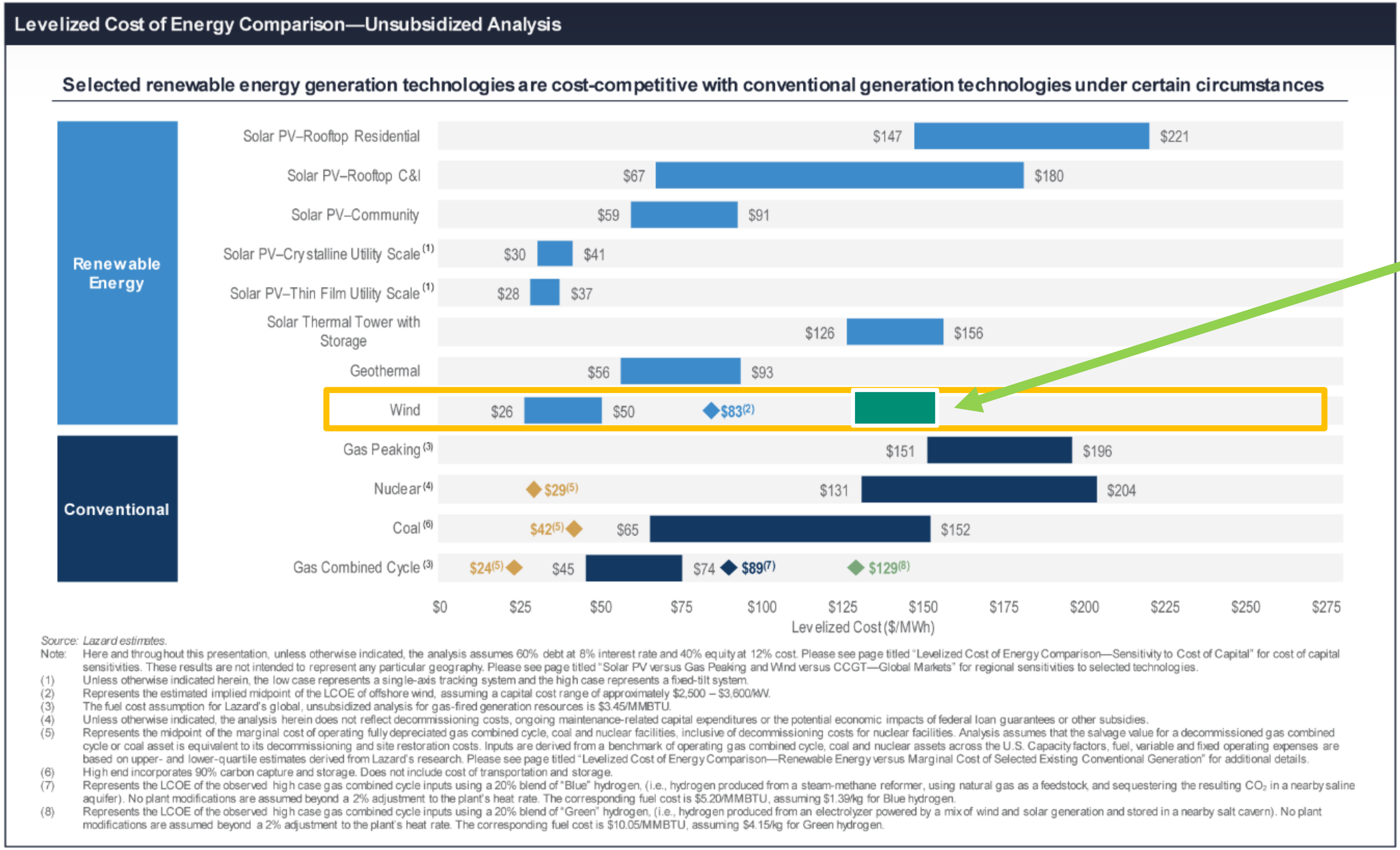
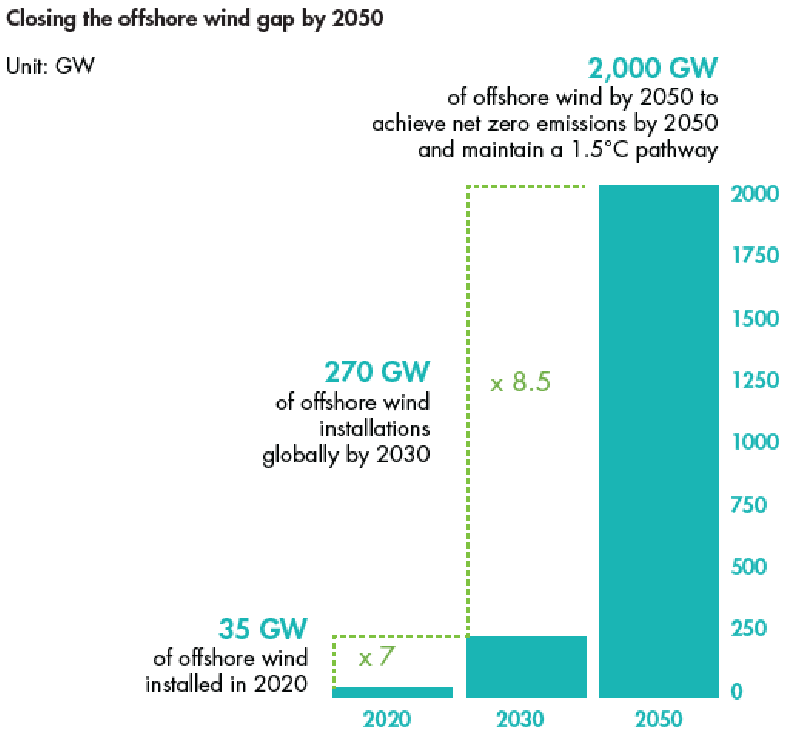
Energy Generation in US: Unsubsidized LCOE Comparison



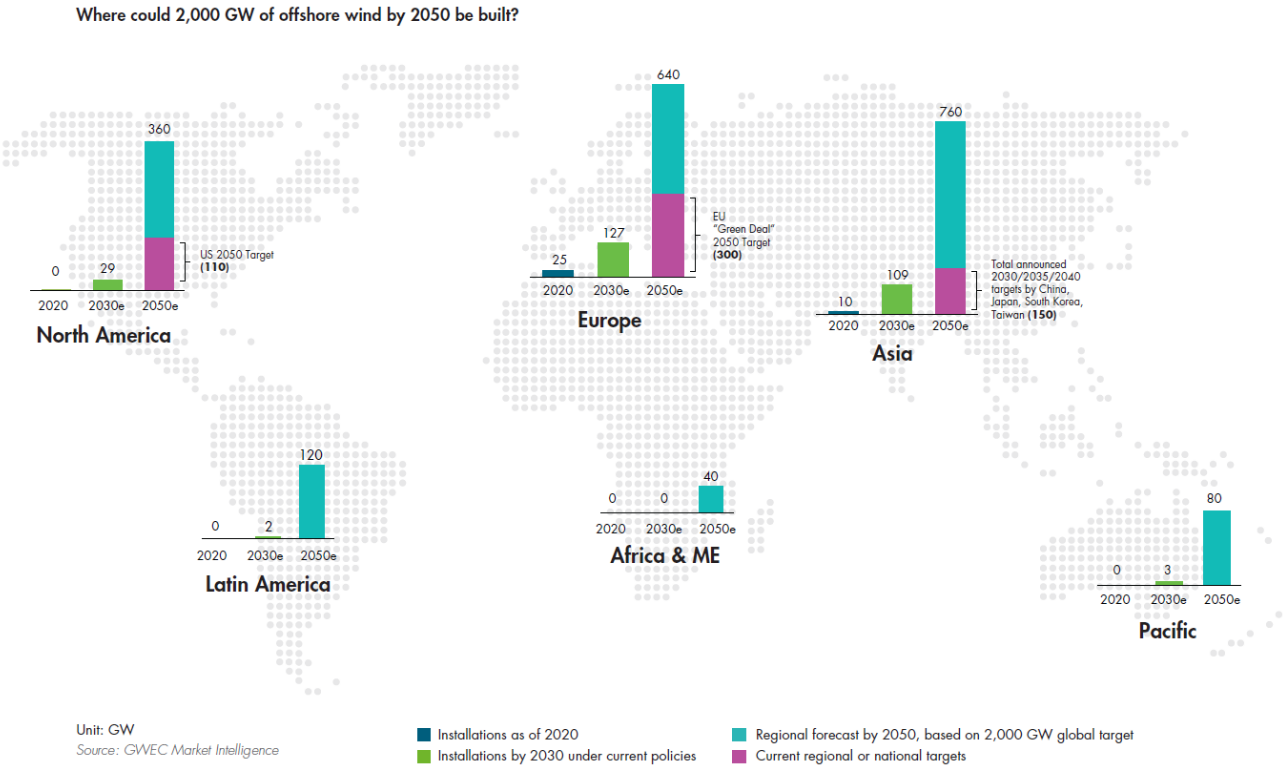
Lazard, *Lazard's Levelized Cost of Energy Analysis – Version 14.0*

Global development of offshore wind energy

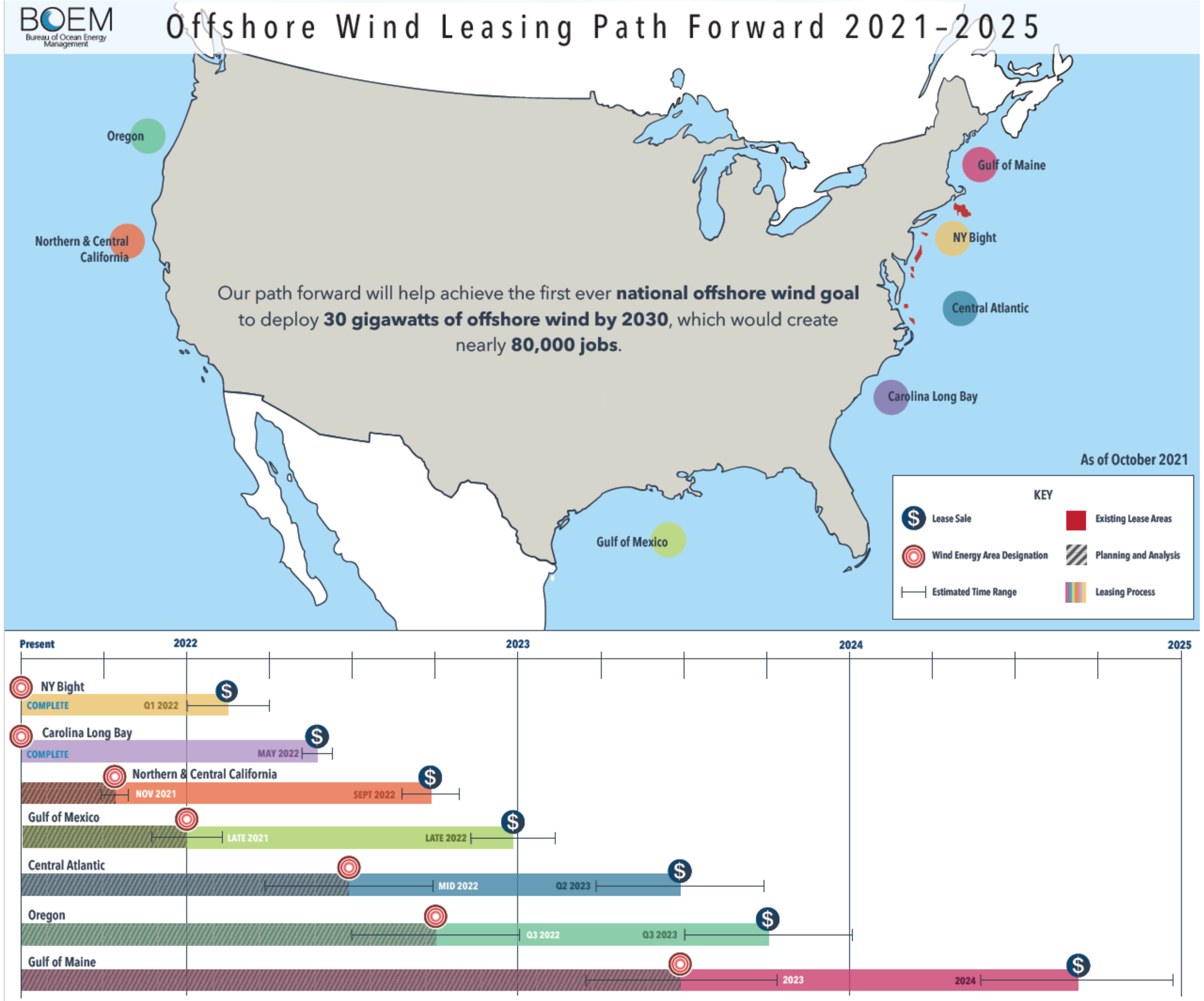
- To meet the IEA and IRENA 1.5°C global warming scenario, forecasts predict more than 2,000 GW of installed offshore wind capacity by 2050 (compared to ~56 GW installed to date)
- This will require floating offshore sites to be developed



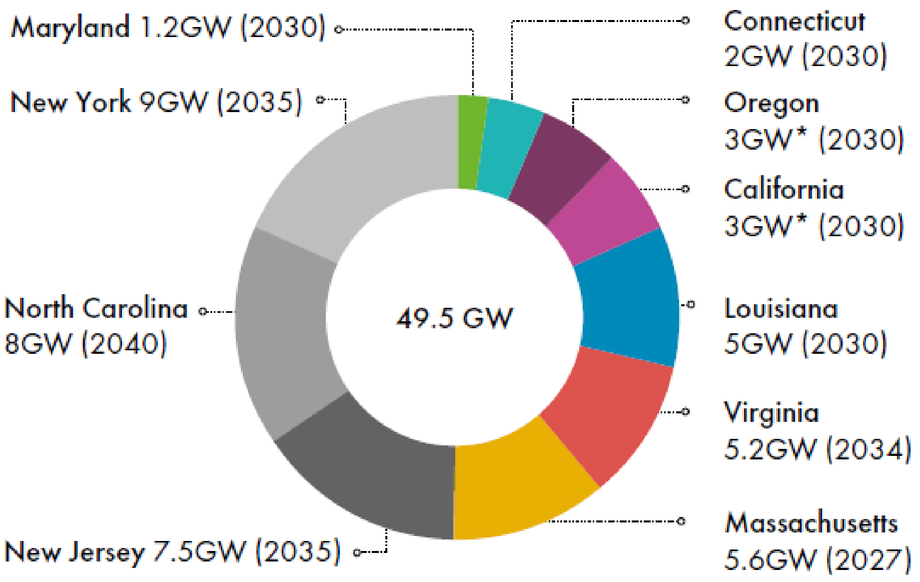
Source: GWEC Market Intelligence; IRENA World Energy Transitions Outlook 2021.



The advent of the offshore wind industry in the US



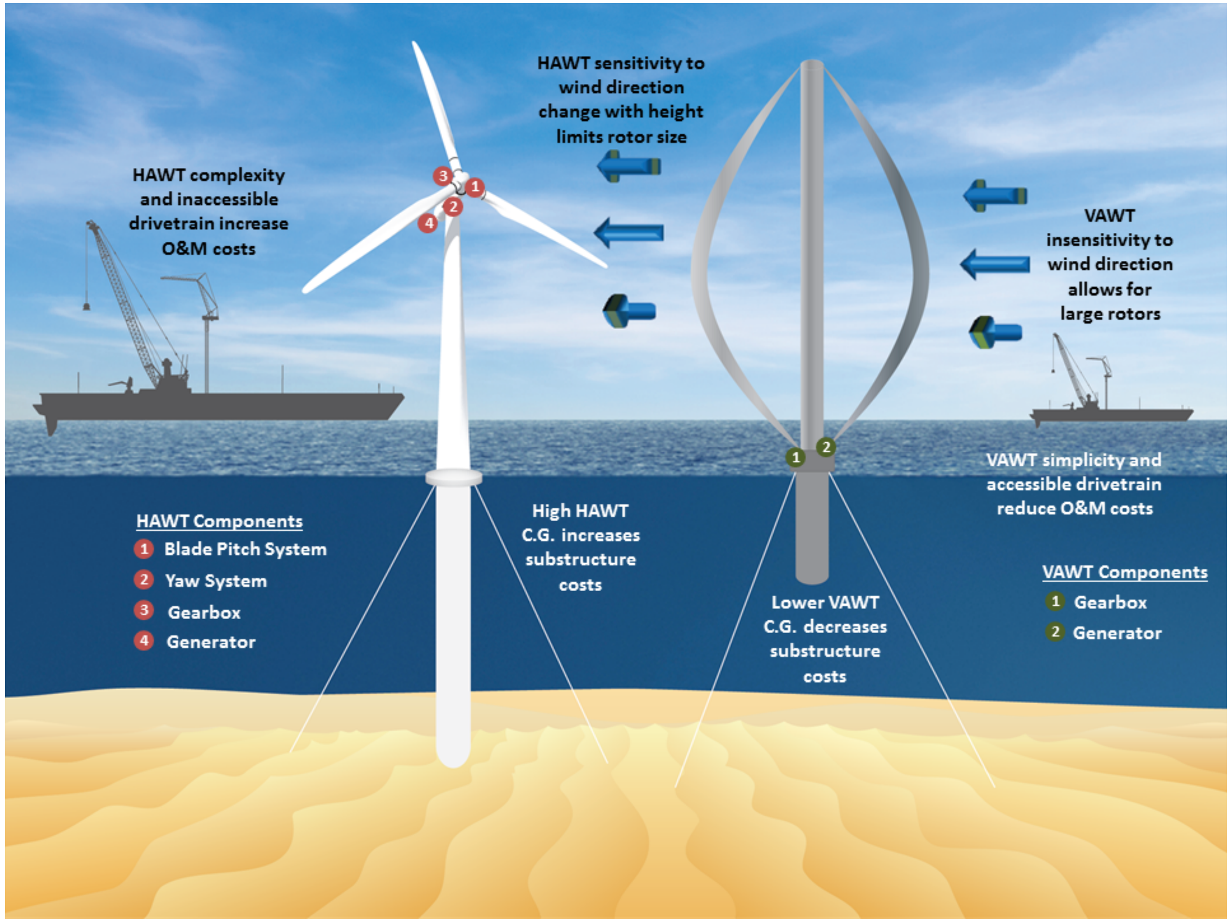
US State-level offshore wind development targets



*Announced plan, not yet signed by law

Could VAWTs be a solution for floating offshore wind?

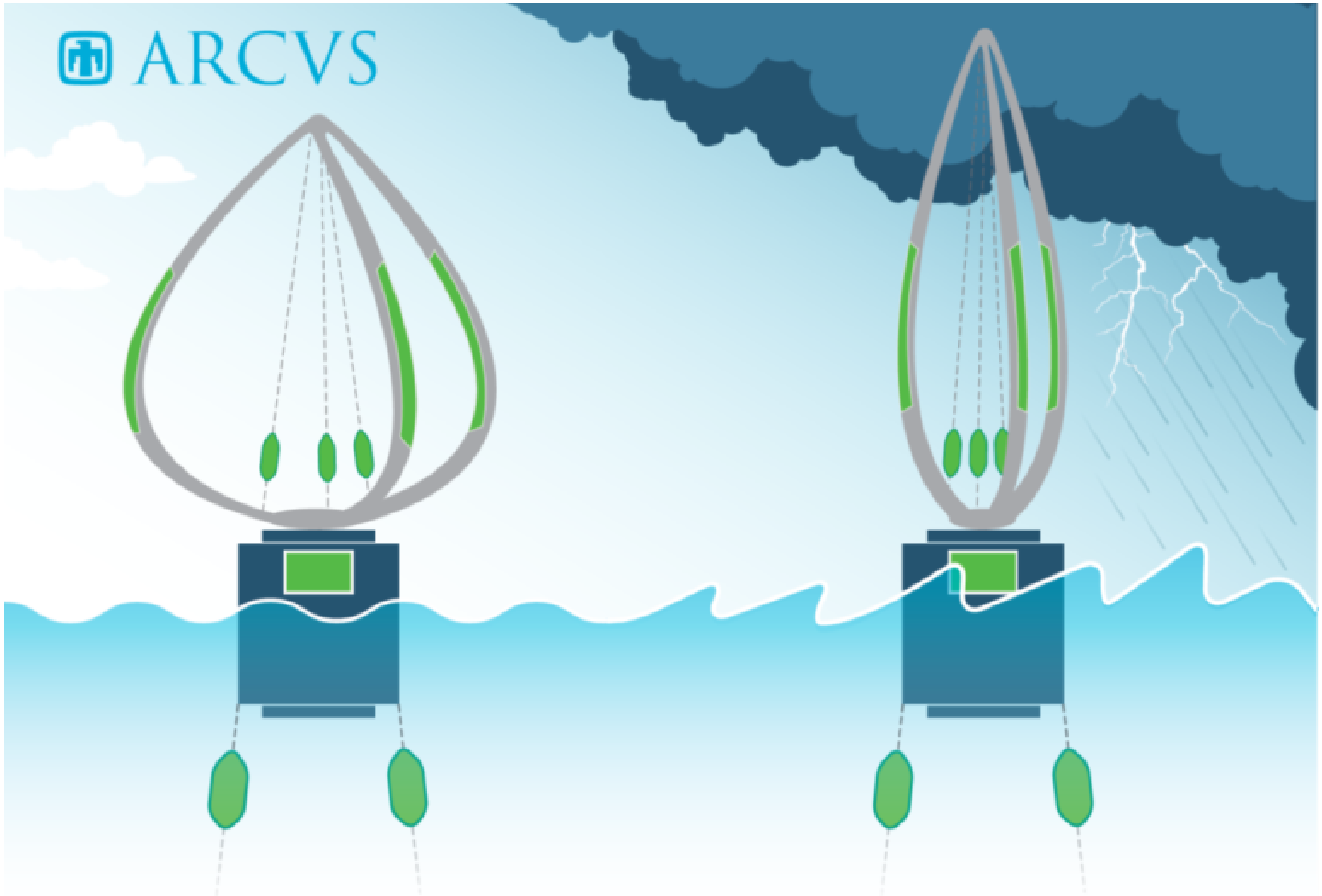
- For floating offshore wind, the platform costs are the single largest contributor to the LCOE
- Turbine costs represent 65% of wind plant costs for land-based sites compared to around 20% for floating offshore sites
- VAWTs are being studied as a lower cost solution for floating offshore wind energy **which have several benefits, including**:
  (1) Lower center of gravity, which reduces topside moment of inertia and resulting platform costs
  (2) Reduced O&M costs through removal of active components and platform-level placement of drivetrain
  (3) Improved energy capture over HAWTs at multi-MW scales
  (4) Insensitive to wind shear, wind veer, and gravitational load cycles



A VAWT designed for floating offshore sites

- The ARCUS rotor is a towerless VAWT that replaces the traditional rigid tower with prestressed blades and tensioned center supports (U.S. 11,421,650 B2)

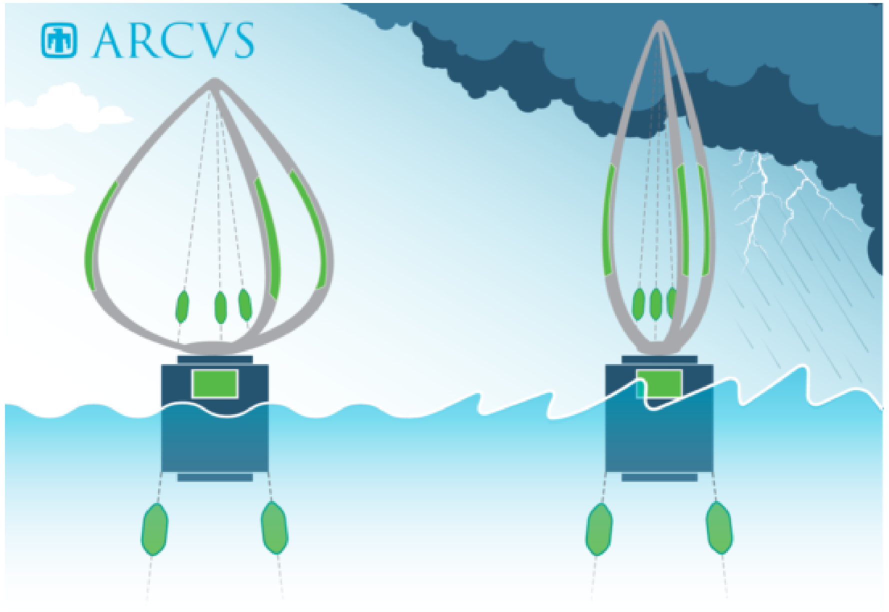
- In previous Sandia studies, the tower represented ~80% of the rotor mass



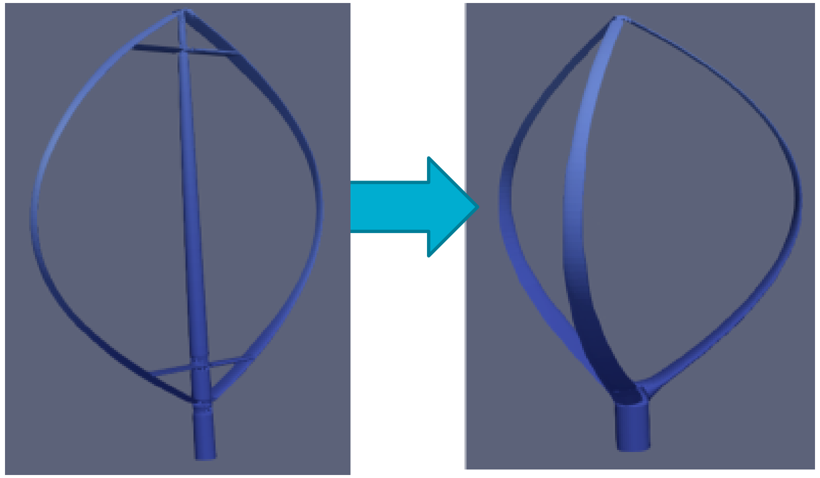
The ARCUS Darrieus VAWT has been designed by Sandia to address the high costs of floating offshore wind.

ARCUS Turbine Design Optimization

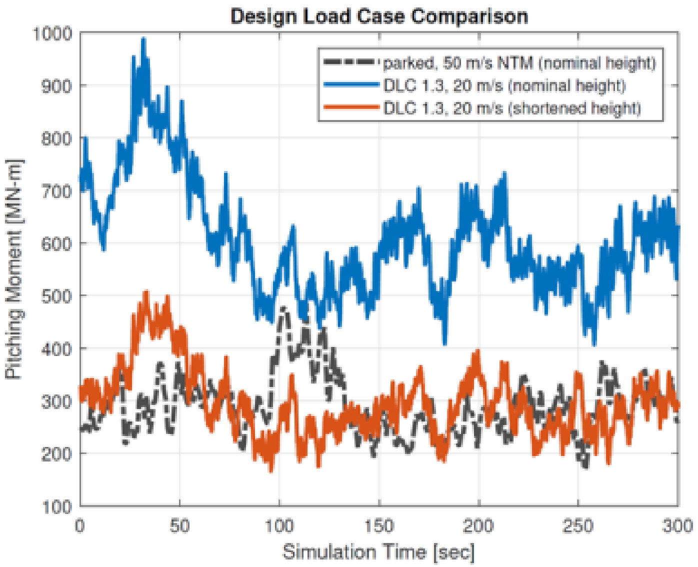
- The towerless ARCUS design enables an efficient use of materials, shifting away from compressive strains
- Rotor area control to reduce loads in high winds
- Project has been funded by ARPA-e within the U.S. Department of Energy for concurrent design of the floating VAWT system



5 MW Rotor Mass Reduction: 52.1%



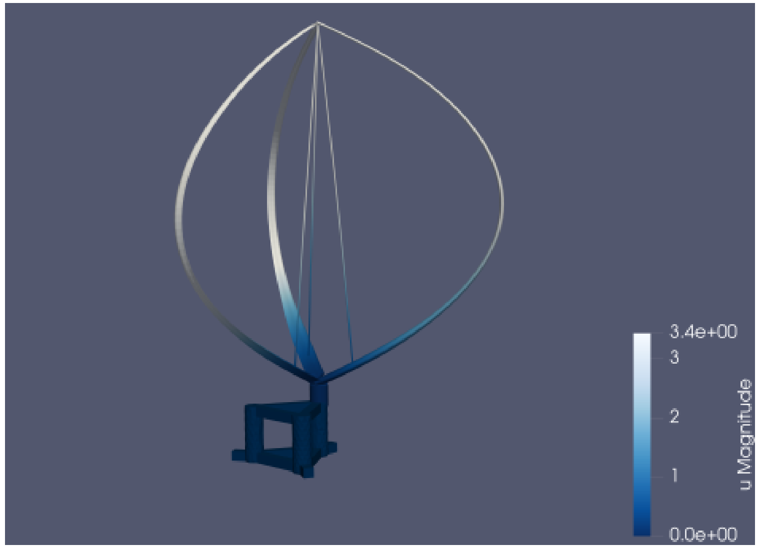
181,888 kg → **87,030 kg**

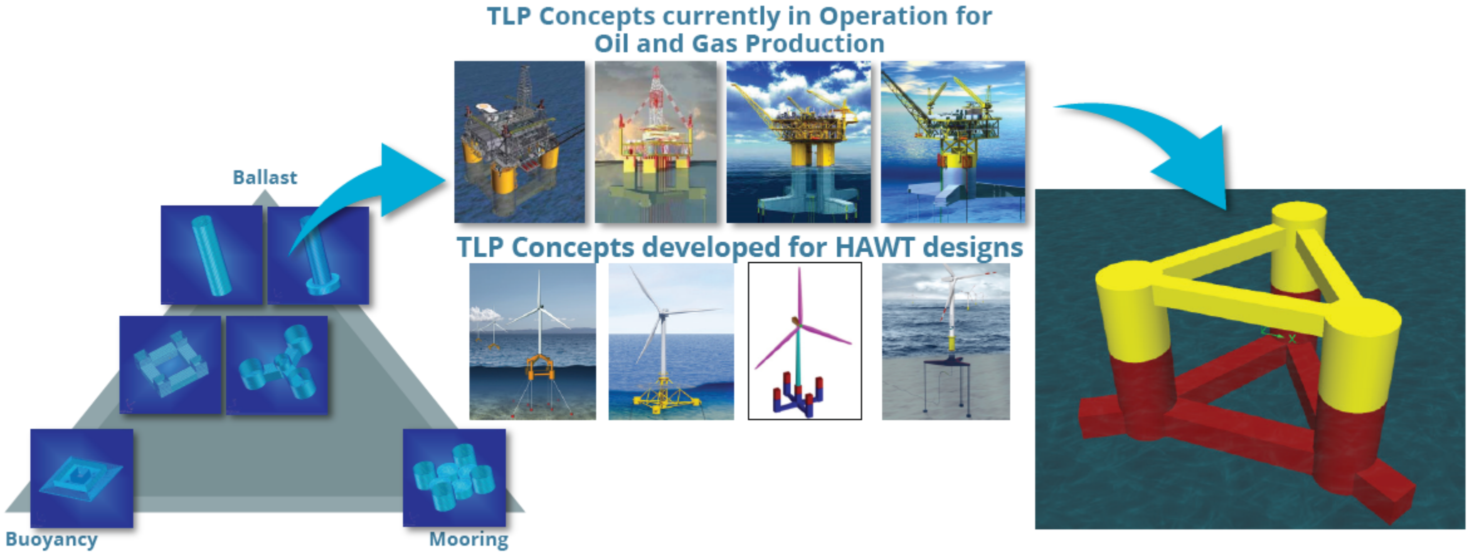


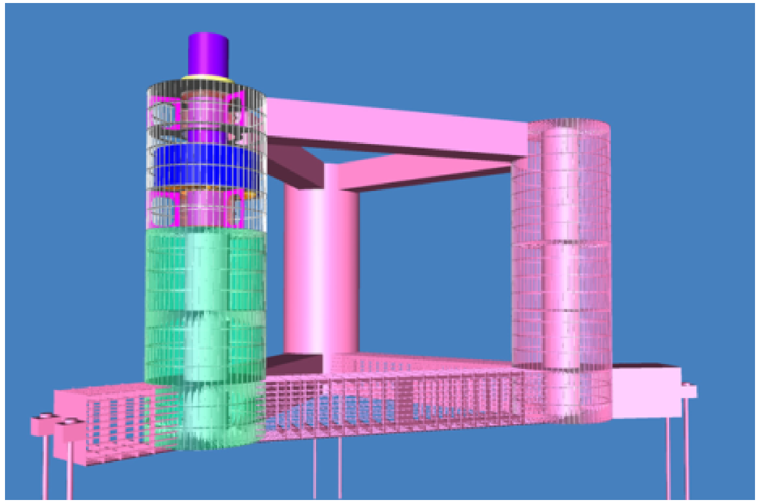
	ARCUS VAWT	Reference HAWT
Topside mass estimate (-)	1.0	1.45
Center of gravity	23 m	75 m
Thrust overturning moment, tow-out (-)	3.2	1.0

Platform Identification and Design Optimization

- A three-column tension-leg platform (TLP) has been identified to optimally reduce mass and cost
  - Quayside integration of turbine
  - Self-stable during tow-out for ease of installation
- Optimization of platform hull and global performance reduces costs by >25% relative to baseline platform
- Detailed scantling design to produce cost models

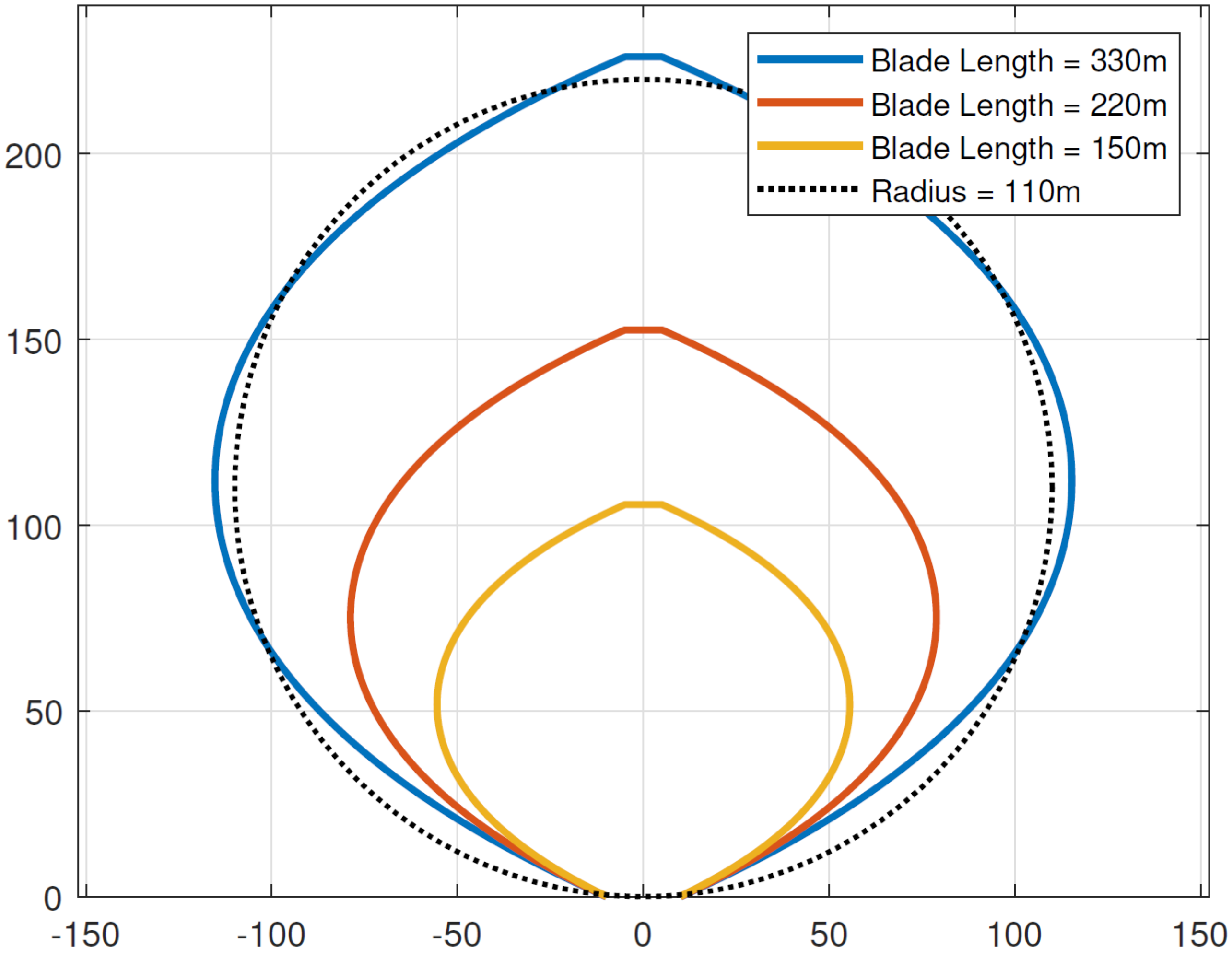






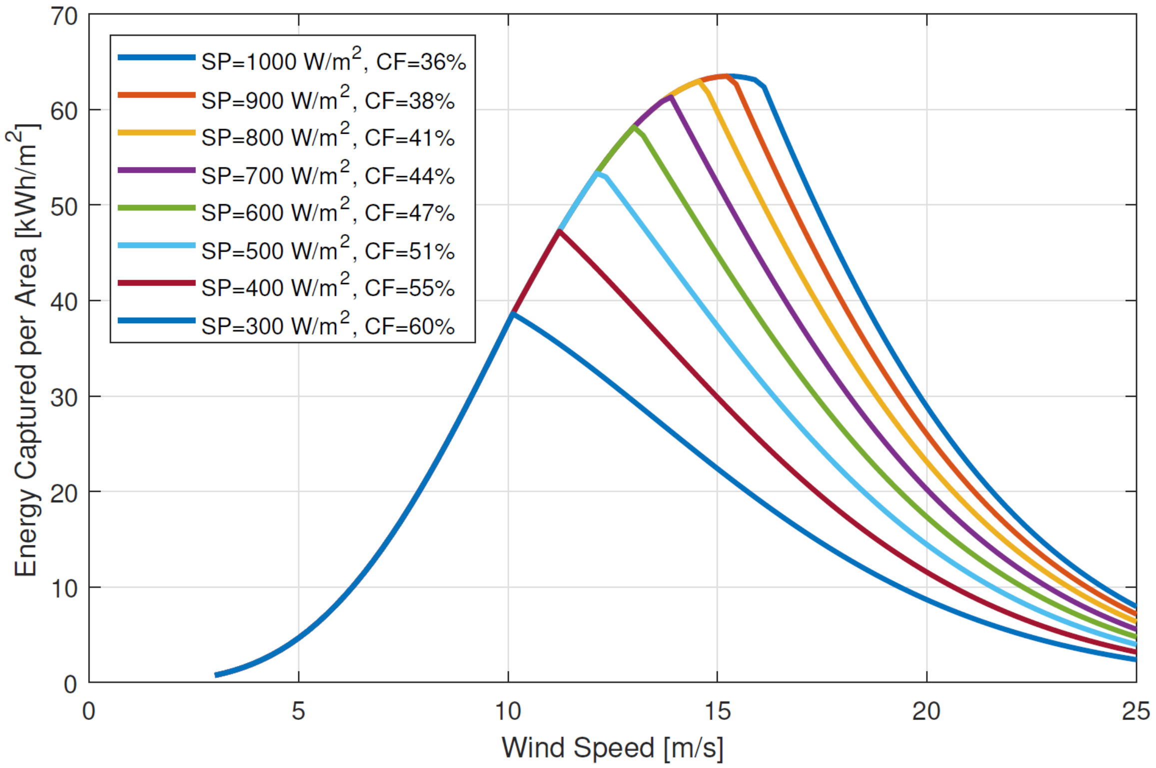
Reference ARCUS Design Definition – Scaling Trends

- Performed a turbine scaling study to identify a turbine size that achieves the most optimal system LCOE
  - Turbine sizes with 1x, 2x, and 4x swept areas
- Balance of system, installation, and operations & maintenance costs dominate for smaller power capacity turbines
- Platform designs were developed for the three reference VAWT sizes to understand capital cost trends



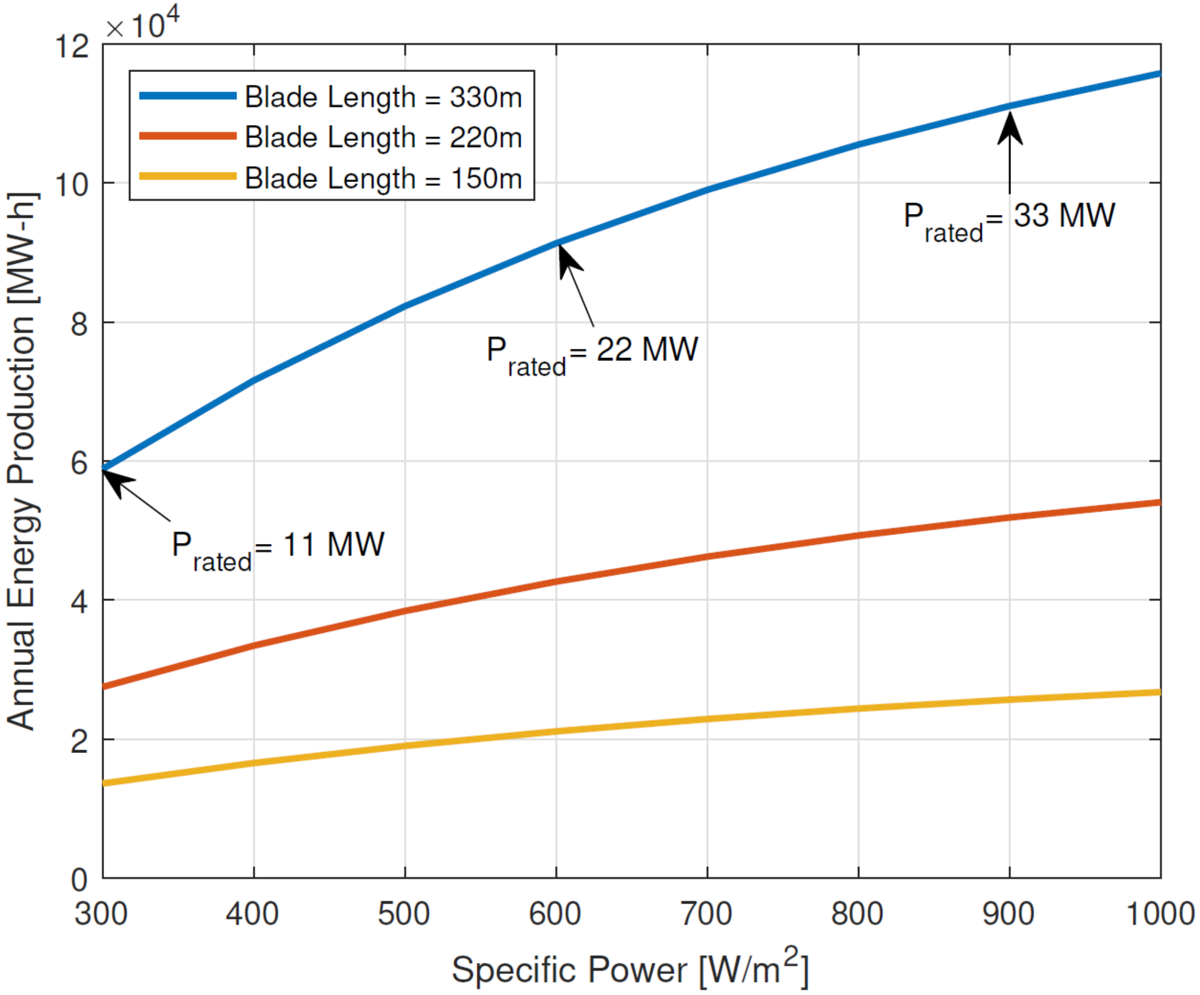
VAWT Scaling Trends – Energy Production

- The annual energy production is the numerator of the LCOE equation, scales annual costs
- The rated power per rotor swept area is a design variable (specific power, SP) that affects energy production and capacity factor (CF)
- Modern offshore wind turbines have a SP = 300-350 W/m^2
- For the IEC Class 1 wind speed distribution, there is a meaningful amount of energy at high wind speeds



VAWT Scaling Trends – Energy Production

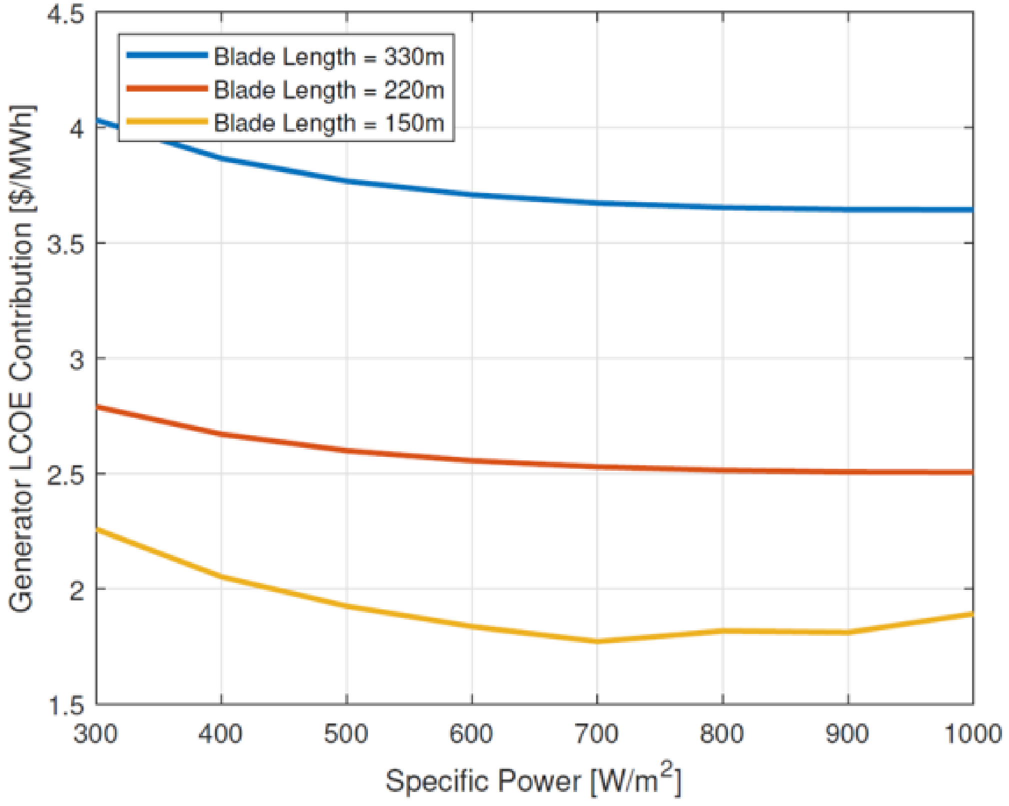
- For high wind resource sites, typical of offshore sites in the US, there is value to designing with a larger generator
- Going from 300 W/m² to 600 W/m² increases energy capture by ~50%
- VAWTs enable this design approach due to their low placement of the drivetrain
  - The additional generator mass for a VAWT is less meaningful to associated turbine and platform costs

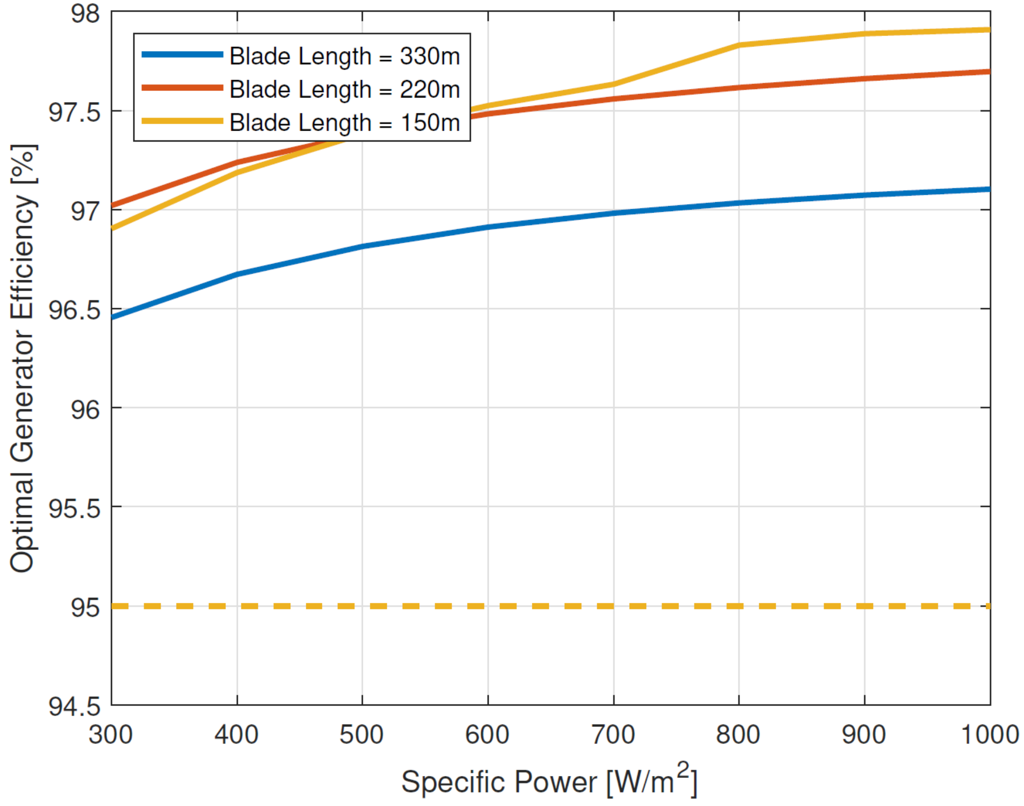


VAWT Scaling Trends – Optimal Generator Design

- Generator optimization using NREL tool GeneratorSE to minimize LCOE relative to a reference baseline value where cost (CG) and efficiency affect LCOE, assuming $LCOE^B = \$70/MWh$ in the analysis:

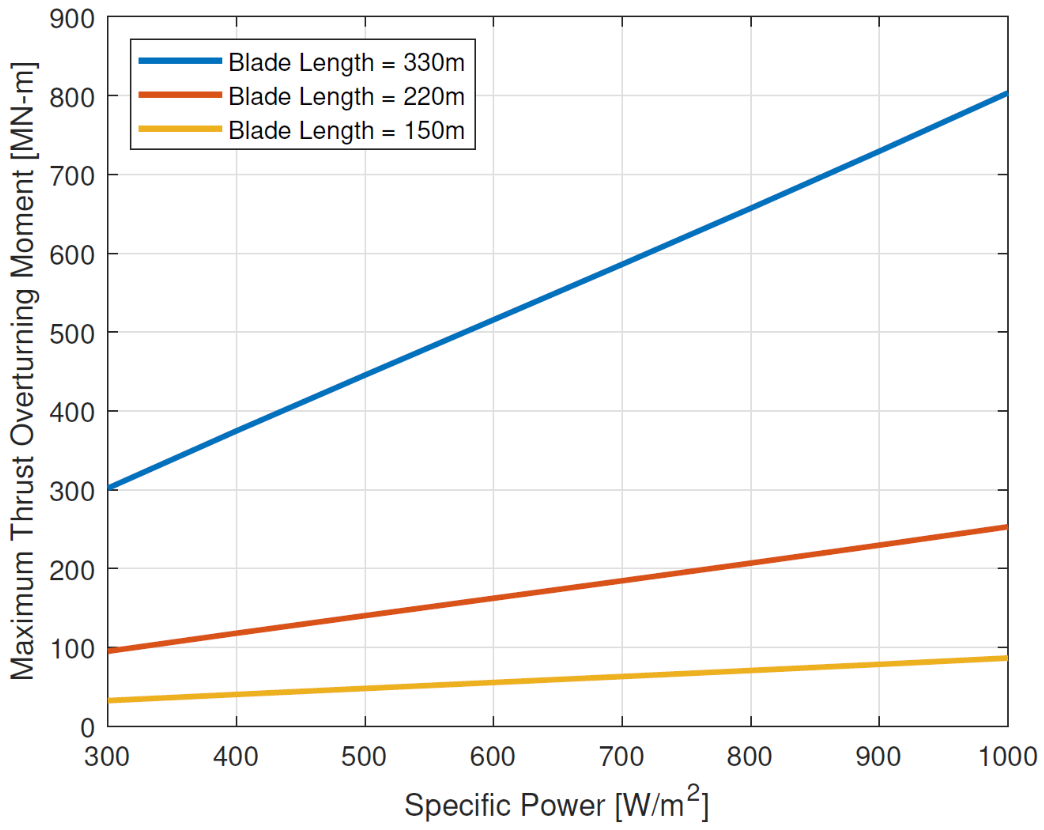
$$LCOE = \frac{\eta_G^B}{\eta_G}\left(\frac{(C_G - C_G^B)\cdot FCR}{AEP_{aero}\cdot \eta_G^B} + LCOE^B\right)$$





VAWT Scaling Trends – Turbine Loads on Platform

- However, for turbines with a larger swept area there is also a higher center of pressure, so the increased thrust force is also at a higher elevation
- Thrust overturning moment is substantially higher for larger turbines, which must be resisted by the floating platform



VAWT Scaling Trends – Platform Capital Costs

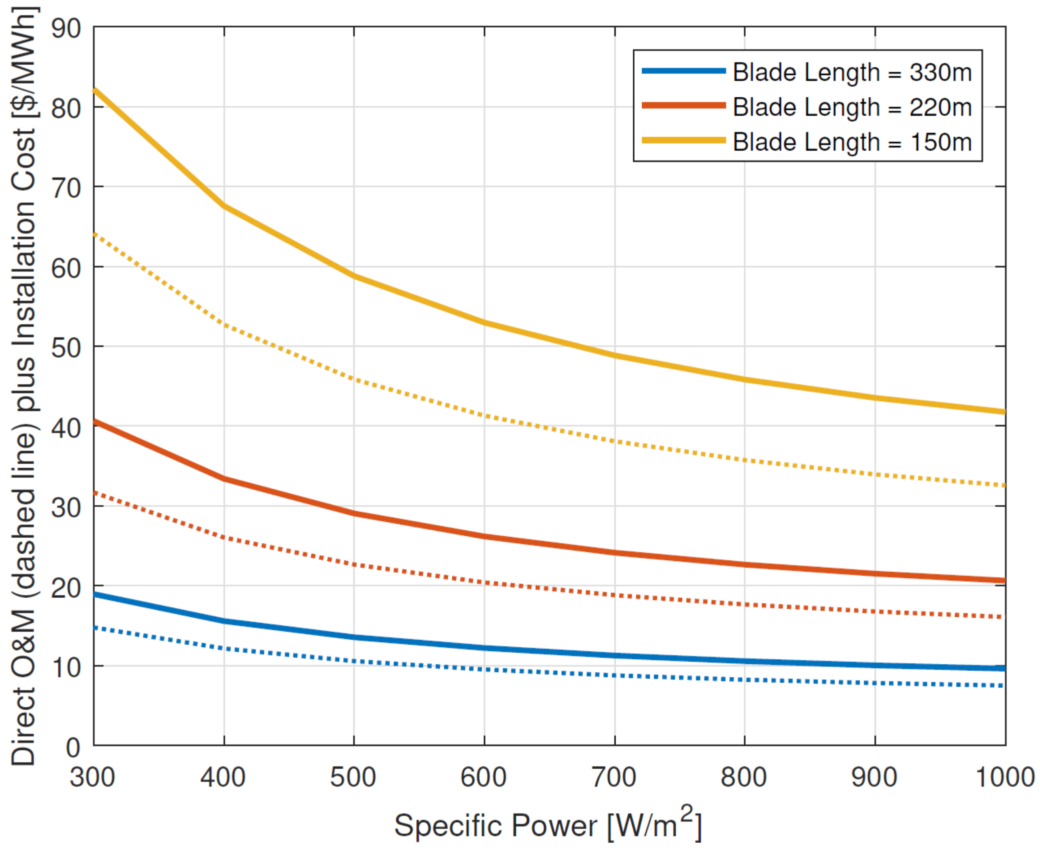
- Platforms were designed by partner FPS Engineering & Technology for the three reference VAWT sizes based on weight and wind loads
- Cycle 1 design mass estimates are higher than the final system, and the designs are not fully optimized
- However, the trends are considered representative and favor larger systems within the bounds of the study

VAWT TLP Cost Estimate Comparison – Cycle 1

VAWT TLP Cost Summary V1 (10-25-2021)				
		330 m Blade	220 m Blade	150 m Blade
Principal Dimensions	**Unit**	**TLP211004_33**	**TLP210601_22**	**TLP211005_15**
Draft	[m]	20.0	20.0	18.0
Displacement	**[mT]**	**11,251**	**9,037**	**6,381**
Turbine + Generator	[mT]	980	475	235
Flexible Riser Vertical loads	[mT]	50	50	50
Total System Payload	**[mT]**	**1,030**	**525**	**285**
Hull Primary Steel Wt (UCF+Tower Base+Hull)	[mT]	2,972	2,434	1,830
Other Steel Weight (Outfitting, Anodes, etc)	[mT]	673	544	396
Total Steel weight	**[mT]**	**3,644**	**2,978**	**2,225**
Marine System + Marine Growth	[mT]	135	109	77
Ballast Weight	[mT]	1,341	1,526	794
Total Platform Weight	**[mT]**	**5,966**	**4,979**	**3,254**
Tendon Pretension/Tendon	[mT]	850	650	500
Tendon Pretension	**[mT]**	**5,100**	**3,900**	**3,000**
Number of Tendons	-	6	6	6
Tendon Outer Diameter x Wall Thickness	[in x in]	30" x 1.150"	26" x 0.900"	22" x 0.850"
Dry Weight / Tendon	[mT]	47.0	32.0	25.5
Estimated Hull Unit Cost	$/ mT	10,000	10,000	10,000
Estimated Tendon Unit Cost	$/ mT	5,750	5,750	5,750
Hull Cost	$	36,442,639	29,778,568	22,254,469
Tendon Cost	$	1,622,660	1,104,842	879,251
Fabrication Cost Summary	$	**38,065,299**	**30,883,410**	**23,133,721**
Installation Cost	$	4,191,500	4,191,500	4,191,500
Operation and Maintenance Cost	$	1,123,200	1,123,200	1,123,200
Total Cost	$	**43,379,999**	**36,198,110**	**28,448,421**
Electrical Power Generation	MW	22.3	10.4	5.1
Estimated MW Cost	**$/W**	**1.95**	**3.48**	**5.58**

VAWT Scaling Trends – O&M, Platform Installation Costs

- Some balance of system costs are independent of the physical design for utility-scale systems
  - Platform tow-out and installation is considered equivalent
  - Direct Operations and Maintenance costs are primarily vessel charters and crew labor
- The only way to reduce the impact of these fixed-type costs on LCOE is through increased energy production
  - Costs become very meaningful for lower energy production designs



VAWT Scaling Trends – System Design Summary

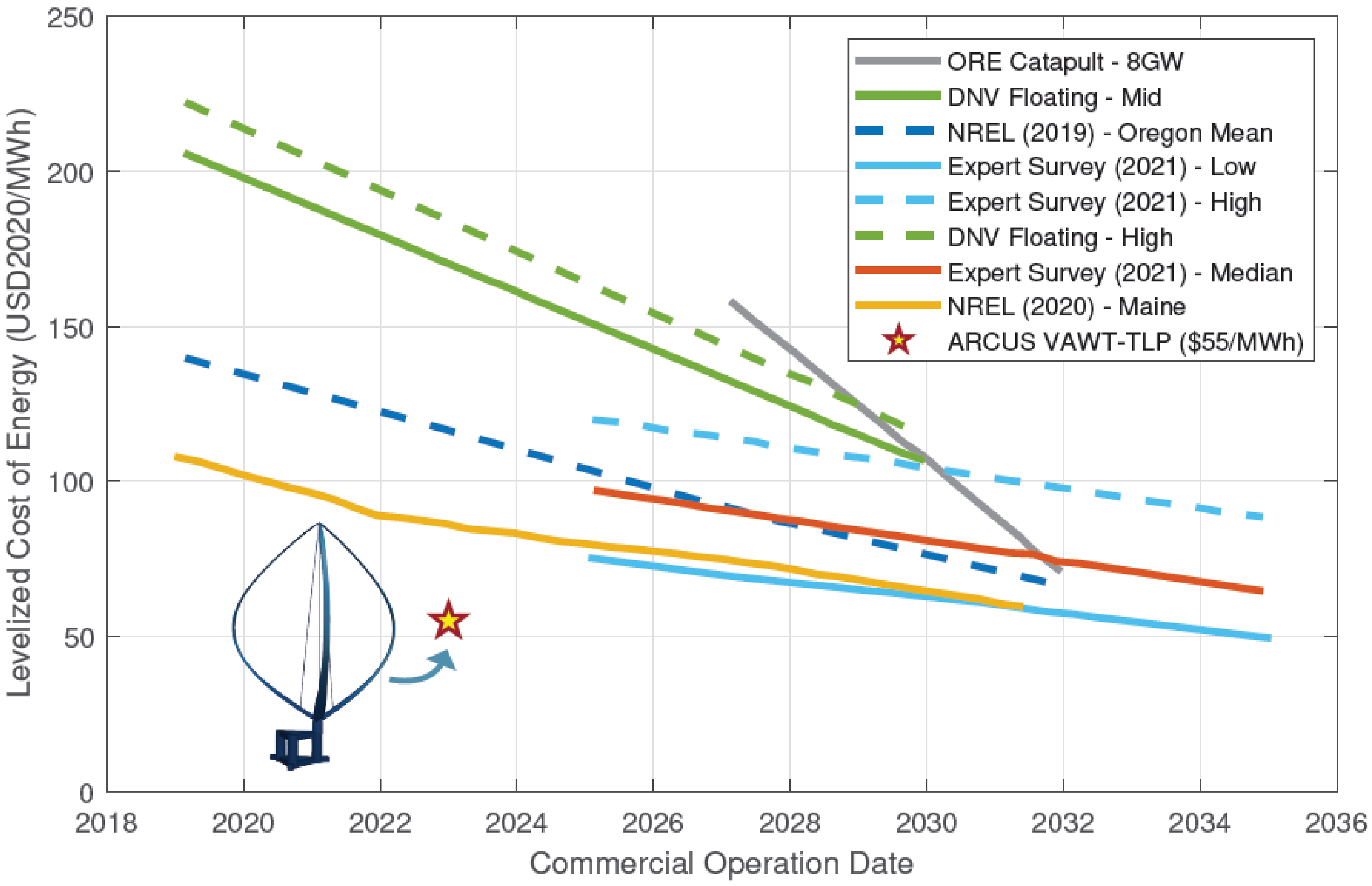
- The largest reference blade length was chosen (swept area of R = ~110m) due to the impact on decreasing balance of system costs and platform capital costs
- Balances cost reductions with blade manufacturing considerations

(SP_{design} = 600 W/m^2)	150m Blade Length (5.1 MW)	220m Blade Length (10.4 MW)	330m Blade Length (22.3 MW)
Annual energy production [-]	1.0	2.0	4.3
Maximum thrust overturning moment [-]	1.0	2.9	9.4
Combined direct O&M and platform installation LCOE contribution [$/MWh]	53.0	26.2	12.2
Cycle 1 platform and tendon cost estimate [$/MWh]	78.5	49.4	27.6

ARCUS-TLP Optimized System Design

ARCUS compared with a reference HAWT:

- 30% lower turbine mass
- 70% lower center of gravity
- 45% increase in energy capture
- $55/MWh levelized cost of energy prediction
- Effectively enables a Tension-Leg Platform

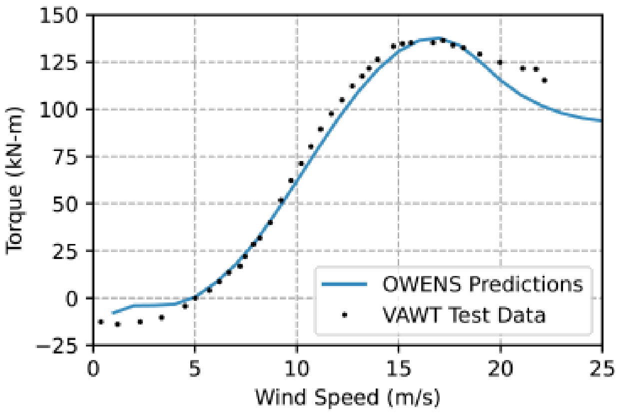


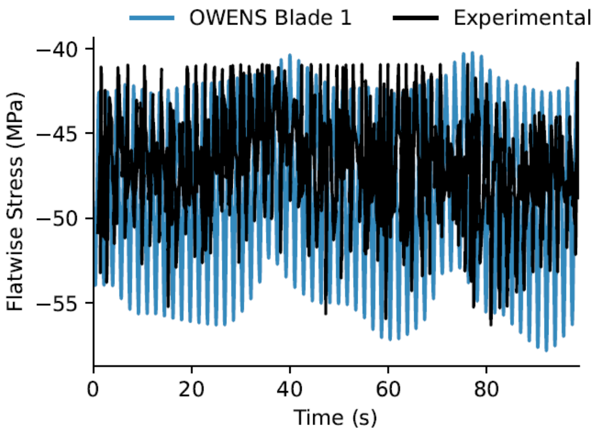
Remaining Uncertainties for VAWTs

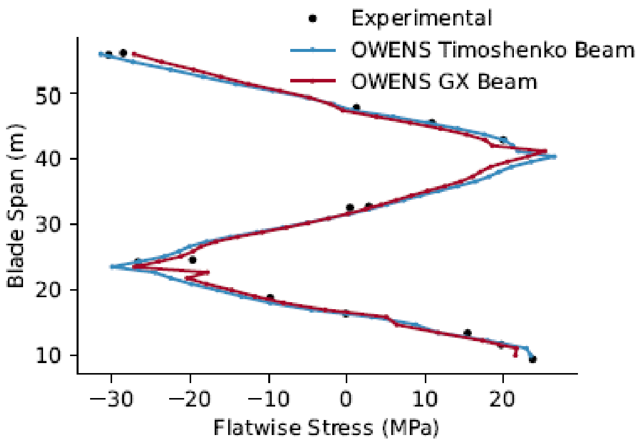
- Validated design tools appropriate for certification
- Large blade length, logistics for transportation and quayside installation
- Emergency shutdown control
- Predominant bearing loads are carried radially, not axially
- Industrialization and pilot-scale demonstration to de-risk and iterate on the design

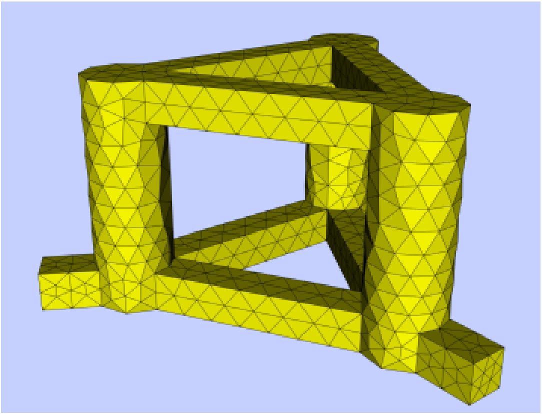
Development of Floating VAWT Design Optimization Tools

- Sandia's Offshore Wind Energy Simulator (OWENS) developed for design and optimization of floating VAWTs
- Required for certification of floating VAWTs and resulting commercialization









AIAA Journal

Vertical-Axis Wind Turbine Steady and Unsteady Aerodynamics for Curved Deforming Blades

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Aeroelastic Validation of the Offshore Wind Energy Simulator for Vertical-Axis Wind Turbines

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Research Article

Enabling Offshore Floating VAWT Design by Coupling OWENS and OpenFAST

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Abstract: Vertical-axis wind turbines (VAWTs) have a long history with a wide variety of turbine archetypes, of which the Darrieus type is the most common. While few utility-scale VAWTs currently exist, VAWTs offer some often-stated advantages over traditional horizontal-axis wind turbines, such as being agnostic to the direction of the wind (no yaw error), reduced tower strike potential, and lower placement of the generator, which could provide particular benefit for floating offshore wind turbines. Presently, there are very few numerical design and analysis tools available for VAWTs. The Offshore Wind ENergy Simulator (OWENS) tool is an aero-servo-elastic solver for simulating VAWTs and has limited functionality to simulate floating VAWTs. This article, a cross-collaboration between Sandia National Laboratories and the National Renewable Energy Laboratory, describes how OWENS has been coupled to several OpenFAST modules to support the coupled aero-hydro-servo-elastic modeling of a floating offshore VAWT and discusses the verification of these new capabilities and features. This collaboration facilitates the development of OWENS for floating VAWT applications by coupling specific OpenFAST modules to enable additional modeling and simulation capabilities in OWENS, thus enabling the design and optimization of floating offshore VAWTs.

Keywords: vertical axis wind turbine (VAWT); floating offshore wind turbine (FOWT); OWENS; OpenFAST, hydrodynamics

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1. Introduction

Floating offshore wind turbines are a relatively young and growing technology domain that can play a significant role in decarbonizing the energy sector, particularly in geographic areas where a deep-water wind resource exists. However, additional research and development is needed to reduce the levelized cost of energy (LCOE) of floating offshore wind energy farms. This creates the need for verified and validated design tools to optimize floating offshore wind turbines and reduce their cost. One open-source, commonly used floating offshore wind turbine design and analysis tool is OpenFAST, which is an aero-hydro-servo-elastic solver developed and maintained by the National Renewable Energy Laboratory (NREL). OpenFAST is continuously being expanded to support many types of mooring systems, floating platform archetypes, and floating system dynamics and controls. OpenFAST has been extensively verified and validated for three-bladed, horizontal-axis, upwind turbines (HAWTs), but supports limited capability for vertical-axis wind turbines (VAWTs).

Vertical-axis wind turbines have a long history with a wide variety of turbine archetypes, of which the Darrieus type is the most common (though not necessarily dominant). VAWTs are more common in small wind or distributed wind applications. While few utility-scale VAWTs currently exist, VAWTs offer some often-stated advantages over HAWTs, such as being agnostic to the direction of the wind (no yaw

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Demonstration is necessary to realize the system benefits