This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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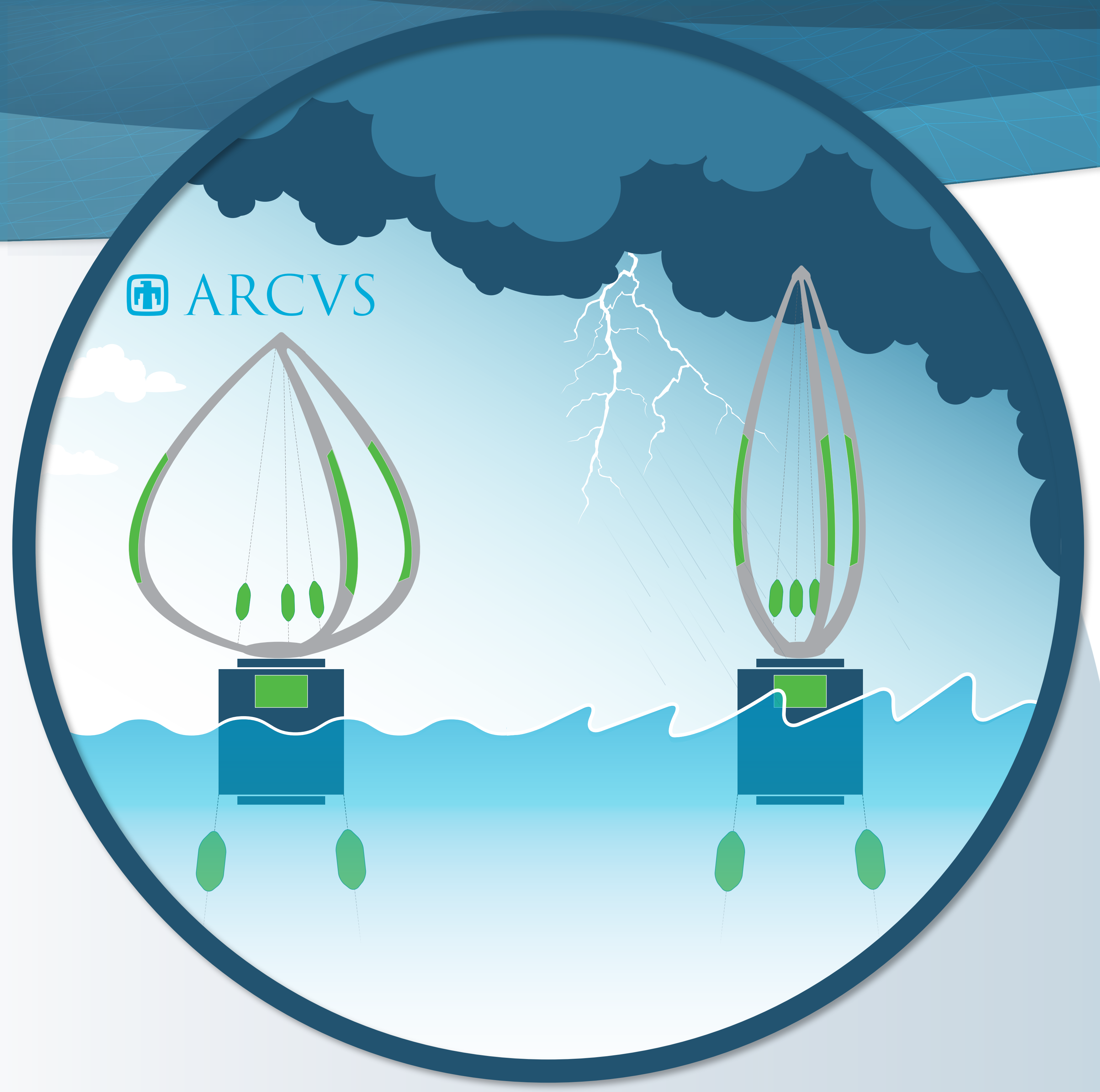
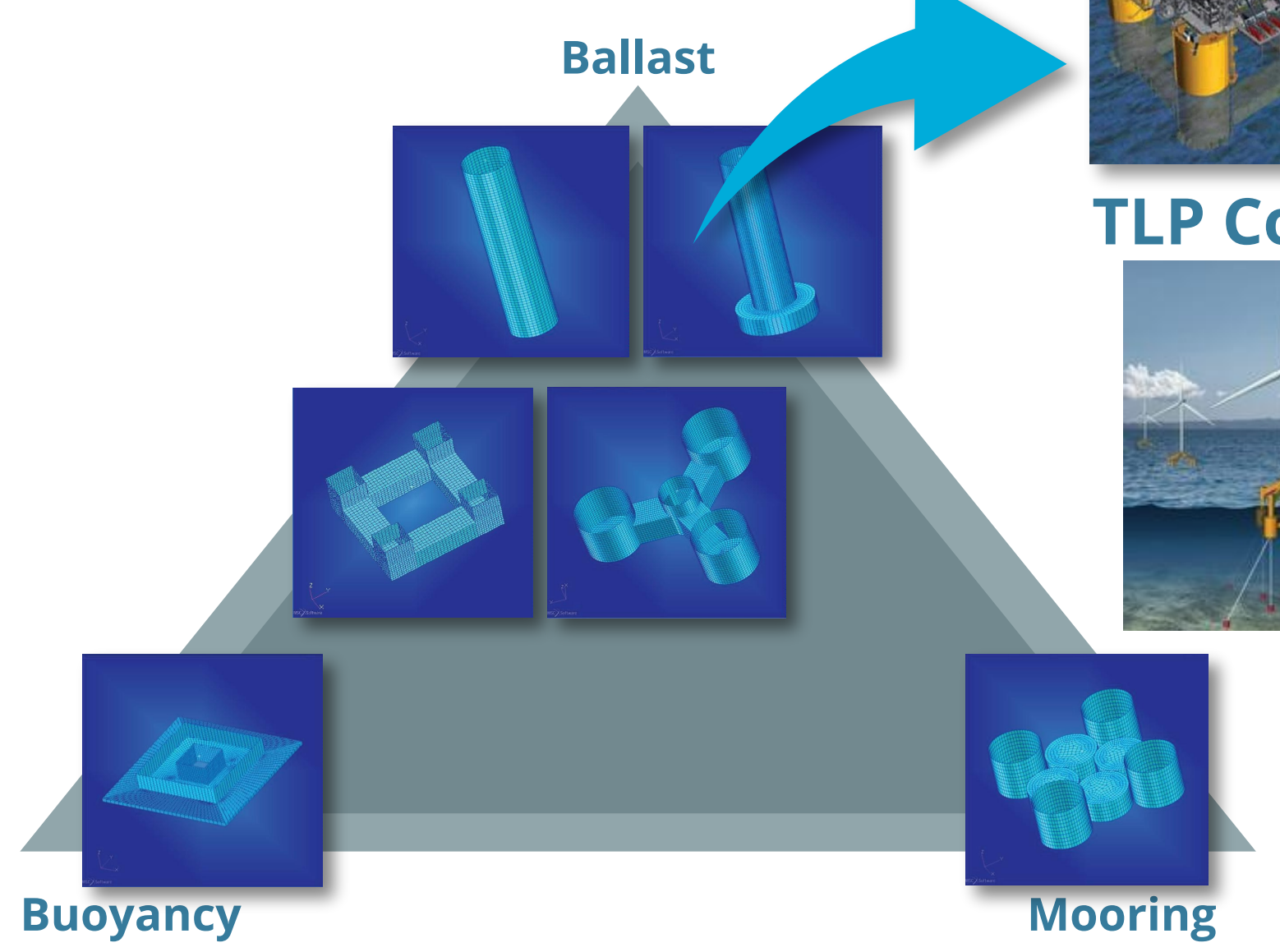
A VERTICAL-AXIS WIND TURBINE OPTIMIZED TO REDUCE THE COSTS OF FLOATING OFFSHORE WIND ENERGY



A turbine designed for offshore sites

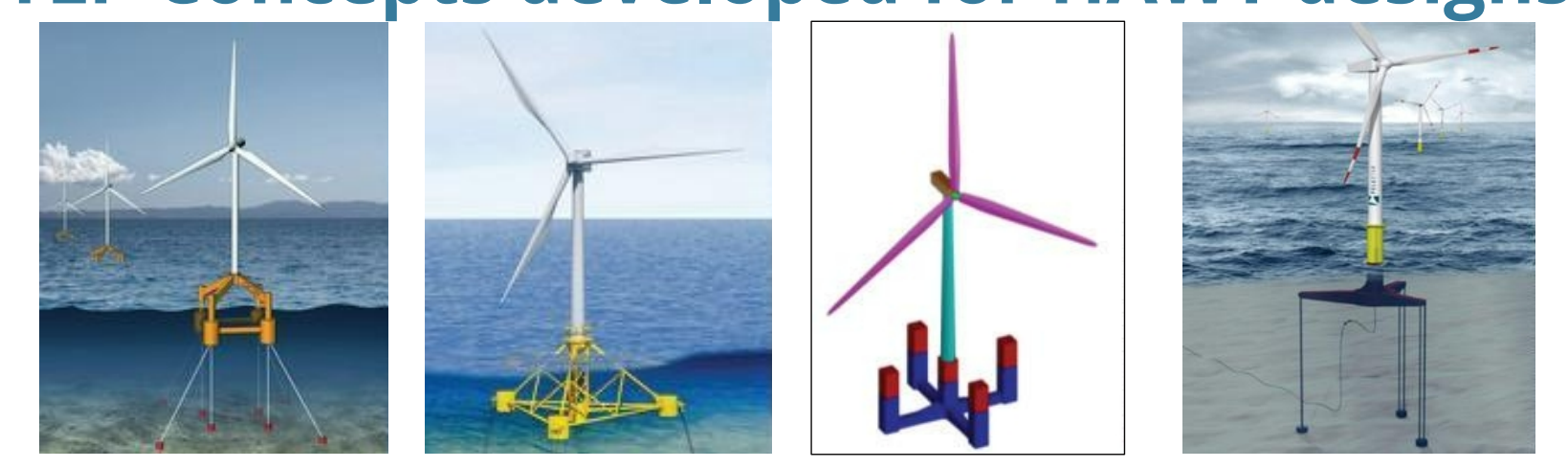
- The ideal wind energy system would remove all mass and cost not directly capturing energy from the wind
- For floating offshore wind energy, this objective is even more significant as increased mass above the water level must be supported by larger and more expensive floating platforms
- ARCUS is a Darrieus VAWT that replaces the traditional rigid tower with pre-stressed blades and tensioned center supports (patent-pending), like a bow, which:
  - Enables an efficient usage of material
  - Enables rotor area control for high wind speed load reduction
  - Results in up to a 50% rotor mass reduction

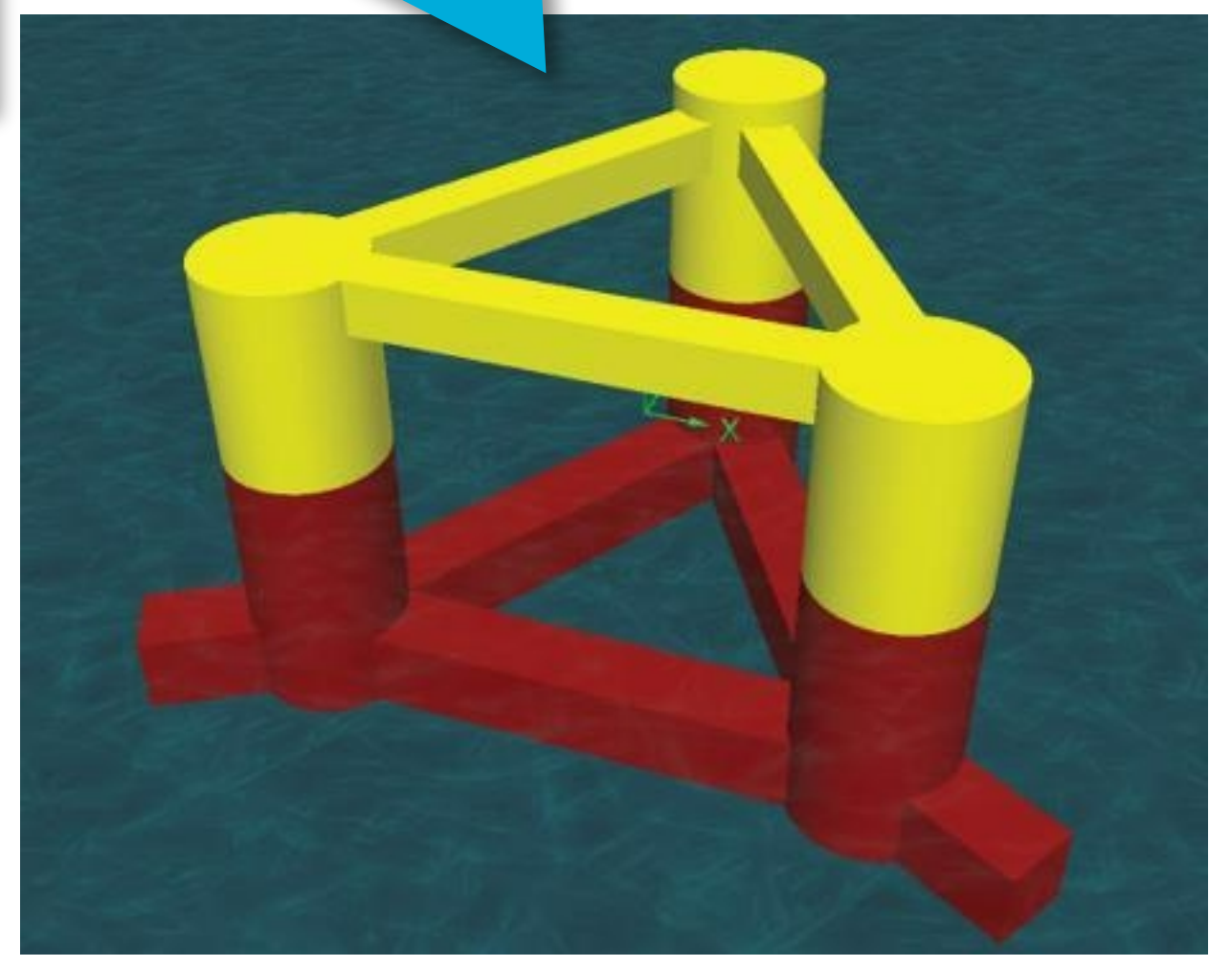
An optimal platform paired with an optimal turbine



TLP Concepts currently in Operation for Oil and Gas Production

TLP Concepts developed for HAWT designs

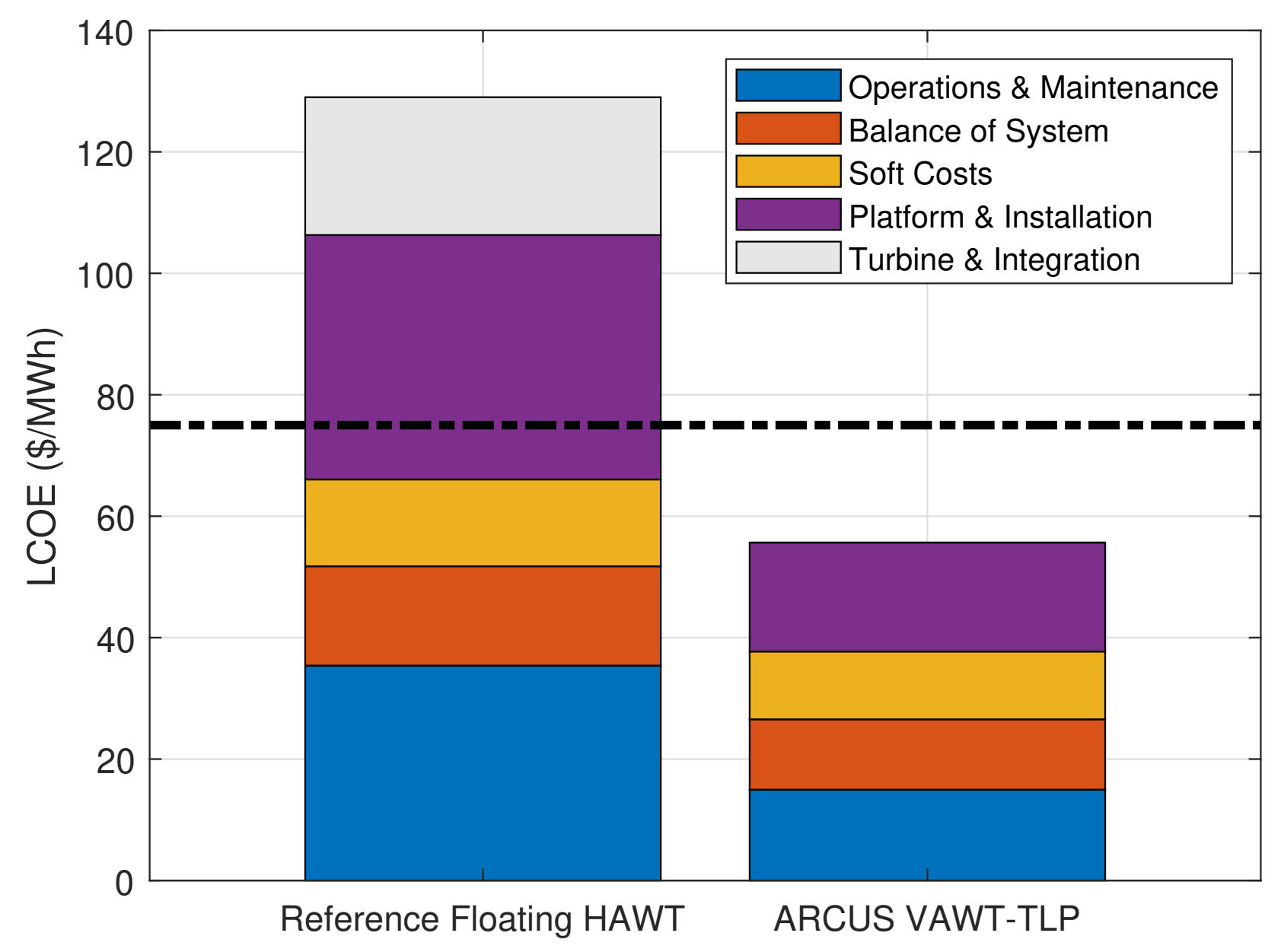




- The low drivetrain placement and mass properties of the ARCUS VAWT, compared to a horizontal-axis wind turbine (HAWT), make it optimally suited for a tension-leg platform, identified as a cost-optimal platform architecture with additional performance benefits
- Tension-leg platforms (TLP) have the lowest hull mass compared to alternative architectures and are ideally suited for both shallow and deep-water sites in the U.S., scalable to beyond 1000m
- An optimal TLP hull architecture was identified through discrete design studies that minimized mass while meeting the design requirements (quayside integration, self-stable during tow out)

Lower costs, higher energy capture

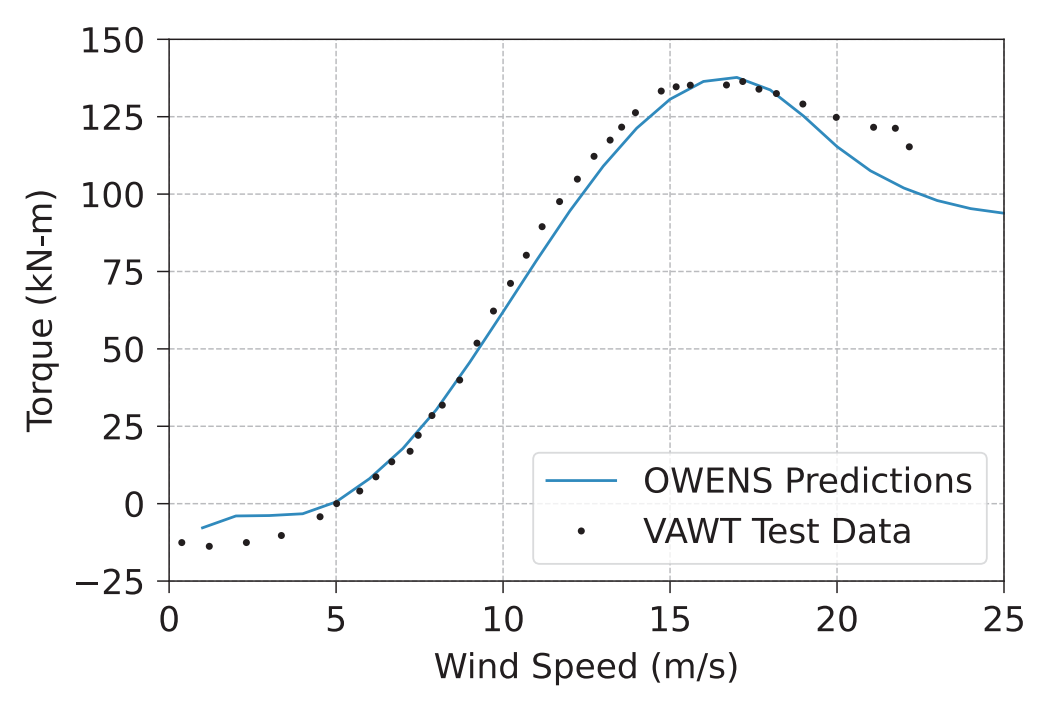
ARCUS initial LCOE calculation, excluding turbine

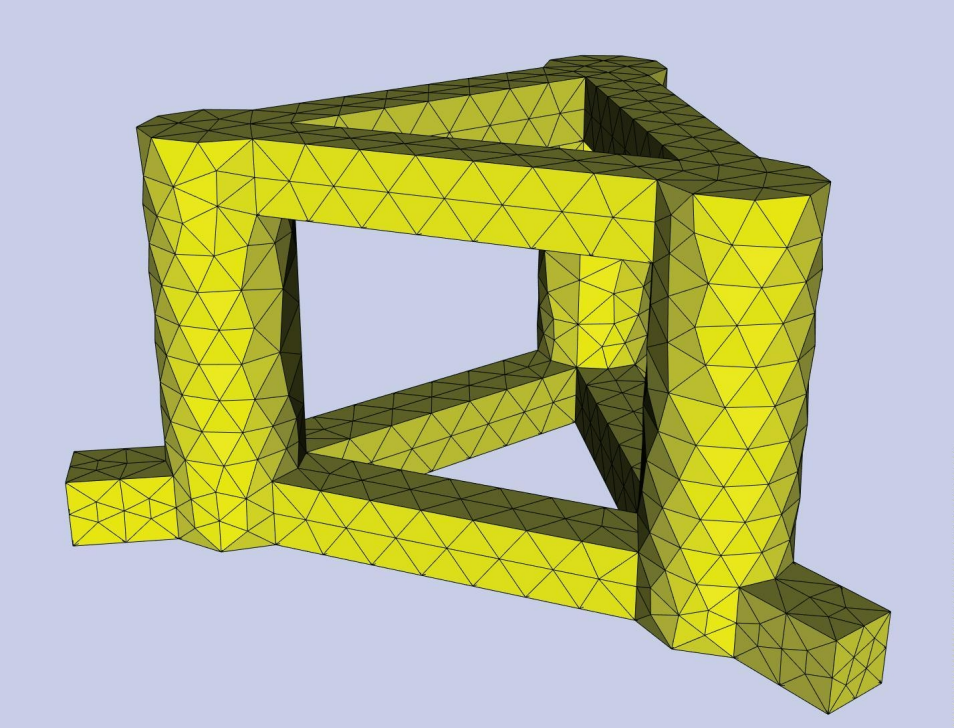


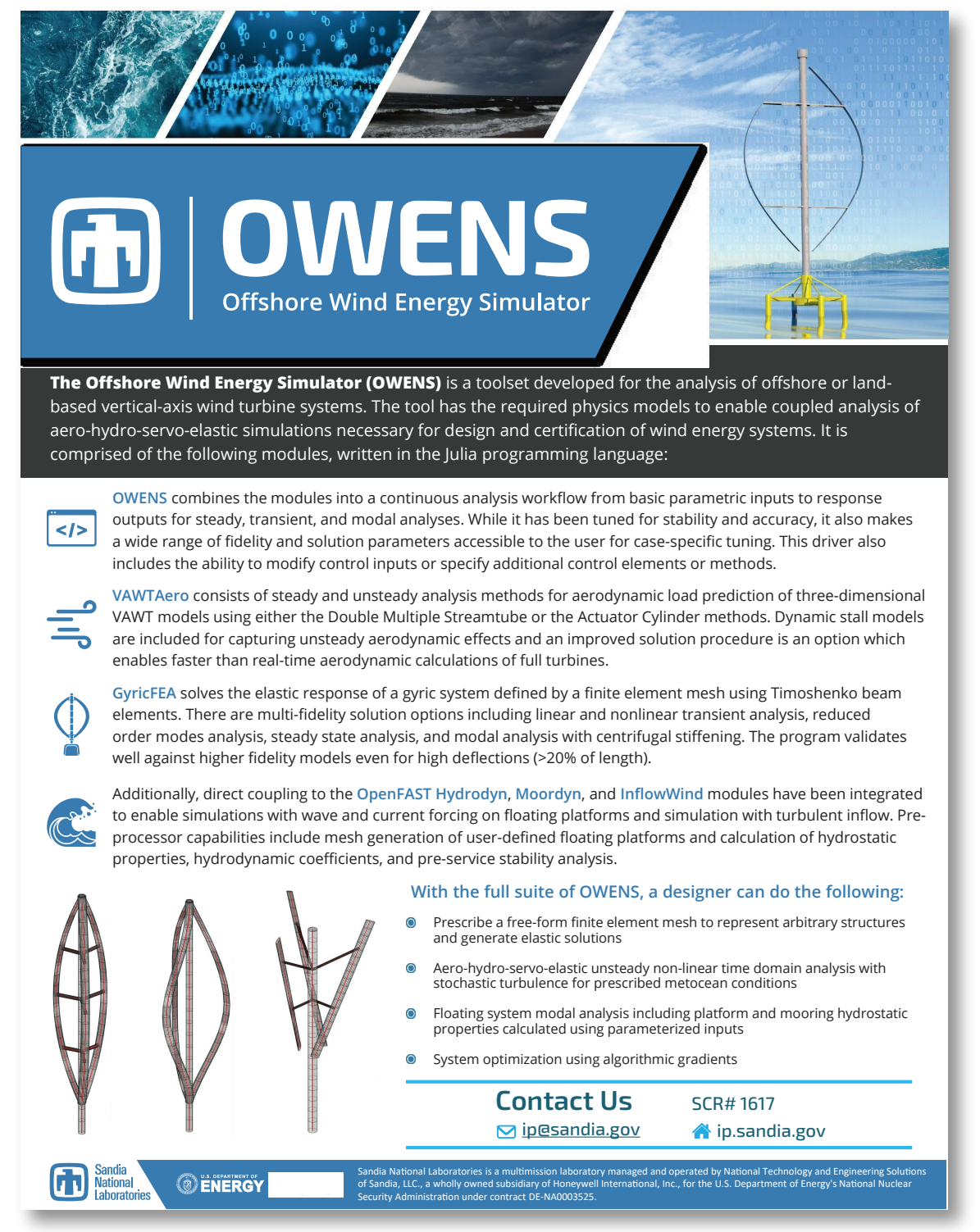
- The project team has the expertise to perform detailed design of the turbine-platform system with accurate cost estimation
- Subsystem design optimization studies reveal opportunity for the ARCUS-TLP system to perform better than the target levelized cost of energy (LCOE) of less than $75/MWh
- Full system control co-design optimization will be used to identify the optimal system (physical and controls), resulting in further LCOE reductions

An analysis tool capable of design and optimization of floating VAWTs

- In order to design floating VAWTs, a tool is needed that can model arbitrary rotor and platform architectures while simulating the coupled dynamic response to wind, waves, and structural displacement
- Sandia has developed the Offshore Wind Energy Simulator (OWENS) to address this need, while ensuring the computational efficiency necessary for complex optimization studies
- There can't be a floating offshore vertical-axis wind turbine industry without a trusted tool like OWENS







OWENS
Offshore Wind Energy Simulator

The Offshore Wind Energy Simulator (OWENS) is a toolset developed for the analysis of offshore or land-based vertical-axis wind turbine systems. The tool has the required physics models to enable coupled analysis of aero-hydro-servo-elastic simulations necessary for design and certification of wind energy systems. It is comprised of the following modules, written in the Julia programming language:

OWENS combines the modules into a continuous analysis workflow from basic parametric inputs to response outputs for steady, transient, and modal analyses. While it has been tuned for stability and accuracy, it also makes a wide range of fidelity and solution parameters accessible to the user for case-specific tuning. This driver also includes the ability to modify control inputs or specify additional control elements or methods.

VAWTAero consists of steady and unsteady analysis methods for aerodynamic load prediction of three-dimensional VAWT models using either the Double Multiple Streamtube or the Actuator Cylinder methods. Dynamic stall models are included for capturing unsteady aerodynamic effects and an improved solution procedure is an option which enables faster than real-time aerodynamic calculations of full turbines.

GyricFEA solves the elastic response of a gyric system defined by a finite element mesh using Timoshenko beam elements. There are multi-fidelity solution options including linear and nonlinear transient analysis, reduced order modes analysis, steady state analysis, and modal analysis with centrifugal stiffening. The program validates well against higher fidelity models even for high deflections (>20% of length).

Additionally, direct coupling to the OpenFAST Hydrodyn, Moordyn, and InflowWind modules have been integrated to enable simulations with wave and current forcing on floating platforms and simulation with turbulent inflow. Pre-processor capabilities include mesh generation of user-defined floating platforms and calculation of hydrostatic properties, hydrodynamic coefficients, and pre-service stability analysis.

With the full suite of OWENS, a designer can do the following:

- Prescribe a free-form finite element mesh to represent arbitrary structures and generate elastic solutions
- Aero-hydro-servo-elastic unsteady non-linear time domain analysis with stochastic turbulence for prescribed metocean conditions
- Floating system modal analysis including platform and mooring hydrostatic properties calculated using parameterized inputs
- System optimization using algorithmic gradients

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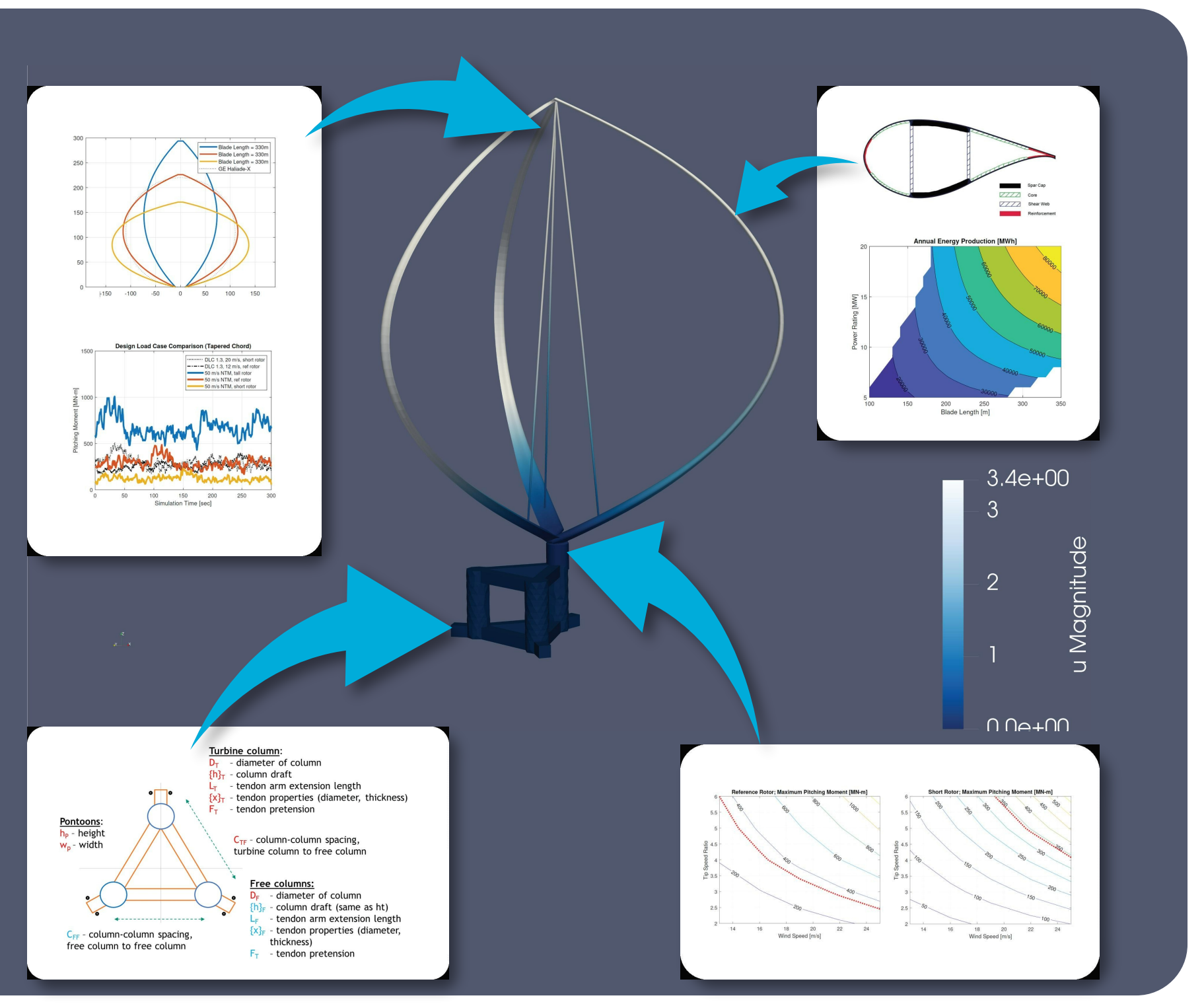
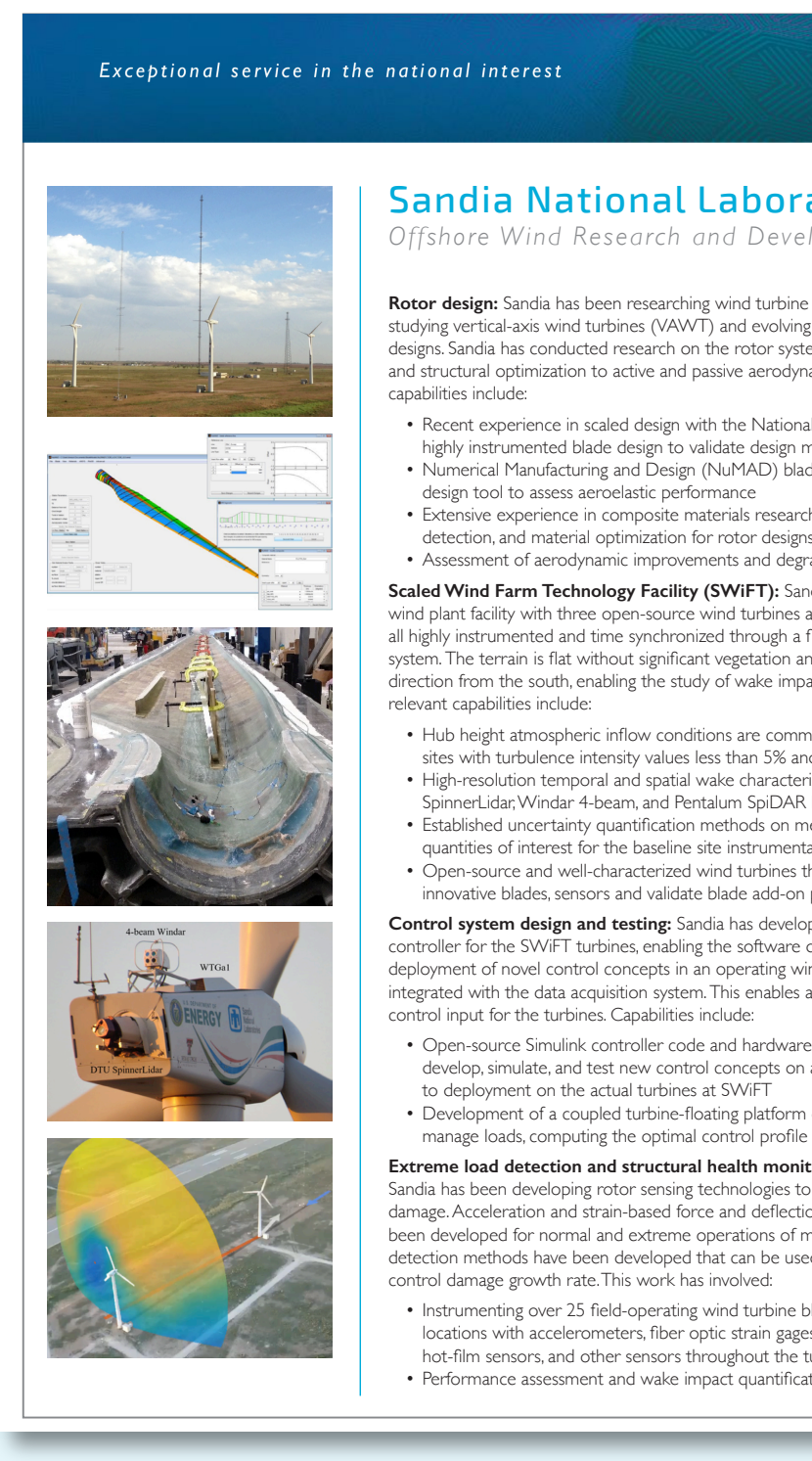
System optimization to exploit complex cost-performance tradeoffs

- In the traditional approach to platform design, platform mass and inertia are used to ensure operational stability for a fixed turbine design, resulting in heavy and expensive platforms
- The optimal ARCUS turbine, platform design, and control approach will be identified through designing the rotor, platform, and controls concurrently using a control co-design methodology developed within the project
- Design tradeoffs will be balanced to find the optimal relationship between loads, energy capture, and dynamic response that minimizes the system levelized cost of energy


Design Load Case Comparison (Tapered Chord)
Annual Energy Production [MWh]
Blade Length [m]
Power Rating [MW]
3.4e+00
3
2
1
0.0e+00
u Magnitude
Turbine column:
D_T - diameter of column
$\{h\}_T$ - column draft
L_T - tendon arm extension length
$\{x\}_T$ - tendon properties (diameter, thickness)
F_T - tendon pretension
Pontoons:
h_P - height
w_P - width
C_{TF} - column-column spacing, turbine column to free column
Free columns:
D_F - diameter of column
$\{h\}_F$ - column draft (same as ht)
L_F - tendon arm extension length
$\{x\}_F$ - tendon properties (diameter, thickness)
F_T - tendon pretension
C_{FF} - column-column spacing, free column to free column
Reference Rotor; Maximum Pitching Moment [MN-m]
Short Rotor; Maximum Pitching Moment [MN-m]
Tip Speed Ratio
Wind Speed [m/s]



Exceptional service in the national interest

Sandia National Laboratories
Offshore Wind Research and Development Capabilities

Rotor design: Sandia has been researching wind turbine rotor systems with programs studying vertical-axis wind turbines (VAWT) and evolving to horizontal-axis wind turbine designs. Sandia has conducted research on the rotor system spanning composite materials and structural optimization to active and passive aerodynamic load control designs. Specific capabilities include:

- Recent experience in scaled design with the National Rotor Testbed design project – a highly instrumented blade design to validate design models
- Numerical Manufacturing and Design (NuMAD) blade structural optimization tool and design tool to assess aeroelastic performance
- Extensive experience in composite materials research, including reliability and damage detection, and material optimization for rotor designs
- Assessment of aerodynamic improvements and degradation (e.g., erosion)

Scaled Wind Farm Technology Facility (SWiFT): Sandia operates an experimental wind plant facility with three open-source wind turbines and two meteorological towers, all highly instrumented and time synchronized through a fiber-optic data acquisition system. The terrain is flat without significant vegetation and has a single predominant wind direction from the south, enabling the study of wake impacts within a wind plant. A few relevant capabilities include:

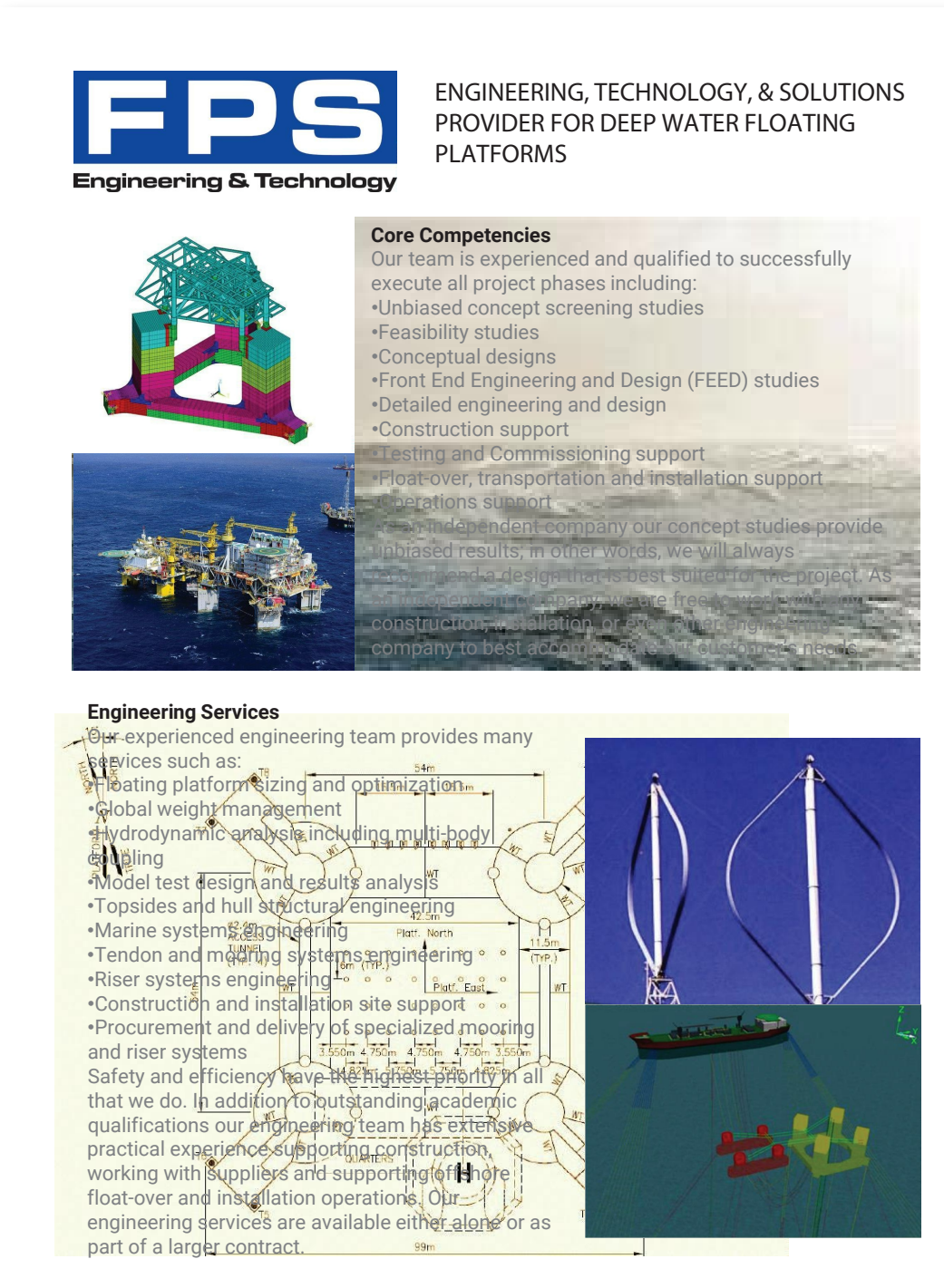
- Hub height atmospheric inflow conditions are commonly representative of offshore sites with turbulence intensity values less than 5% and low wind shear
- High-resolution temporal and spatial wake characterization and analysis using the DTU SpinnerLidar, Windar 4-beam, and Pentalum SpiDAR lidar
- Established uncertainty quantification methods on measurements and derived quantities of interest for the baseline site instrumentation
- Open-source and well-characterized wind turbines that can be modified to operate innovative blades, sensors and validate blade add-on performance

Control system design and testing: Sandia has developed a completely open-source controller for the SWiFT turbines, enabling the software development, testing and deployment of novel control concepts in an operating wind plant environment that is integrated with the data acquisition system. This enables any sensor at the site to serve as a control input for the turbines. Capabilities include:

- Open-source Simulink controller code and hardware-in-the-loop system to rapidly develop, simulate, and test new control concepts on a realistic hardware system prior to deployment on the actual turbines at SWiFT
- Development of a coupled turbine-floating platform controller to optimize power and manage loads, computing the optimal control profile

Extreme load detection and structural health monitoring: For the past 10 years Sandia has been developing rotor sensing technologies to monitor blade loading and damage. Acceleration and strain-based force and deflection estimation methods have been developed for normal and extreme operations of modern wind turbines. Damage detection methods have been developed that can be used in wind turbine controllers to control damage growth rate. This work has involved:

- Instrumenting over 25 field-operating wind turbine blades at various scales and locations with accelerometers, fiber optic strain gages, pitot tubes, pressure taps, hot-film sensors, and other sensors throughout the turbine
- Performance assessment and wake impact quantification via SCADA data

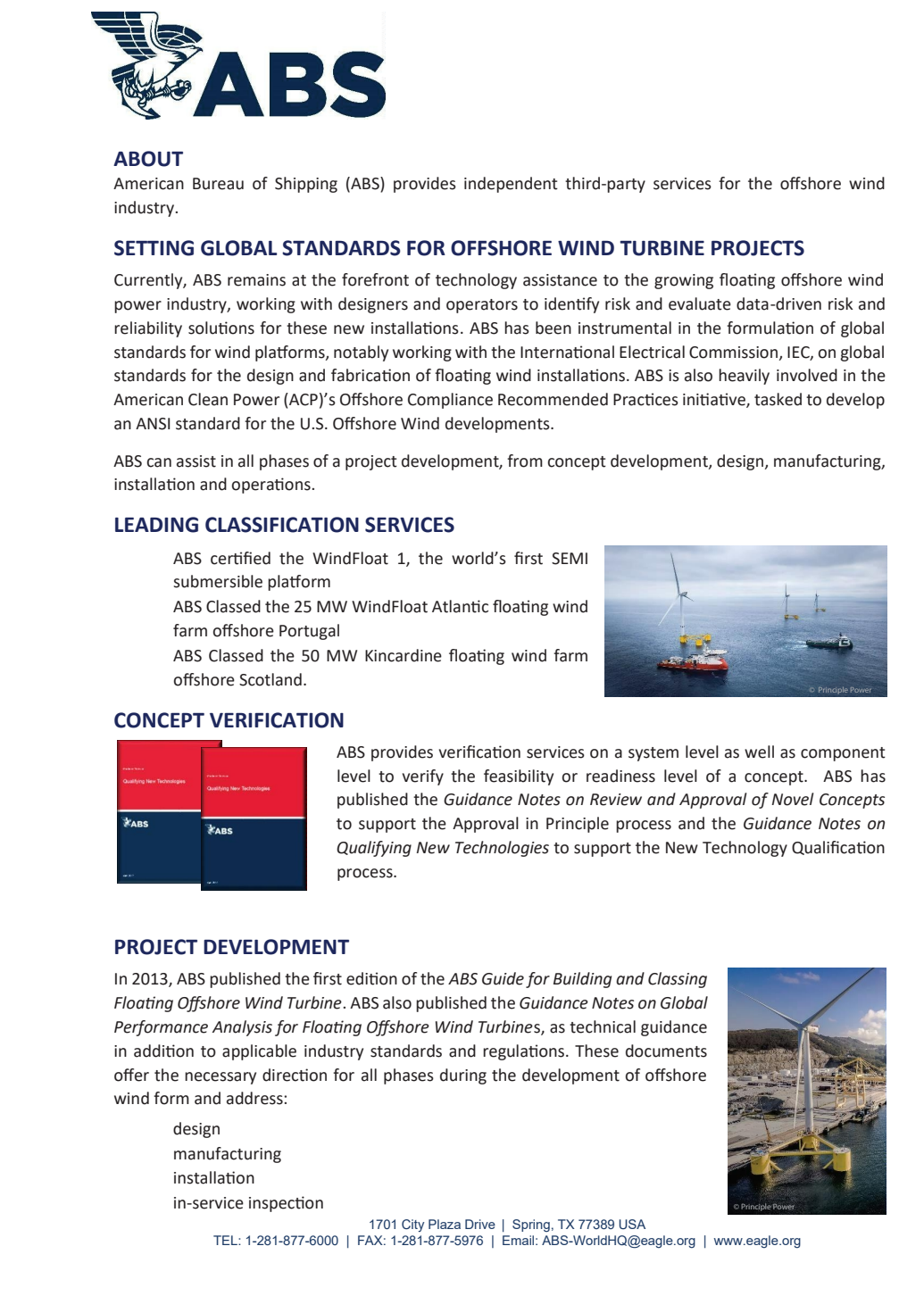


ENGINEERING, TECHNOLOGY, & SOLUTIONS PROVIDER FOR DEEP WATER FLOATING PLATFORMS

Core Competencies
Our team is experienced and qualified to successfully execute all project phases including:
•Unbiased concept screening studies
•Feasibility studies
•Conceptual designs
•Front End Engineering and Design (FEED) studies
•Detailed engineering and design
•Construction support
•Testing and Commissioning support
•Float-over, transportation and installation support
•Operations support
•As an independent company our concept studies provide unbiased results; in other words, we will always recommend a design that is best suited for the project. As an independent company we are free to work with any construction, installation, or even other engineering company to best accommodate our customer's needs.

Engineering Services
Our experienced engineering team provides many services such as:
•Floating platform sizing and optimization
•Global weight management
•Hydrodynamic analysis including multi-body coupling
•Model test design and results analysis
•Topsides and hull structural engineering
•Marine systems engineering
•Tendon and mooring systems engineering
•Riser systems engineering
•Construction and installation site support
•Procurement and delivery of specialized mooring and riser systems
Safety and efficiency have the highest priority in all that we do. In addition to outstanding academic qualifications our engineering team has extensive practical experience supporting construction, working with suppliers and supporting offshore float-over and installation operations. Our engineering services are available either alone or as part of a larger contract.

For more information contact Ed Huang at 281-798-8893 • ehuang@fpset.com



ABOUT
American Bureau of Shipping (ABS) provides independent third-party services for the offshore wind industry.

SETTING GLOBAL STANDARDS FOR OFFSHORE WIND TURBINE PROJECTS
Currently, ABS remains at the forefront of technology assistance to the growing floating offshore wind power industry, working with designers and operators to identify risk and evaluate data-driven risk and reliability solutions for these new installations. ABS has been instrumental in the formulation of global standards for wind platforms, notably working with the International Electrical Commission, IEC, on global standards for the design and fabrication of floating wind installations. ABS is also heavily involved in the American Clean Power (ACP)'s Offshore Compliance Recommended Practices initiative, tasked to develop an ANSI standard for the U.S. Offshore Wind developments.

ABS can assist in all phases of a project development, from concept development, design, manufacturing, installation and operations.

LEADING CLASSIFICATION SERVICES
ABS certified the WindFloat 1, the world's first SEMI submersible platform
ABS Classed the 25 MW WindFloat Atlantic floating wind farm offshore Portugal
ABS Classed the 50 MW Kincardine floating wind farm offshore Scotland.

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CONCEPT VERIFICATION
ABS provides verification services on a system level as well as component level to verify the feasibility or readiness level of a concept. ABS has published the *Guidance Notes on Review and Approval of Novel Concepts* to support the Approval in Principle process and the *Guidance Notes on Qualifying New Technologies* to support the New Technology Qualification process.

PROJECT DEVELOPMENT
In 2013, ABS published the first edition of the *ABS Guide for Building and Classing Floating Offshore Wind Turbine*. ABS also published the *Guidance Notes on Global Performance Analysis for Floating Offshore Wind Turbines*, as technical guidance in addition to applicable industry standards and regulations. These documents offer the necessary direction for all phases during the development of offshore wind form and address:

design
manufacturing
installation
in-service inspection

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