An Engineering Judgment and Systems Engineering Perspective from Sandia's Floating Offshore VAWT Project

PRESENTED BY

Brandon L. Ennis

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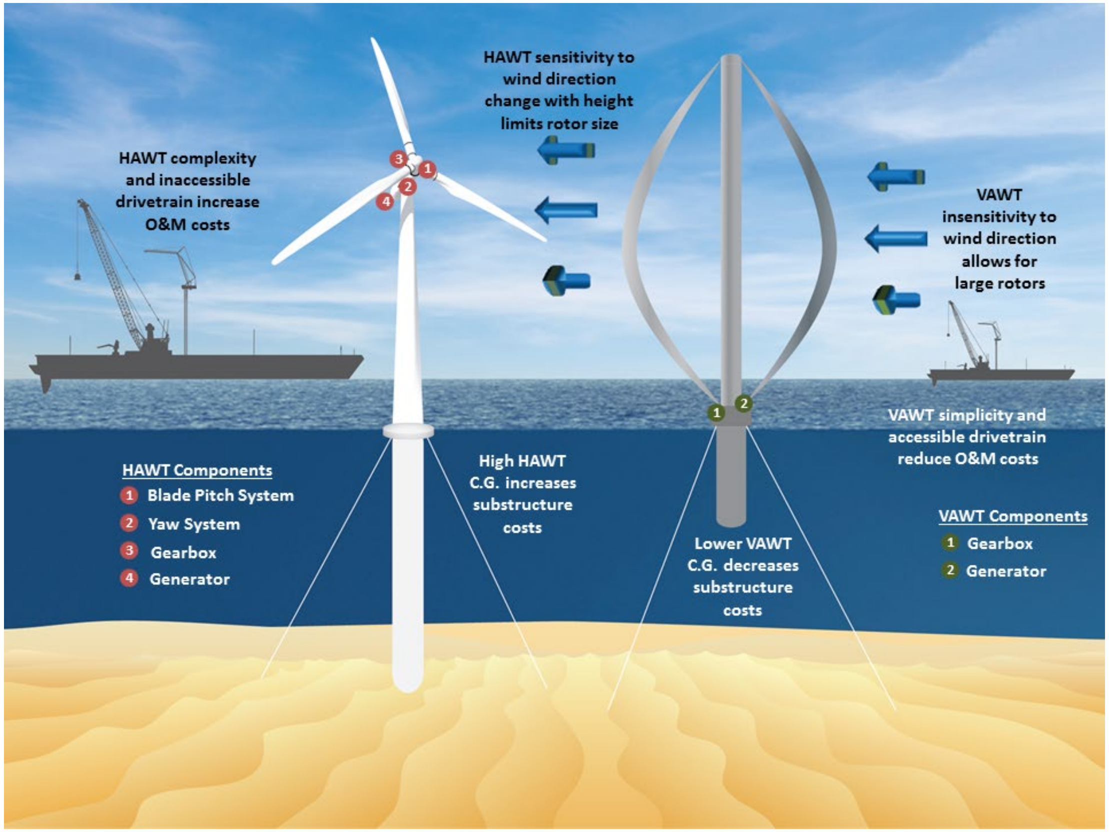
How can optimization be used to find radically new designs?

Thought exercise: How can an optimization of this floating horizontal-axis wind turbine (HAWT) identify a vertical-axis wind turbine (VAWT) as an optimal system?

- You could let the tower height vary to unrealistic design values to reveal trends of system levelized cost of energy (LCOE) vs. tower height
  - Then you could identify the sensitivities of the rotor and drivetrain mass and center of gravity to the resulting cost
- You could let the nacelle tilt angle vary up to 90 degrees and use precone and prebend to emulate a V-VAWT rotor architecture
  - This would be very inefficient and the optimizer would have to pass through regions of degraded performance

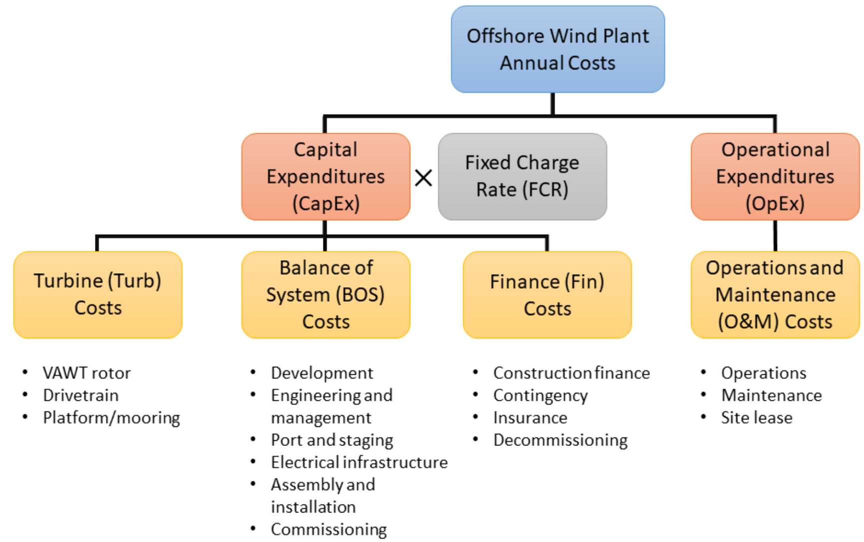
Floating Offshore Wind Energy in the U.S.

- Floating offshore wind plants have more components than land-based machines
- There are strong relationships between design variables which affect the cost of other components
- Turbine costs represent 65% of wind plant costs for land-based sites compared to around 20% for floating offshore sites
- Platform costs now represent the largest single contributor to LCOE
- Vertical-axis wind turbines have been studied as a potential solution for floating offshore wind energy which have several benefits, including:
  - Lower center of gravity, which reduces platform costs
  - Improved efficiency over HAWTs at multi-MW scales
  - Reduced O&M costs through removal of active components and platform-level placement of drivetrain

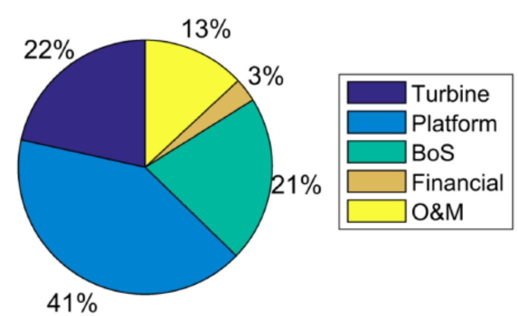


Levelized Cost of Energy Design Objective

- Energy generation sources have traditionally been selected based on an LCOE comparison with alternative sources
- Annual expenses include capital costs and operational expenses, which become significant for offshore systems
  - The relatively low cost of the turbine suggests that a more expensive turbine system than would be considered for land-based applications might be optimal for a system LCOE by reductions in the platform costs
- Energy production divides the entire cost formula, however a larger rotor also results in a larger drivetrain and platform which increases the system capital expenditures
  - The sensitivities of the sub-component relationships with cost must be understood to produce the optimal system



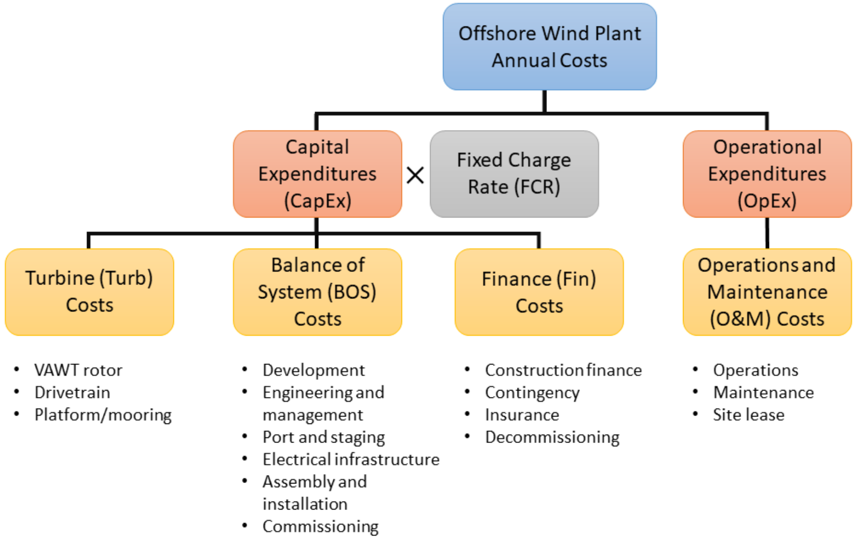
$$LCOE = \frac{(CapEx * FCR) + OpEx}{AEP_{net}}$$



Levelized Cost of Energy Design Objective

- The solution for LCOE minimization is to reduce the system costs and increase energy capture
- The ideal wind energy system would eliminate all mass and cost that is not directly capturing energy from the wind
- This objective is even more significant for floating offshore sites where increased mass above the water level must be supported by larger and more expensive floating platforms

- Based on this objective…



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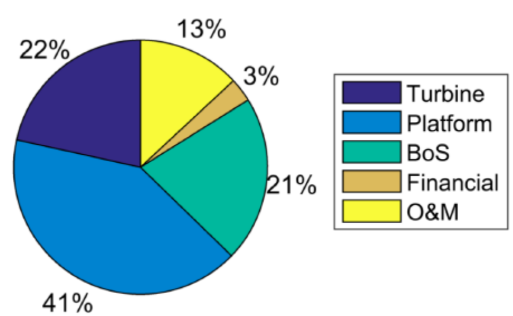

A more optimal turbine design for floating offshore sites?

…the future??

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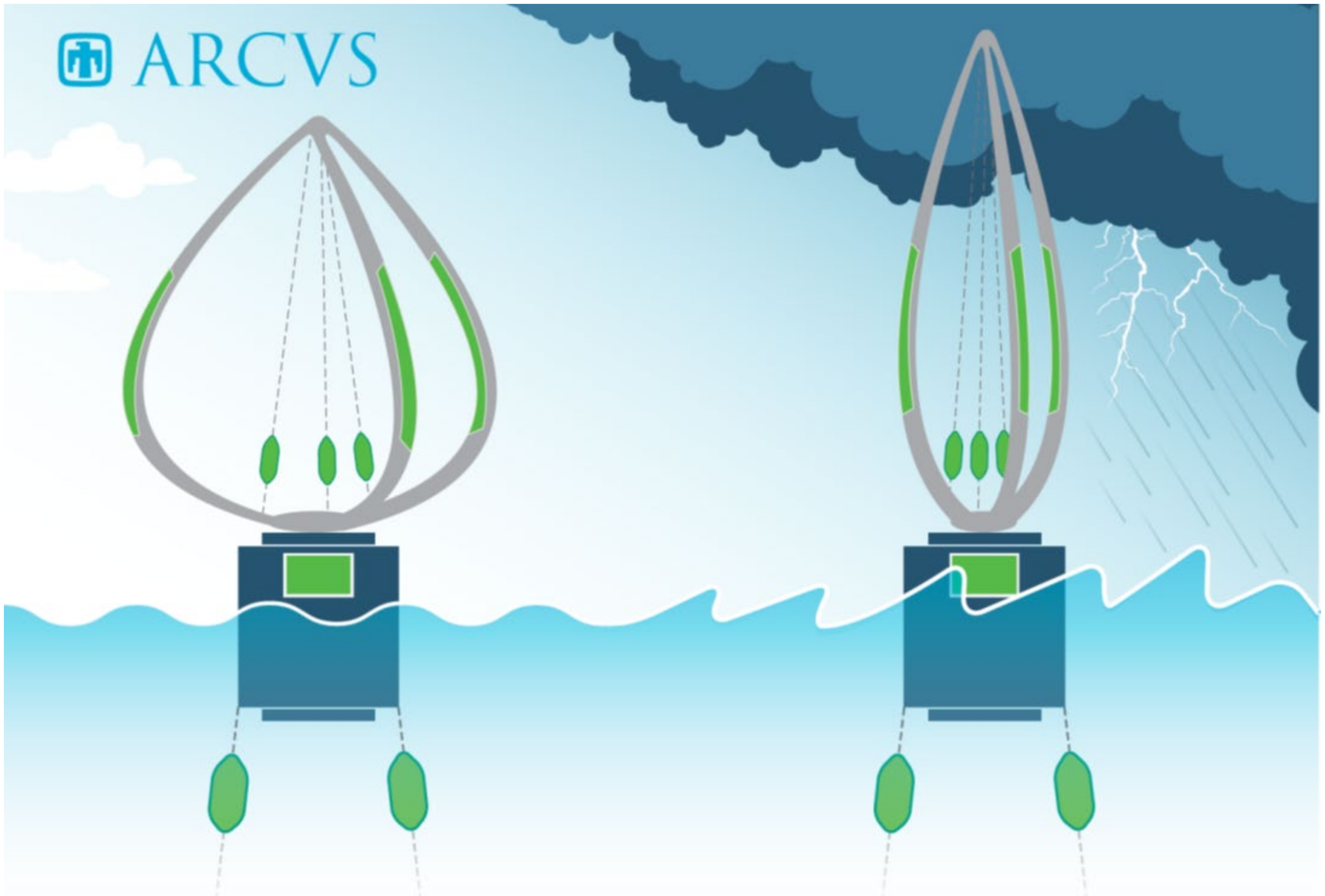
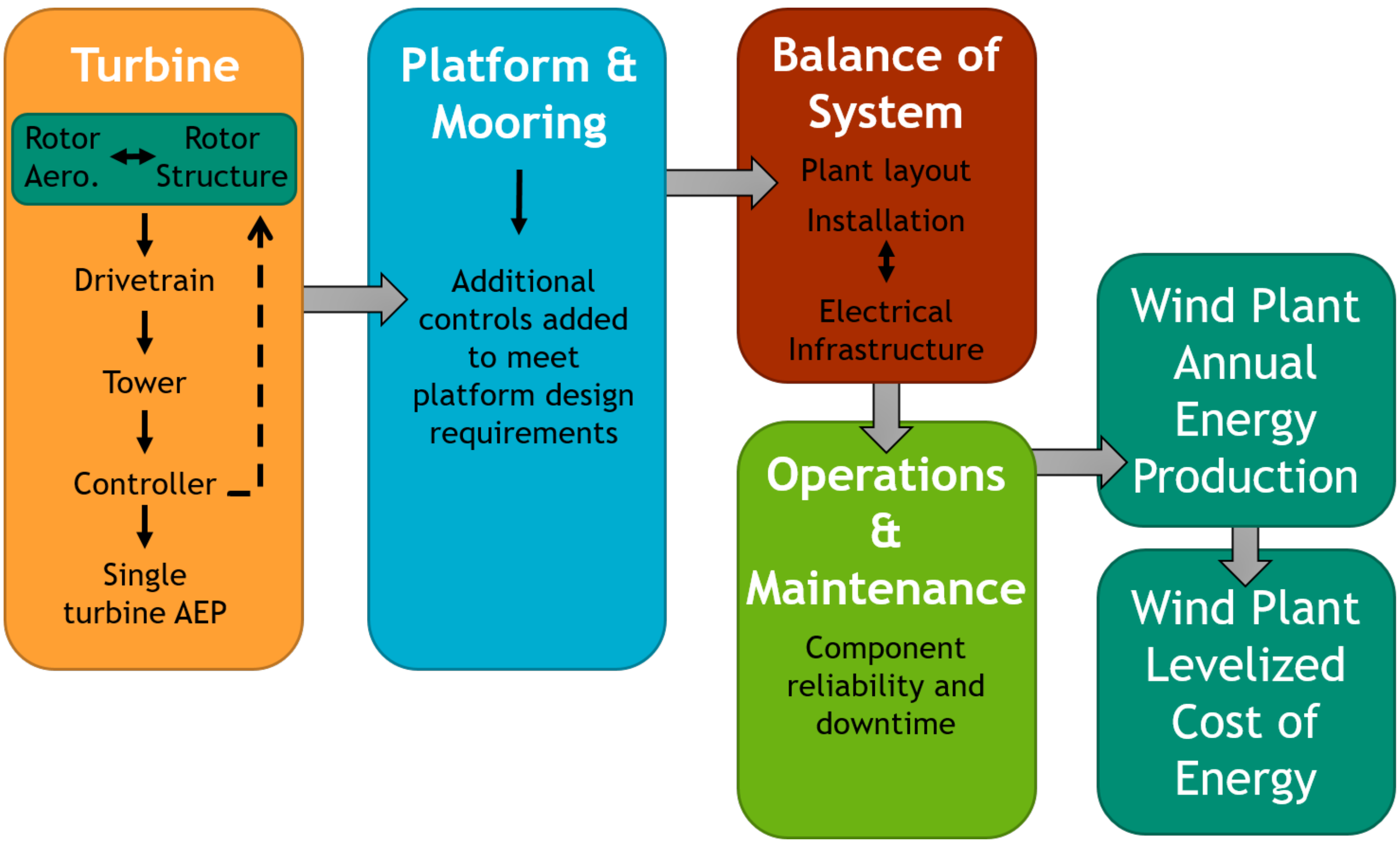


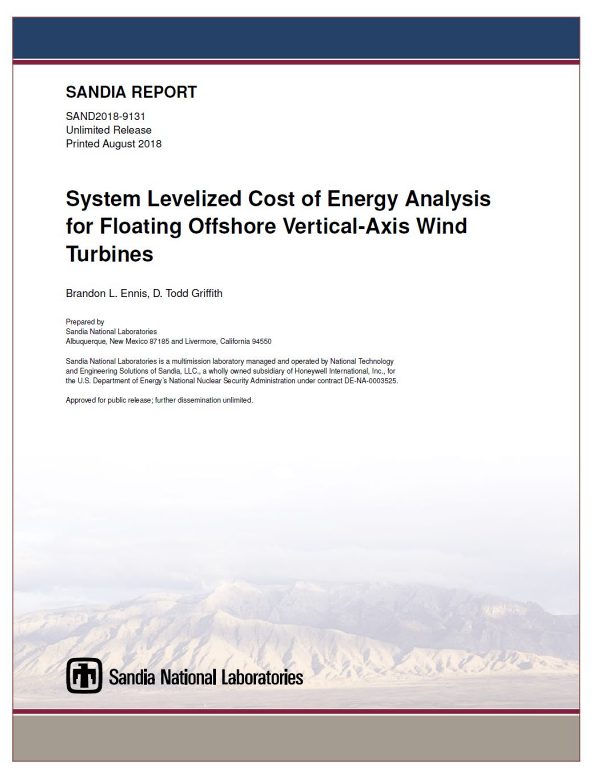
Traditional Offshore Wind System Design Process

How will we know using the traditional, de-coupled approach for design?

How will we know if we over-constrain our solution space, or if we don't try to gain understanding from the observed trends to consider new approaches?



The Sandia 5 MW floating offshore VAWT project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System Levelized Cost of Energy Analysis for Floating Offshore Vertical-Axis Wind Turbines

Brandon L. Ennis, D. Todd Griffith

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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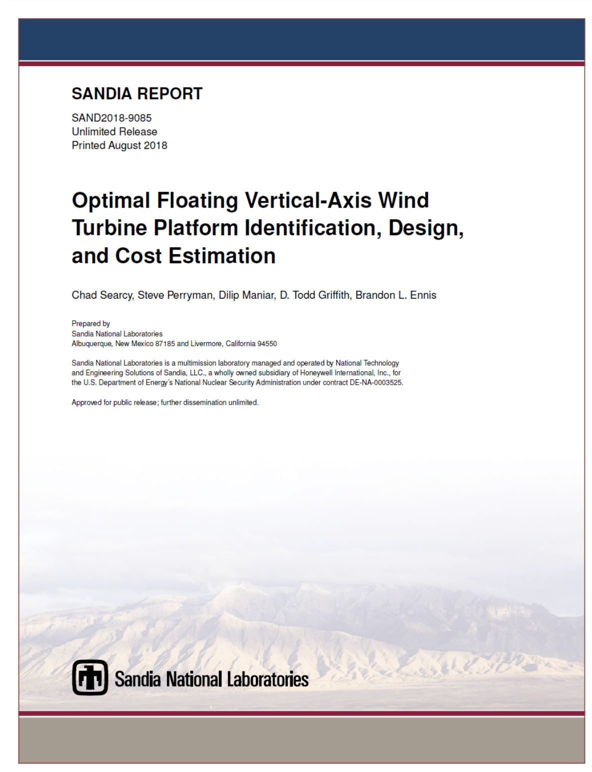
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Optimal Floating Vertical-Axis Wind Turbine Platform Identification, Design, and Cost Estimation

Chad Searcy, Steve Perryman, Dilip Maniar, D. Todd Griffith, Brandon L. Ennis

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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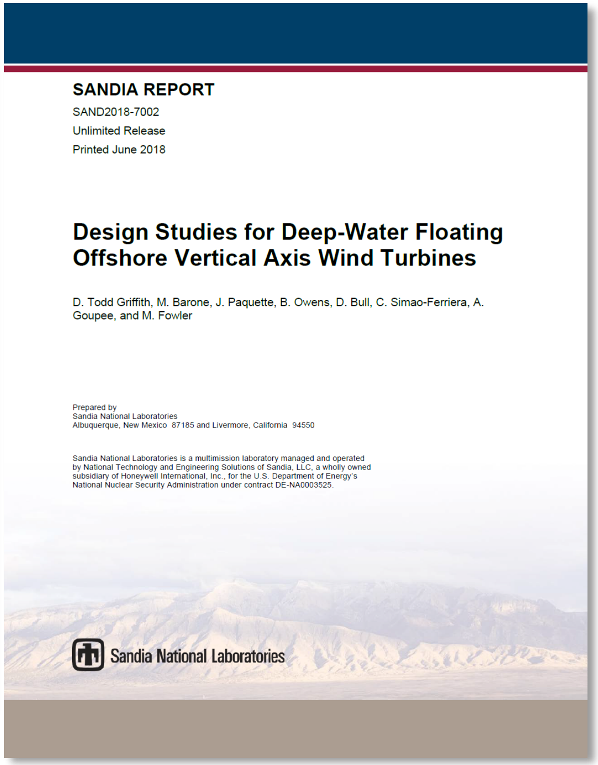
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Design Studies for Deep-Water Floating Offshore Vertical Axis Wind Turbines

D. Todd Griffith, M. Barone, J. Paquette, B. Owens, D. Bull, C. Simao-Ferriera, A. Goupee, and M. Fowler

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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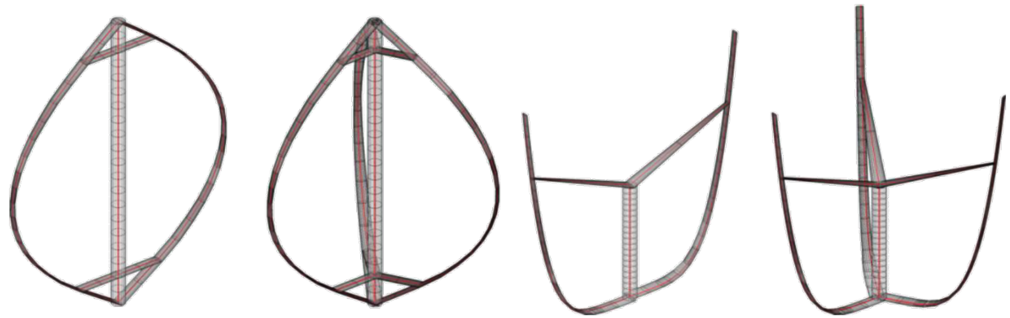
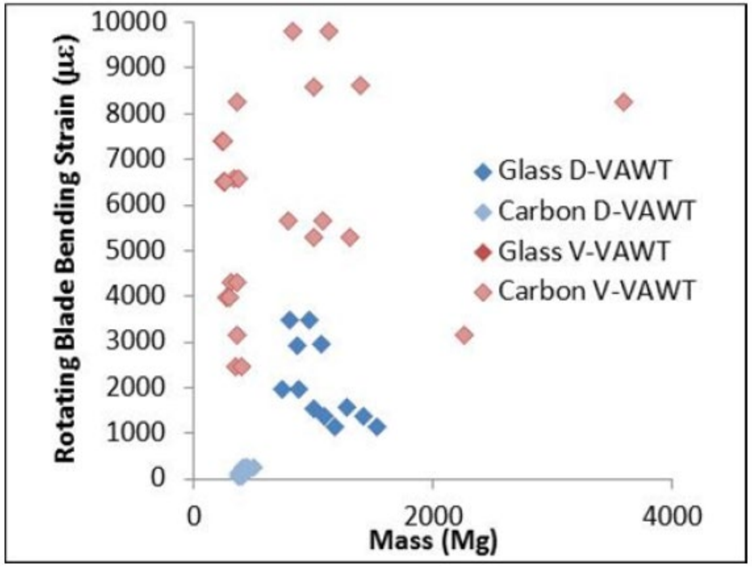
Vertical-Axis Wind Turbine Rotor Architecture Optimization

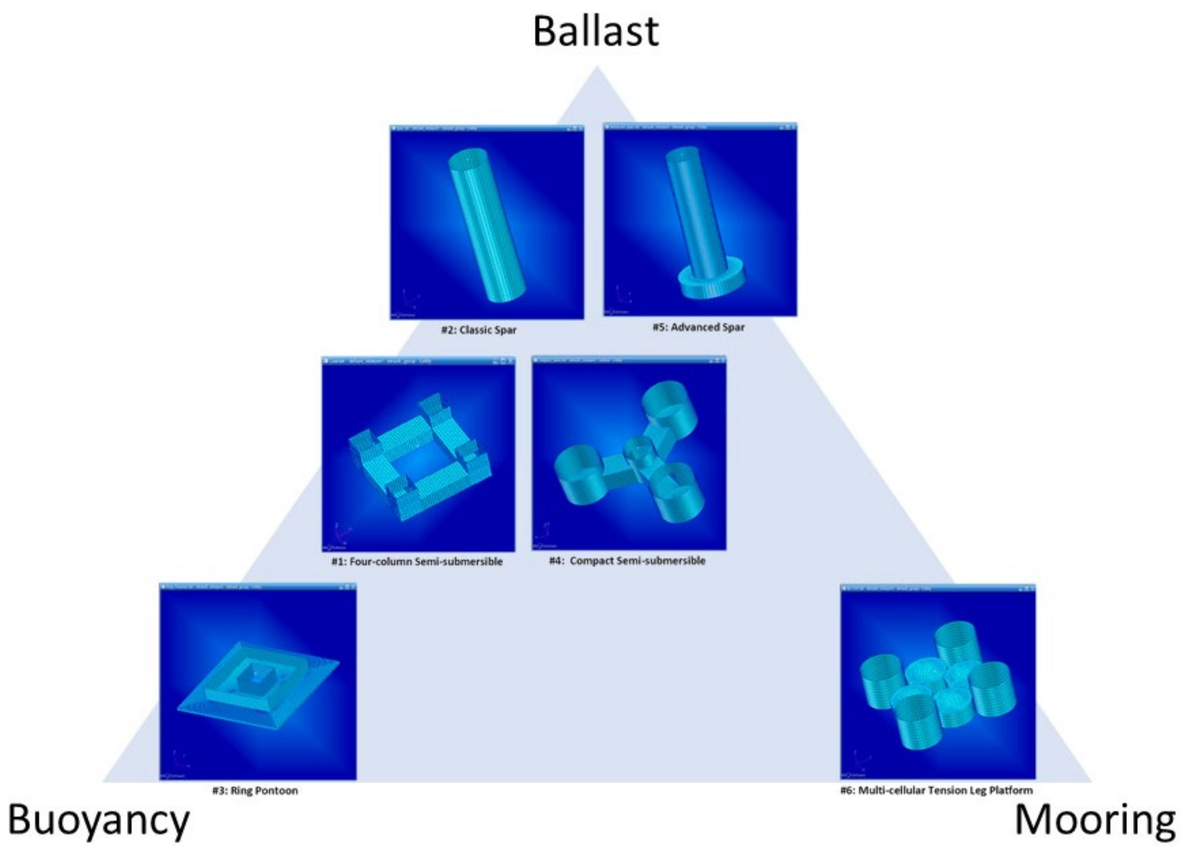
- The optimal VAWT rotor architecture was unknown at the beginning of the project
- Darrieus and V-VAWT architectures with exponents ranging from 'V' to 'U'-shaped rotors were studied with variable blade number and rotor solidity to compare designs
- The rotor with the greatest potential to reduce turbine-platform LCOE was determined to be the Darrieus design due to its lowest mass and cost, where loads are carried mostly axially as opposed to being carried through bending moment





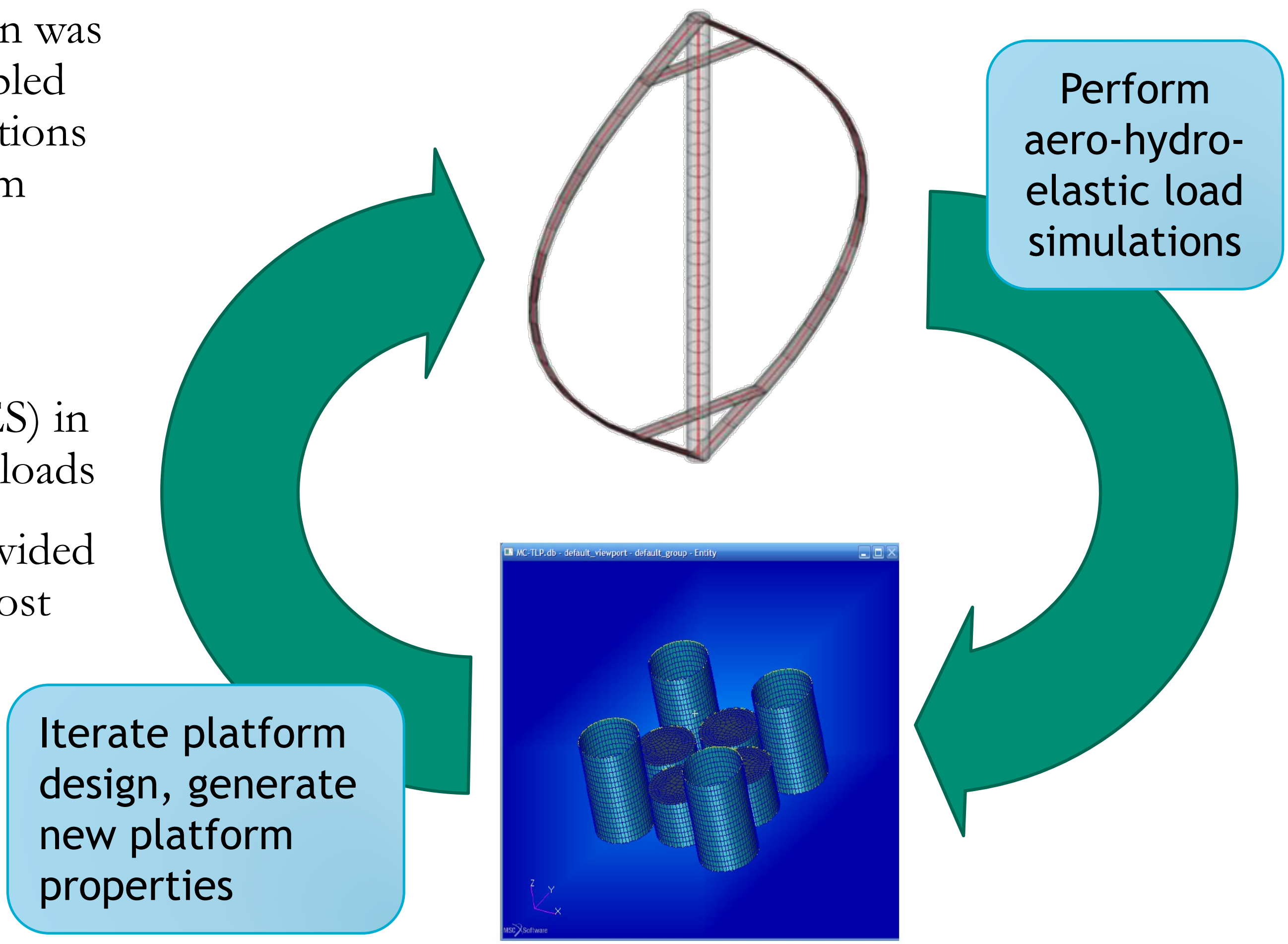
Optimal Platform Design Studies

- Floating platform design and analysis was performed to determine the optimal floating platform architecture for LCOE and performance
- 6 platforms covering the range of floating system stability mechanisms were studied and compared
- A tension-leg platform with multiple columns was the lowest cost option per Stress Engineering Services
- Performance benefits from the small roll/pitch motions include increased energy capture and reduced inertial loading on the turbine



Coupled Platform Design Iterations

- The final platform design was determined through coupled aero-hydro-elastic simulations of the VAWT-TLP system performed at Sandia
- The platform would be redesigned by Stress Engineering Services (SES) in response to the dynamic loads
- Cost estimates were provided by SES using industrial cost data

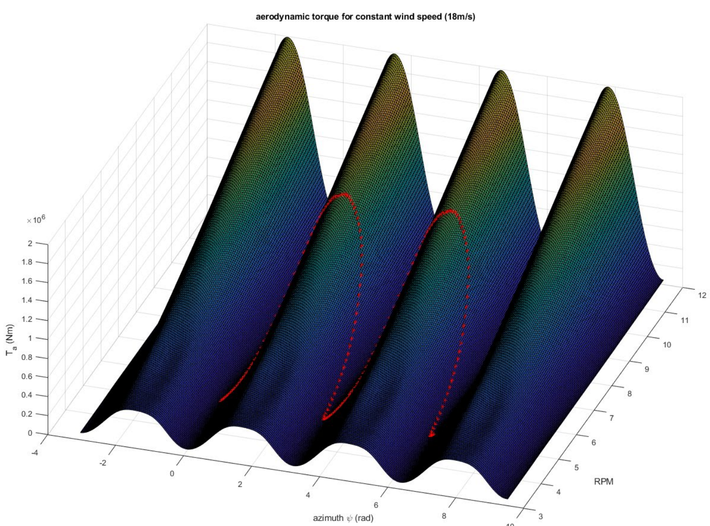


Dynamic Controls Optimization of the Coupled Models

Multibody dynamic model
(rotor-platform interaction)
$$\dot{x}_1 = f_1(x_1, x_2, x_3, u\ )$$

Hydrodynamic model
(water-body interaction)
$$\dot{x}_2 = f_2(x_2, x_1)$$

Aerodynamic model
(air-rotor interaction)
$$\dot{x}_3 = f_3(x_3, x_1)$$



Coupled dynamic model

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_1 \\ \dot{x}_1 \end{bmatrix} = \begin{bmatrix} f_1(x_1, x_2, x_3, u\ ) \\ f_2(x_2, x_1) \\ f_3(x_3, x_1) \end{bmatrix}$$

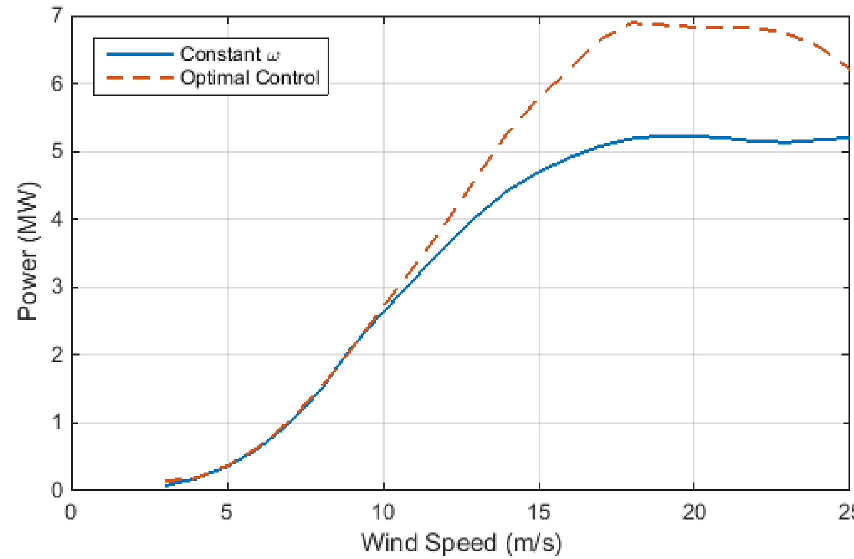
Objective:
Optimize the control input u to maximize power

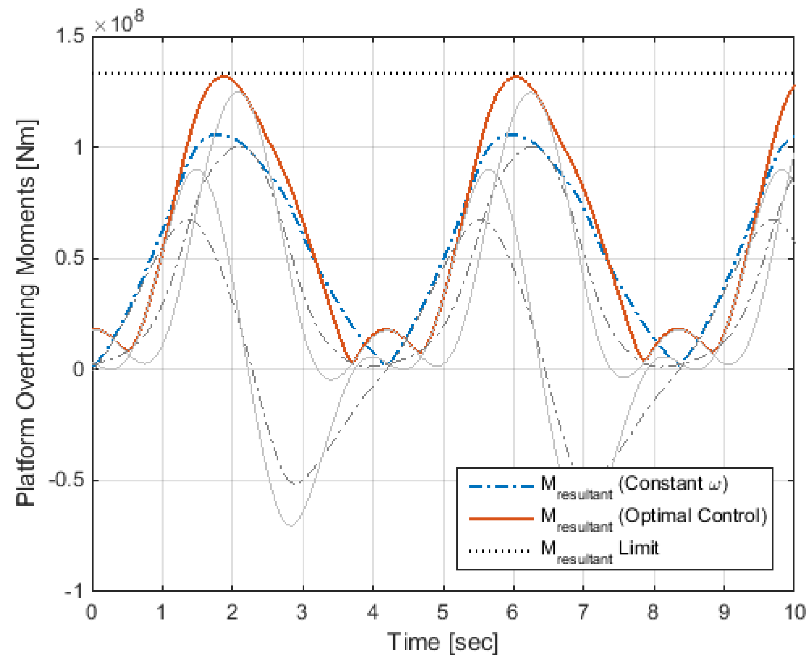
Constraints:
S.T. limitations in torque and RPM

Dynamic Controls Optimization of the Coupled Models

- The dynamic controls optimization routines were used to exploit design margin in the platform at low wind speeds
- Rotor torque and rotational speed were allowed to vary, subject to the maximum resultant roll/pitch overturning moment of the platform

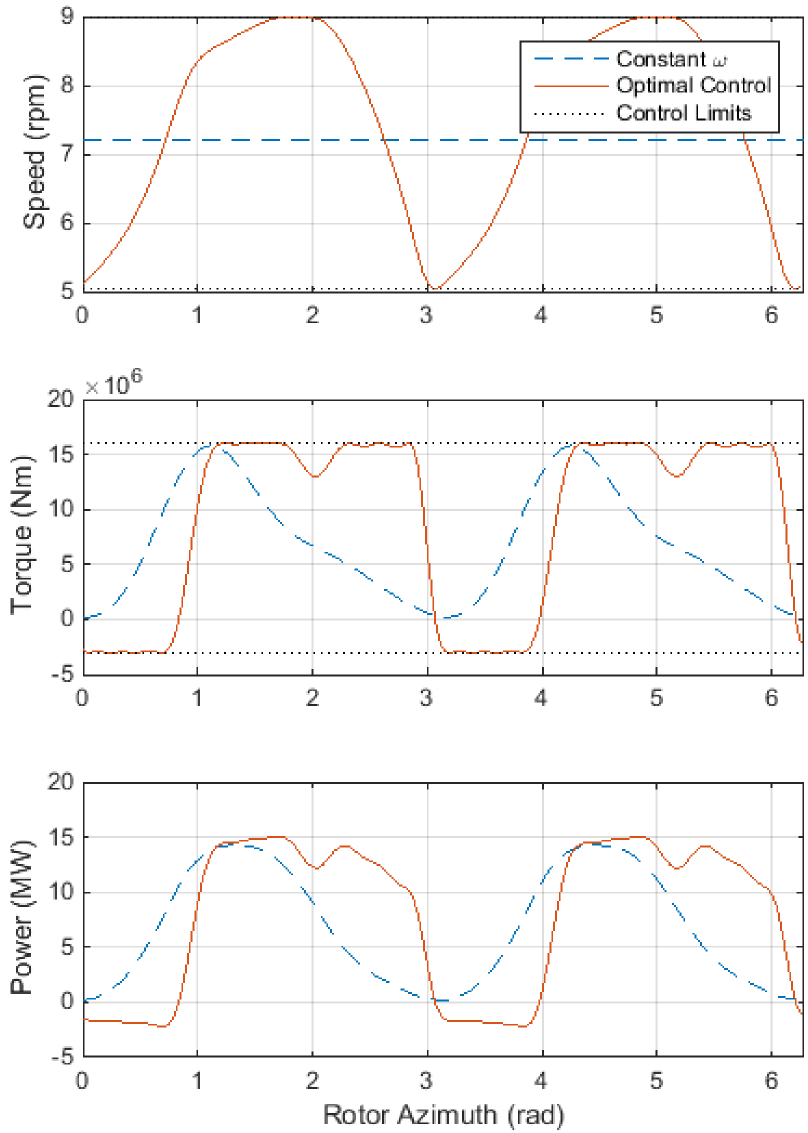
- The objective function results in a 16.1% increase in annual energy production over the typical constant rotational speed control strategy at a given wind speed for the VAWT





Dynamic Controls Optimization of the Coupled Models

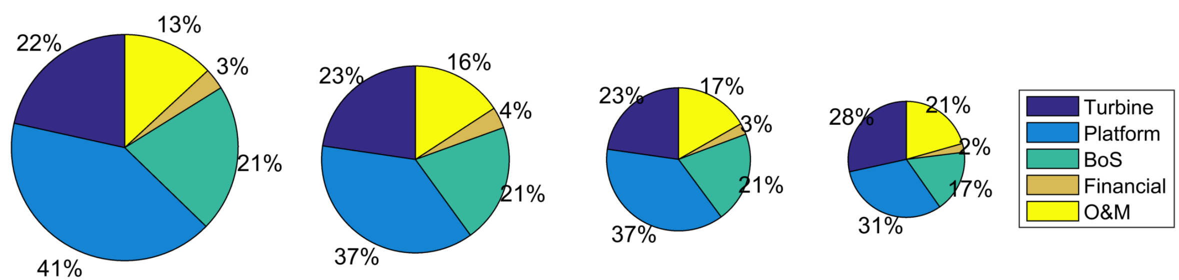
- The maximum energy production objective function optimized towards a bang-bang, or hysteresis, controller
- This results in larger torque variations, which would effect generator cost and mass
  - This operation could result in a very different electrical conversion mechanism than electrical generators
- As an alternative use case, the controls objective could be used to reduce the variation in loads which may have a larger system reduction on LCOE



Floating Offshore VAWT Levelized Cost of Energy Analysis

- Cost components were each estimated using the most trusted analysis and references available
- LCOE near-term value is most representative of current estimates, and is much higher than for land-based wind energy
- Technology advances to the platform, rotor structural design, and reductions in operations and maintenance reduce the LCOE to as low at $135/MWh
- The preferred design methodology considers all of the system design tradeoffs that affect the final performance and cost, where design decisions are all made in parallel and influence the design of other components

	Baseline LCOE	Upper-bound LCOE	Projected near-term LCOE	Project mid-term LCOE	Projected longer-term LCOE
AEP	Baseline	Baseline	16.1% increase from advanced controls	Advanced controls	47% increase in energy capture
Rotor costs	Baseline	Baseline	Rotor material optimization	Reduction from low-cost carbon fiber	78.2% increase in rotor cost
Platform and mooring	Most-likely value	Upper-bound estimate	13.6% reduction for optimal system platform	25% reduction for mid-term optimization	Mid-term optimization
Installation	Most-likely value	Upper-bound estimate	15.3% reduction for the improved installation procedure	25% reduction for mid-term optimization	Mid-term optimization
O&M direct costs	Baseline	Baseline	Baseline	19% reduction by eliminating jack-up vessel charters	Elimination of jack-up vessel charters
Levelized cost of energy (USD/MWh)	274	323	213	176 (FCR=10.3%) 135 (FCR=7.9%)	110 (FCR=7.9%)



LCOE = $213/MWh LCOE = $176/MWh LCOE = $135/MWh LCOE = $110/MWh

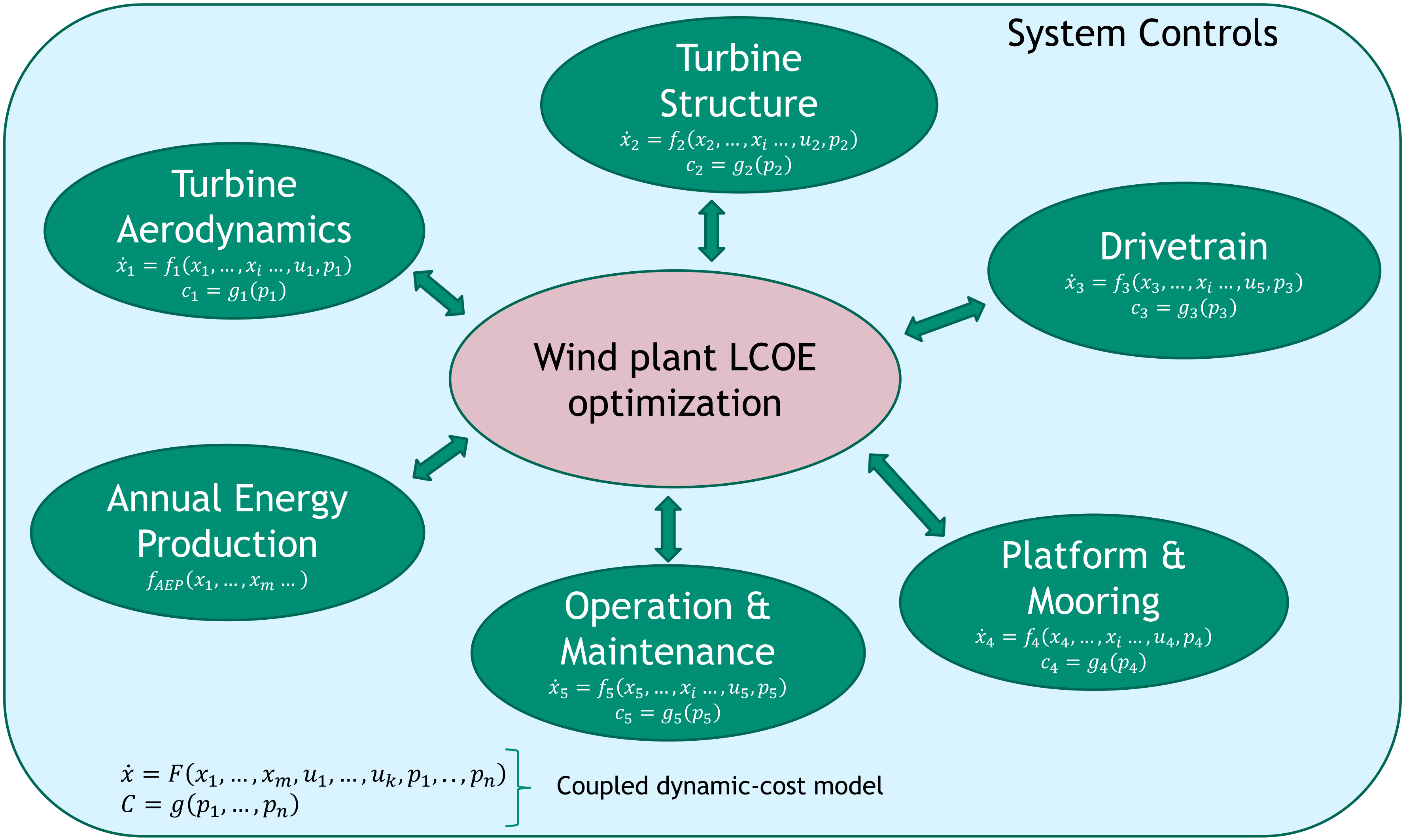
Component Design and System Tradeoffs

The components of a floating offshore wind system do not operate independently, and they should not be designed independently.

Some example relationships between the component designs include:

System component	Design Decision	System Implications
Wind turbine rotor	Decrease rotor mass	▪ Increases rotor cost (using carbon fiber) ▪ Reduces platform costs with lower turbine-drivetrain center of gravity and mass moments of inertia
Drivetrain	Use a high efficiency generator	▪ Increase AEP, which divides entire annual expenses in LCOE calculation ▪ Increase cost and mass of drivetrain ▪ Likely results in platform cost increase
Floating platform	Platform architecture selection	▪ Design architecture selected will result in larger or smaller motions ▪ Platform motions can result in significant inertial loads added to the turbine tower and blades ▪ If the platform is unstable in high winds it will require additional control, reducing reliability and AEP
Turbine controls	Optimize for power	▪ Increases AEP, divides full annual expenses ▪ Increases variation in loads, could result in mooring or drive bearing fatigue concerns
Turbine reliability	Over-design system to account for probabilistic failures of components	▪ Increases turbine and drivetrain costs ▪ Results in a more reliable turbine, which reduces operations and maintenance costs and downtime

System Optimal Co-Design Process



Optimal design $(p_1, \ldots, p_n)^*: \ \underset{(p_1,\ldots,p_n)}{\arg\min}\, LCOE$

$f_i(\ldots)$: dynamic model of i-th subsystem
$g_i(p_i)$: cost model of i-th subsystem, as function of the set of parameters p_i