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Moving Toward Cost-Competitive, Commercial Floating Wind Energy

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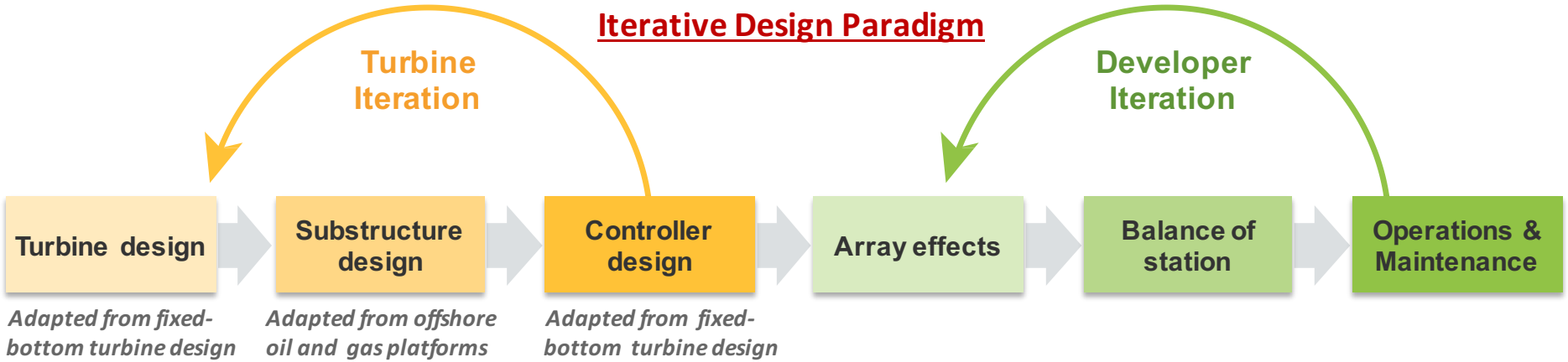
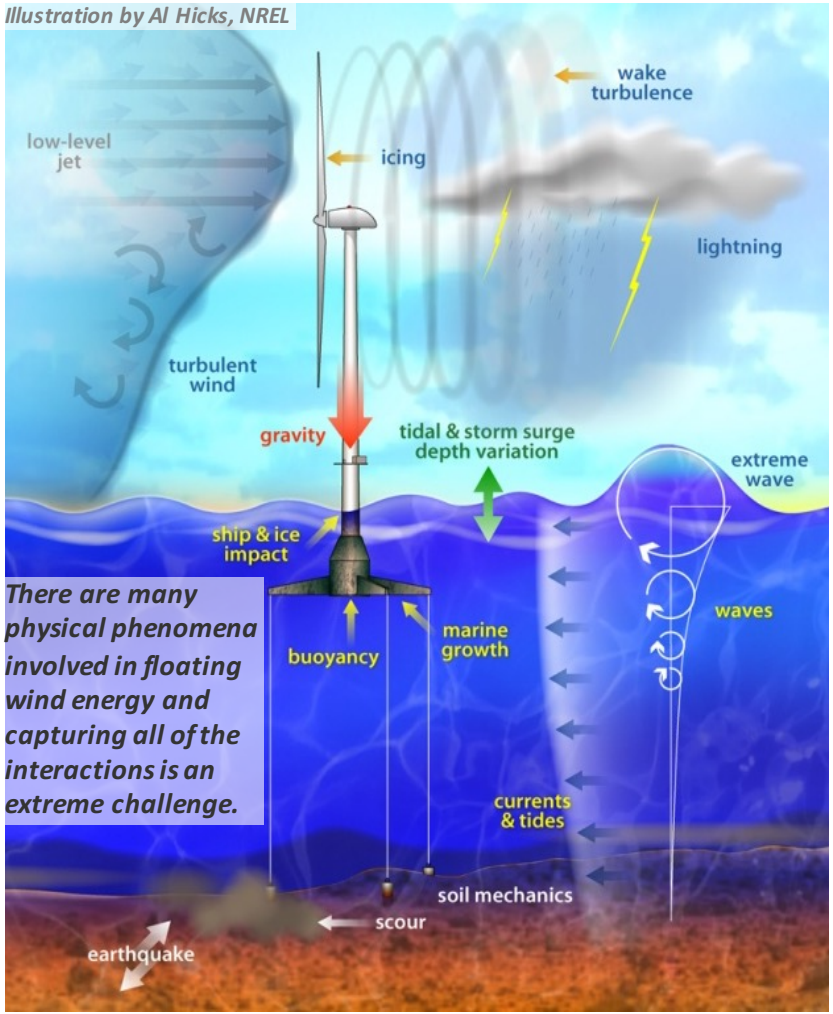
Current offshore turbine design is more "Iterative" than "Integrated" because of market realities

- **Iterative design approach is a byproduct of industry expertise, power purchase agreements, and financing agreements**
  - Companies need to leverage their expertise and protect their intellectual property
- **Growth of wind industry over the past 20 years is a testament to the success of the "Iterative" approach**
- **Floating wind turbines can be designed in this paradigm, but they will be more costly than necessary.**

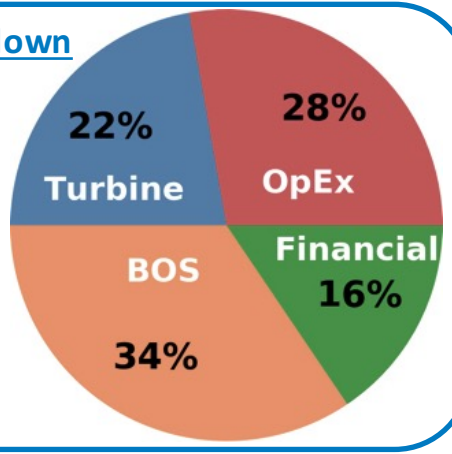


Physical and economic complexities make the floating challenge well-suited to system-focused solutions



Floating Wind LCOE Breakdown

Source: Mone et al. (2017)



78% of LCOE does not come from the turbine (but is impacted by its design)
****BOS: balance of station***

Given the complexity of:

- **Physics** – aerodynamic and hydrodynamic loading on a compliant structure
- **Logistics** – manufacturing, operational expenditures (OpEx), installation, and assembly
- **Economics** – over 50 types of costs are impacted.

A multidisciplinary, systems-focused approach is needed!

MDAO allows for linking engineering design decisions to the LCOE balance sheet, but will require tool and expertise development

MDAO Framework

- **Union of all disciplines and costs into a single simulation framework**
  - Enables optimization and tradespace exploration

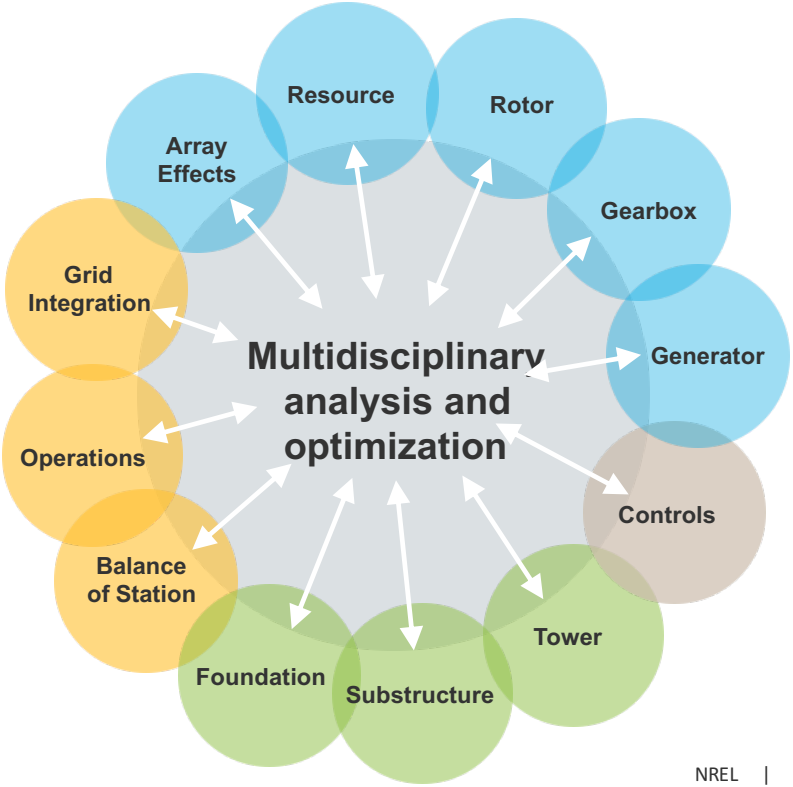
MDAO Benefits and Output

- **Accelerates engineer's exploration of the tradespace and discovery of hybrid innovations**
- **Prior expertise is essential to achieve credible objectives**
  - Optimization does not replace the engineer!

Floating Wind MDAO Tool Requirements

- **Integrated design: Design systems holistically, considering the turbine, tower, controller, and floater as one integrated system**
- **Lifetime cost accounting: Consider cost impact of all factors including manufacturing, installation, operation, maintenance, and decommissioning.**

Integrated paradigm: Multidisciplinary analysis and optimization (MDAO)

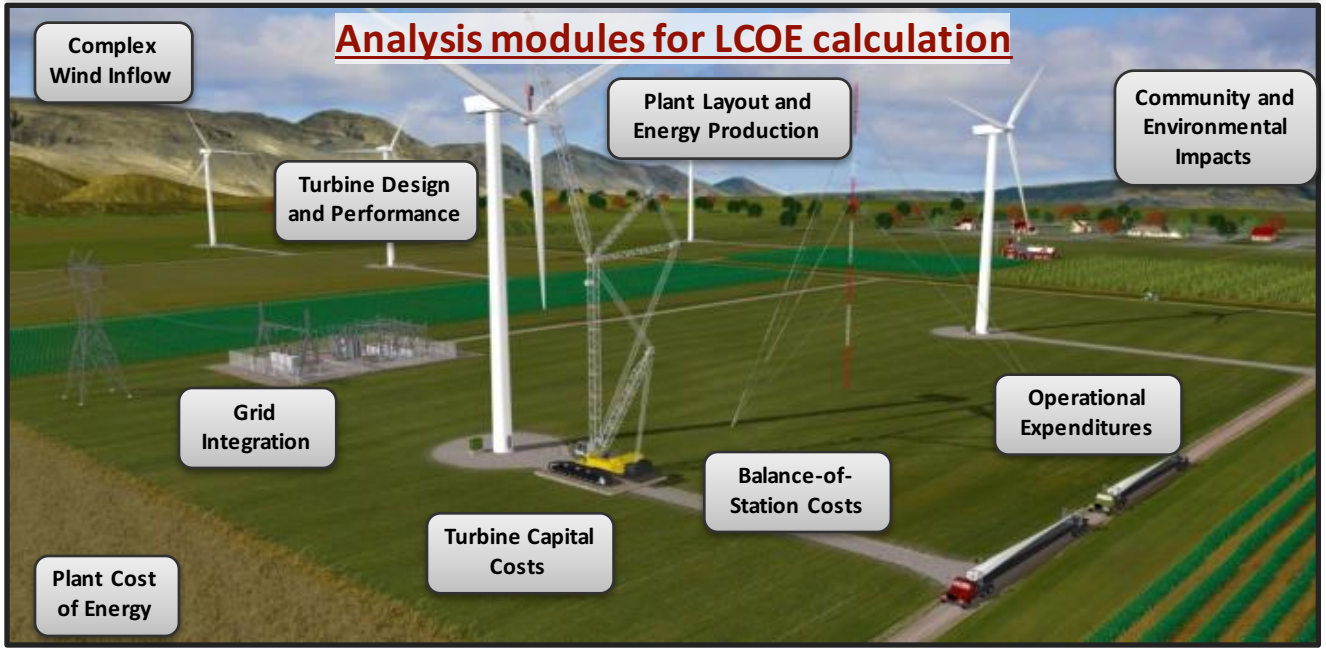


Optimization objective is LCOE, the full lifecycle cost of the whole plant, to (try to) capture the entire value chain

- **Capture the entire lifecycle cost in LCOE**
  - CapEx is the capital expenditures (sum of balance-of-station and turbine capital cost)
  - OpEx are the annual operational expenditures
  - FCR is the fixed charge rate to annualize CapEx
  - AEP is the net annual energy production
- **LCOE isn't perfect**
  - Only captures costs, not revenue
  - Would like to capture the "value chain" for the developer.

Optimization Objective

$$LCOE = \frac{FCR * (CAPEX) + OPEX}{AEP}$$



Optimization will help mix and match "Building Blocks" together and refine parameters to create viable designs

Building Block: An architecture, design feature, or technology that can be combined together to form a wind energy system

Partial List of Building Blocks

Turbine
- Two/three blades
- Up/downwind
- Horizontal and vertical-axis turbines
- Multirotor
- Controls

Platform
- Ballast
- # of columns
- Plates
- Ship shaped
- Pontoons
- Multiple turbines

Mooring
- Catenary
- Taut
- Fiber/rope
- Turret

Anchors
- Drag
- Suction
- Torpedo
- Gravity

Tower
- Steel
- Concrete
- Composite

Drivetrain
- One/multistage gearbox
- Direct drive
- Superconducting
- Hydraulic

Assembly
- Quayside/on-site
- Crane selection

Electrical
- Array cable voltage
- Substation technology
- Grid interconnection

Operation and Maintenance (O&M)
- Vessel selection
- Quayside/on-site

Plant
- Controls
- Layout
- Anchors
- DC interconnects

Candidate System Sampled from Building Blocks

Turbine Building Block → Three-bladed, downwind rotor; Direct drive

Drivetrain Building Block →

Tower Building Block → Composite tower

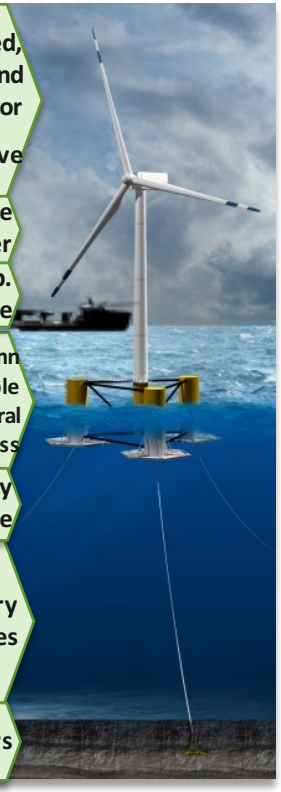
O&M Building Block → Service op. vehicle

Platform Building Block → Three-column semisubmersible with central turbine and truss

Electrical Building Block → 66-kV array cable

Mooring Building Block → Three catenary mooring lines

Anchor Building Block → Drag anchors



System Optimization

- Iterate on design variables
- Minimize objective (LCOE)
- Apply constraints
- Assign LCOE "score" to building block combination
- Repeat.

Rotor Building Blocks: Two blades would have system benefits down through the substructure as well as O&M advantages

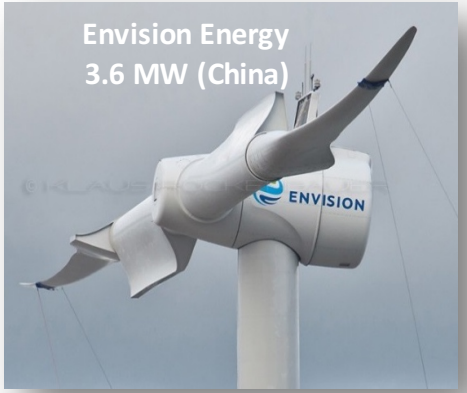
Pros

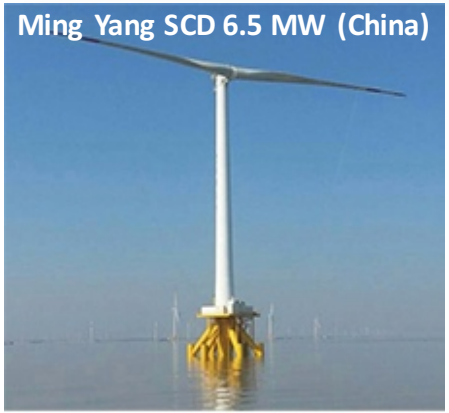
- **Lighter rotor nacelle assembly means lighter substructure, lower material cost**
  - Lighter rotor (20%–25%)
  - Higher tip speeds mean lower torque, lighter drivetrains
- **More resiliency to high sea states**
- **Installation and O&M advantages**
  - Rotor assembly on ground
  - Easier compliance with height-limited transport (e.g., bridge underpass, Federal Aviation Administration regulations, and so on)
  - Easy helipad access

Cons

- **Less solidity means larger chords, heavier single blades**
- **Greater dynamic imbalance requires a teeter or independent pitch controller**
- **Higher tip speed means:**
  - Higher loads on some components
  - Noise concerns.

Source: Rick Damiani, NREL





Taking assembly into account in the design

Small draft allows for:

- Wide port availability
- Quayside assembly that minimizes costly specialized vessel and labor hours at sea
- Usage of land-based crawler cranes (cheapest option).

Off-center turbine alleviates crane boom and loading requirements

Taking transport and installation into account in the design

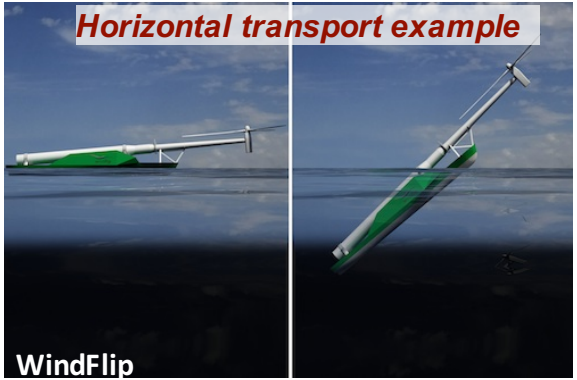
Turbine and Platform

- **Compliance with common port facilities**
- **Towable designs eliminate need for customized vessels**
  - Some designs have different towed and operational configurations (e.g., TetraSpar)
- **Horizontal transport of turbines would open up new solutions as well**
  - Have to design drivetrain and bearings for this load case

Mooring and Anchors

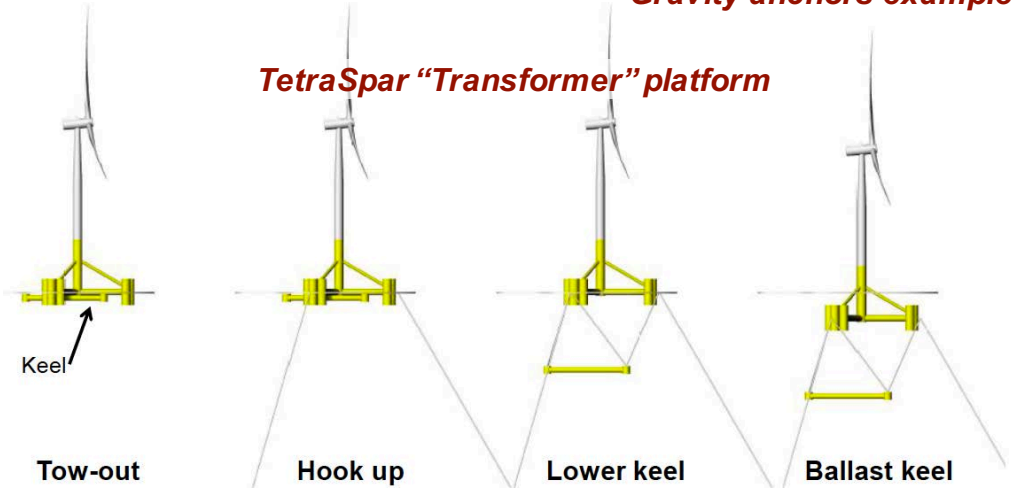
- **DNV-GL: Built-in support for winches simplifies mooring line tensioning (also, may be eliminating need for specialized vessels)**
- **Gravity anchors simplify anchor installation and mooring line connection**
- **As turbine size grows, may need new mooring architectures or materials for manufacturing and vessel compliance.**

Horizontal transport example



Gravity anchors example

TetraSpar "Transformer" platform



Source: Stiesdal Offshore Technology A/S

Thank You!

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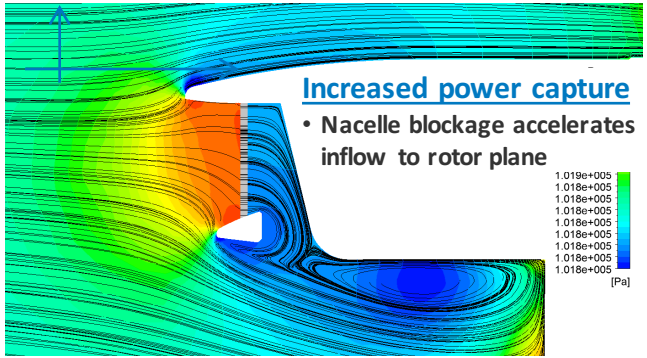
Rotor Building Blocks: Downwind rotors have system-level benefits

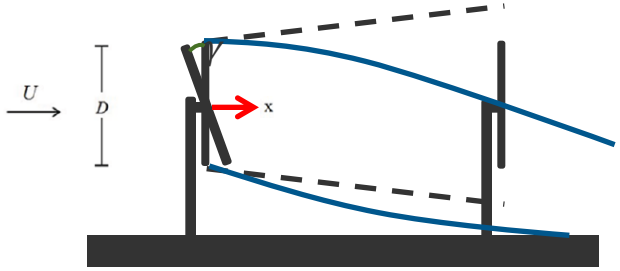


Increased power capture

- Nacelle blockage accelerates inflow to rotor plane

Wind plant flow control

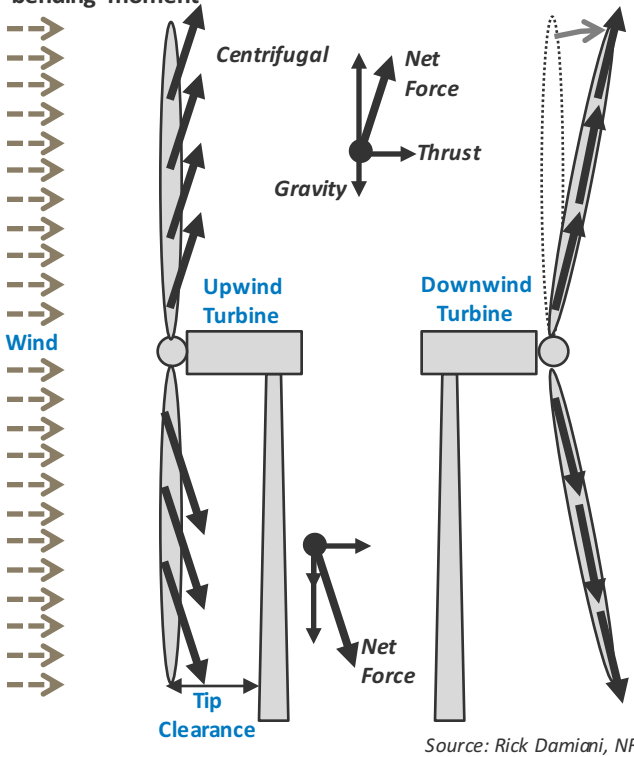
- Wake steering with tilt may be more effective than yaw
- Upwind turbines cannot tilt due to tower strike
- Has not been explored on floating platform yet



Source: Annoni et al. (2017)

Lighter, flexible blades

- Upwind blades must be stiff to prevent tower strike
- Downwind blades can be lighter and allowed to flex
- May even align with the net force vector, eliminating bending moment

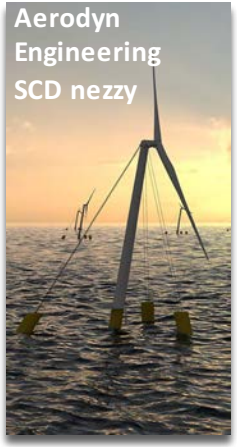


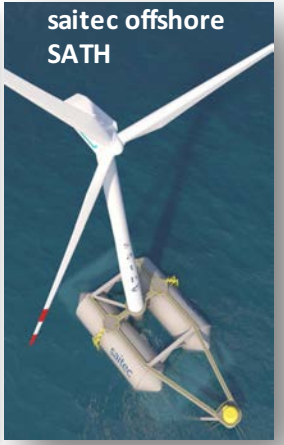
Source: Rick Damiani, NREL

Semipassive yaw

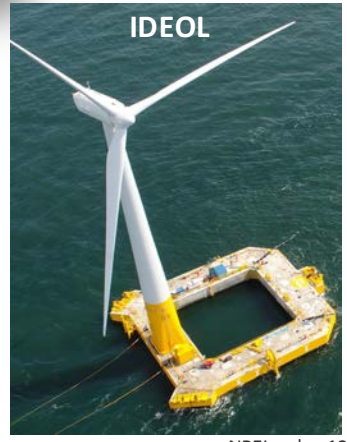
- Weather-vane-like dynamics increases yaw stability
- Relaxes demands on yaw motor and control system
- Has not been proven yet.

In the "Wild West" of alternative floating substructure ideas, there is no clear winner (yet), but many promising ideas





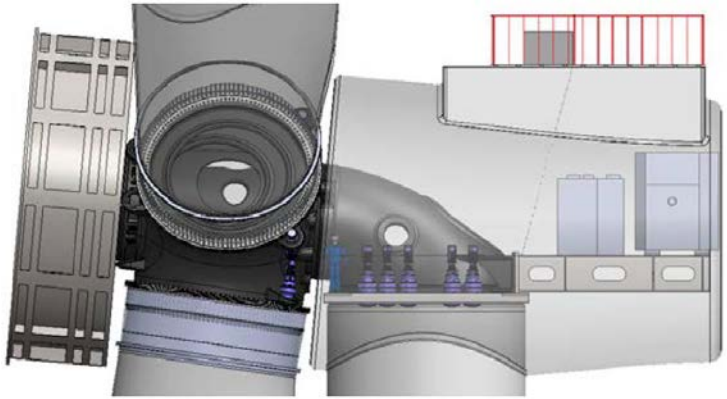
Many of these designs combine elements from the three archetypes to compound the "pros" and reduce the "cons."



Taking operation and maintenance into account in the design

- **Heavy maintenance will still be required over the lifetime of a floating turbine, for example:**
  - DNV-GL: At least 1–2 events over a 20- to 25-year lifetime
- **Quayside maintenance strategy (for major events) design requirements include:**
  - A towable platform design
  - Electrical and mooring lines designed for easy disconnection
  - Plant cabling designed to continue power production from other turbines in string
- **In-situ repair strategy design requirements include:**
  - Plant cabling designed to continue power production from other turbines in string
  - Tower design that supports self-climbing cranes to simplify marine operations and vessel requirements
- **INNWIND project proposed a front-mounted generator to simplify the more labor-intensive drivetrain maintenance operations.**

Source: Lagerwey https://www.lagerwey.com/blog/2017/08/30/lagerwey-test-climbing-crane-eemshaven

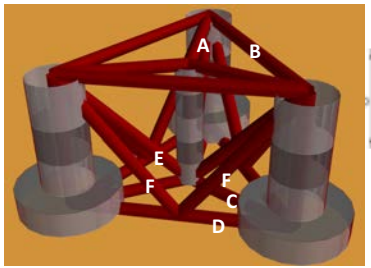


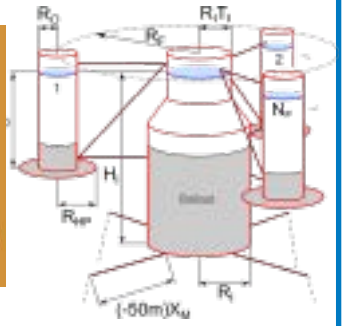
Source: Asger et al. (2017)

Existing work in literature gives an example of how this might be done for the substructure

Parameterize platform geometry

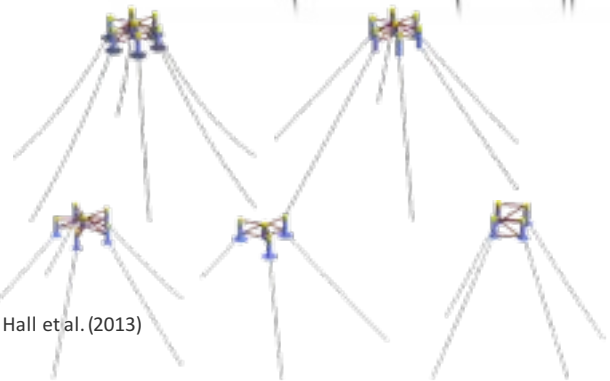
- Position of platform in water
- Number of columns and their spacing
- Diameter, wall thickness for each column
- Supporting internal stiffeners
- Ballast properties
- Connecting truss members
- Number of mooring lines
- Mooring line length, diameter

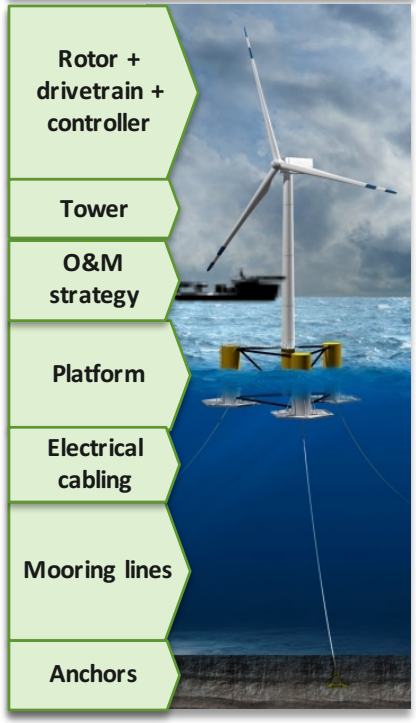




Optimize over candidate geometries

- Heuristic algorithm to respect multiple local minima
- Mixed-integer support for geometry parameterization



Source: Hall et al. (2013)

Couple with full turbine engineering and plant economics for greatest benefit!