CHANGING WHAT'S POSSIBLE

ATLANTIS

Industry Day

ENVISIONED NEW PROGRAM

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U.S. Department of Energy

Alexandria VA, January 15th, 2019

ATLANTIS = acronym for "***A**erodynamic **T**urbines, **L**ighter and **A**float, with **N**autical **T**echnologies and **I**ntegrated **S**ervo-control*".

The Greek philosopher Plato (428-348 BC) cited Atlantis in his dialogues as the lost continent of the ancient times that disappeared in the depths of the sea.

Outline

1.- Envisioned Program Summary

2.- Approach: Control Co-Design

3.- Floating offshore wind energy

- Sub-system interaction
- Potential/Impact
- Current developments

4.- Foundational elements

- New designs
- Computer tools
- Experiments

5.- Potential Program Structure

- Coordination, schedule
- Multidisciplinary collaboration

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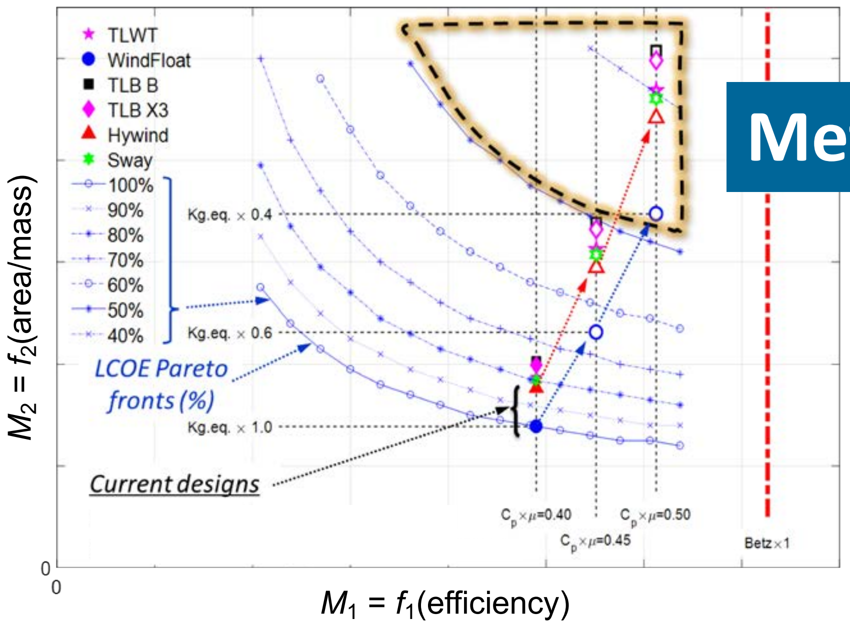
Courtesy Repower, 5M offshore wind turbine

1. Envisioned program summary

Objective → Create pathway for economically competitive **Floating Offshore Wind Turbines (FOWT)**

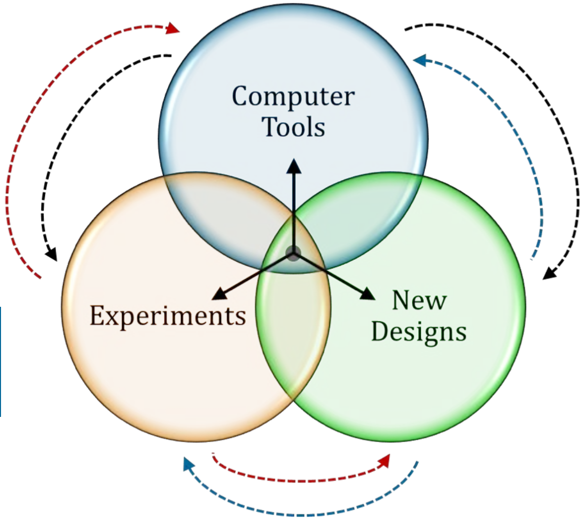
Approach → Design philosophy - **Control Co-Design (CCD)**



Metric Space

$$M_1 = f_1(\text{efficiency})$$

$$M_2 = f_2\left(\frac{\text{area}}{\text{mass}}\right)$$

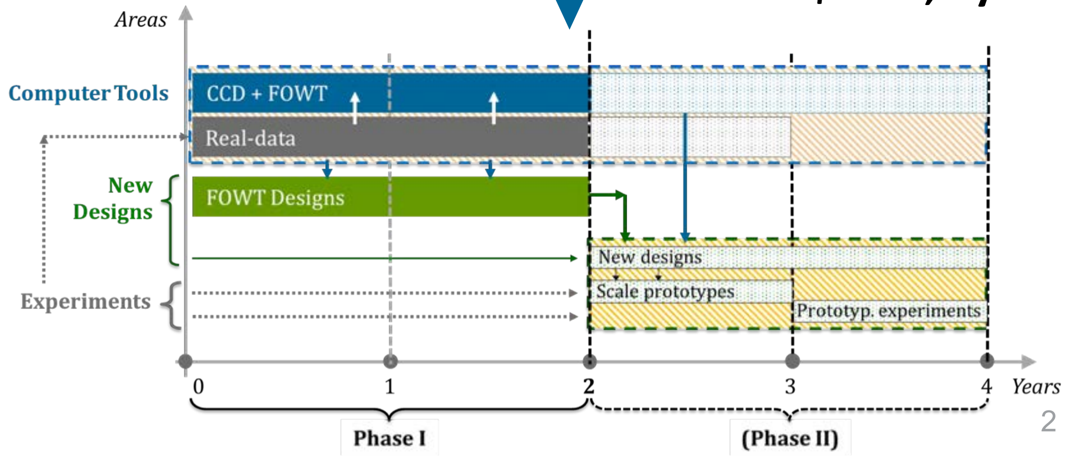


Technical Thrusts

1. Radically **New Designs**
2. Enhanced **Computer Tools**
3. Physical **Experiments**

Program Structure

Phase I: $28M, 2yr



2. Approach: Control Co-Design

Sequential

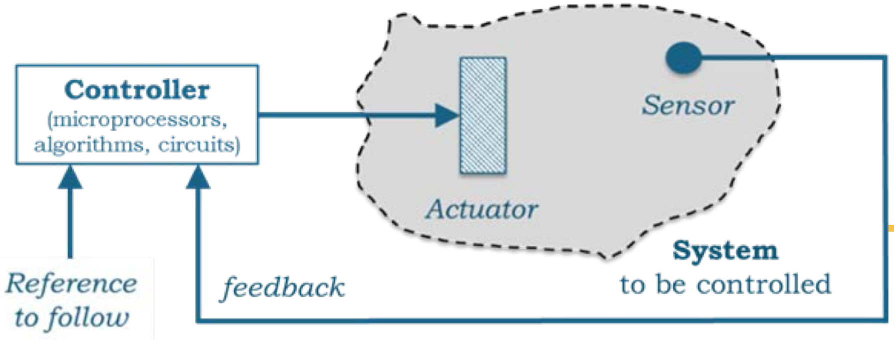
Each step limits the next one

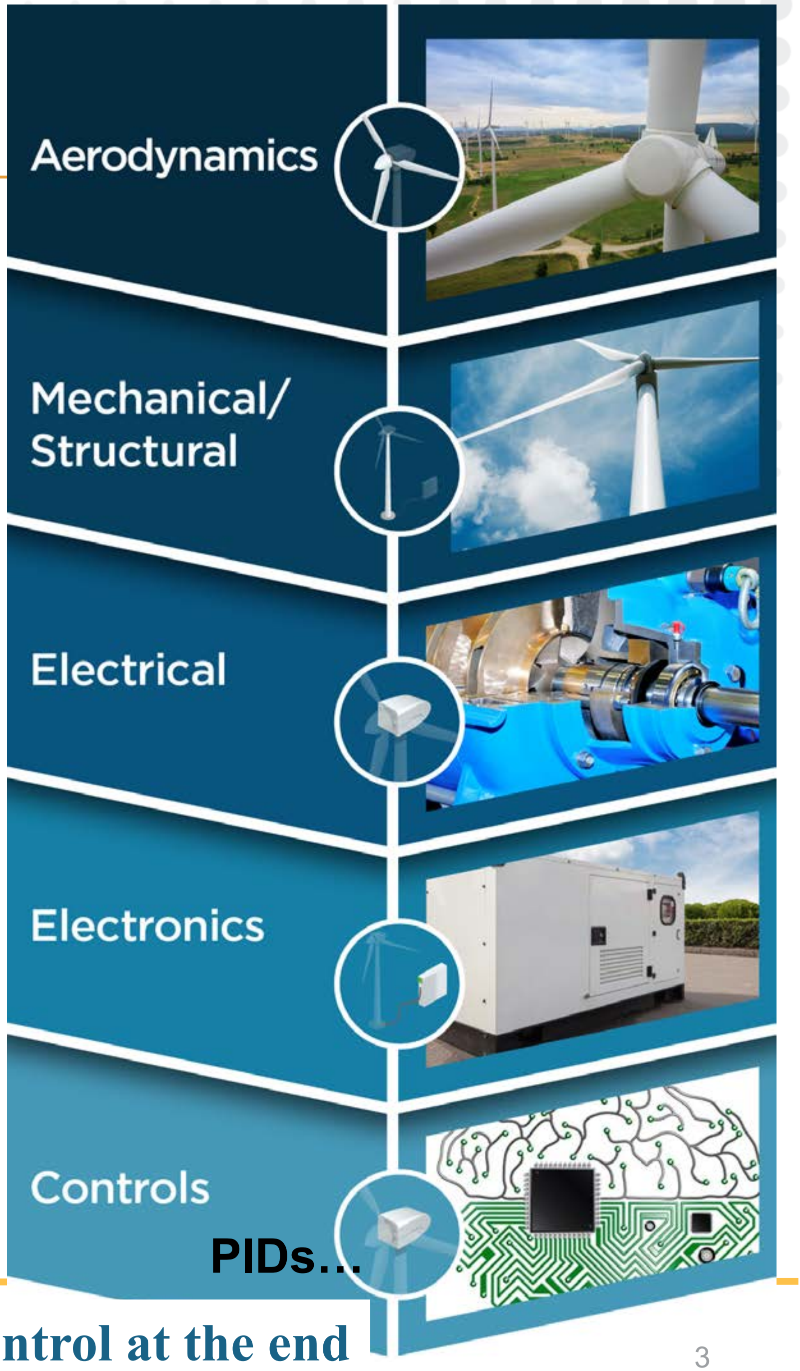
- The increasing **complexity** of technology has changed the way we study engineering.
  Engineering **careers** are now much more **specialized**.

- New **engineers**: - have a deeper knowledge of some aspects
  - at the cost of a much **narrower picture!!**

- Consequences:
  - **Sequential way of working** in industry
  - **Control** = algorithms/circuits to regulate **existing systems**

- This sequential approach **limits** the **possibilities** of the design.





Control at the end

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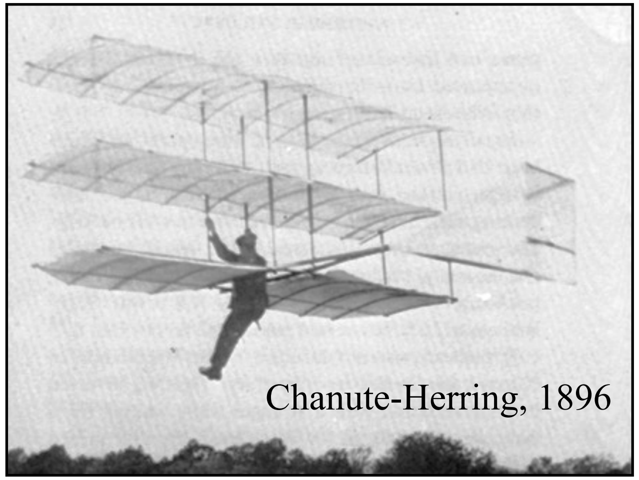
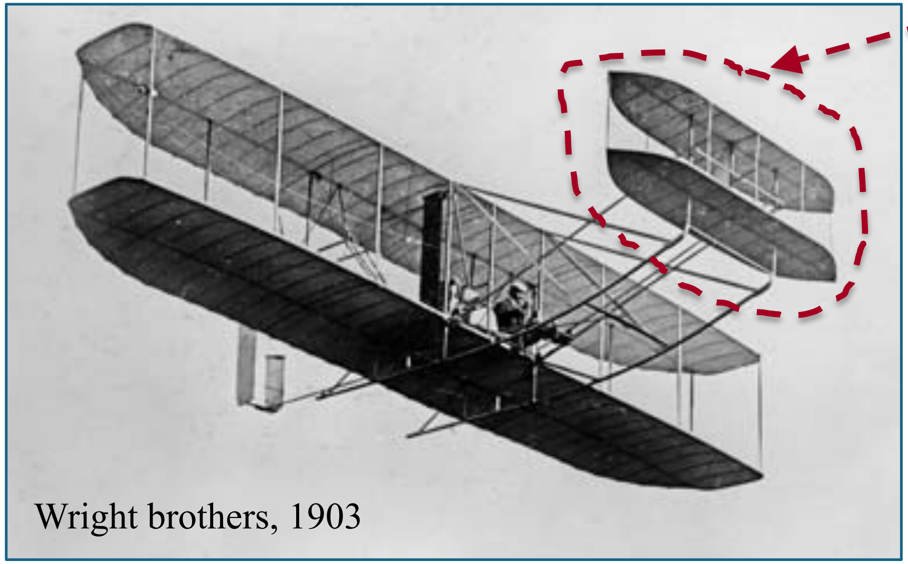
Control Co-Design: *Concurrent*



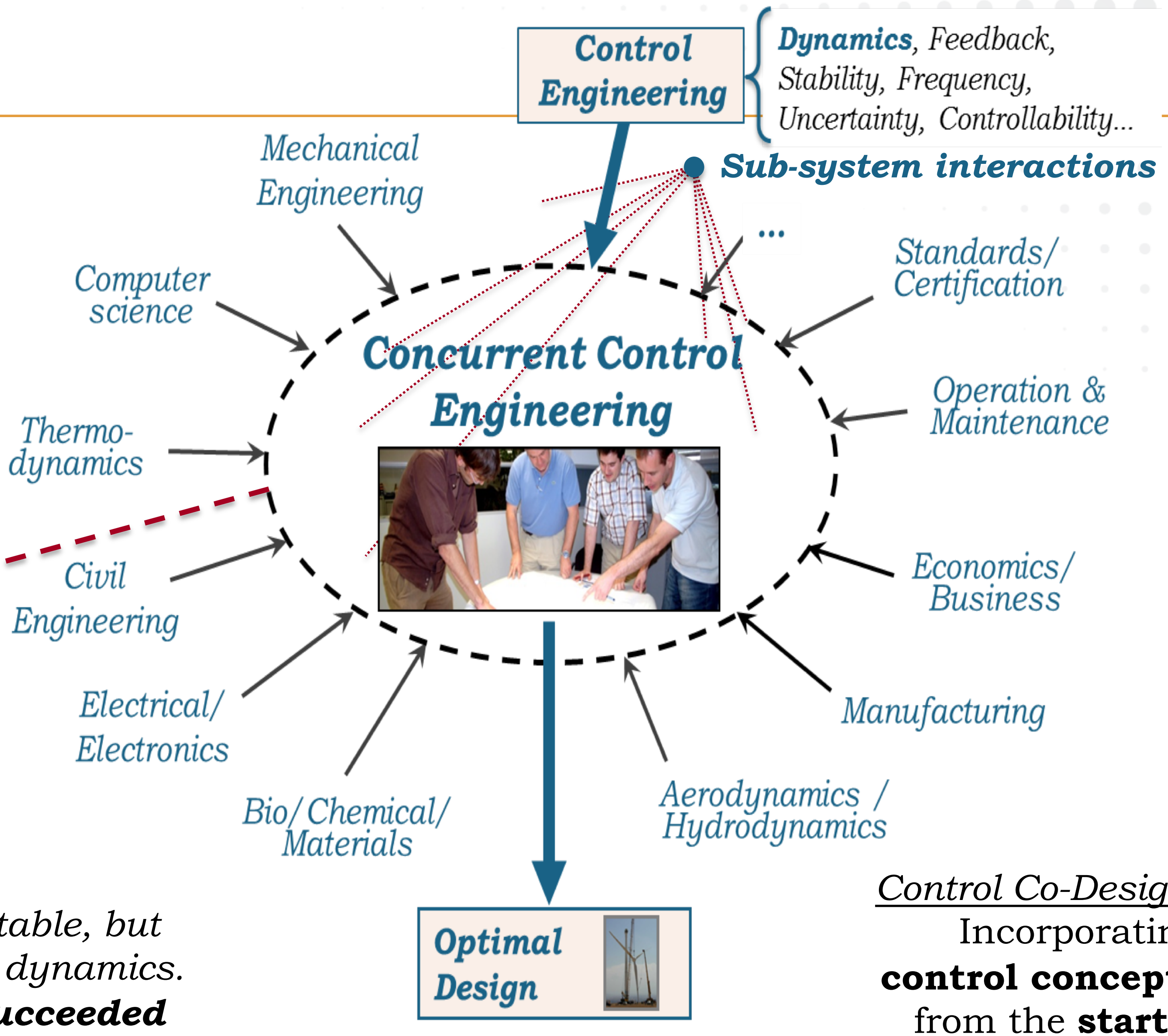
Chanute-Herring, 1896

Stable, but
slow dynamics.
It failed



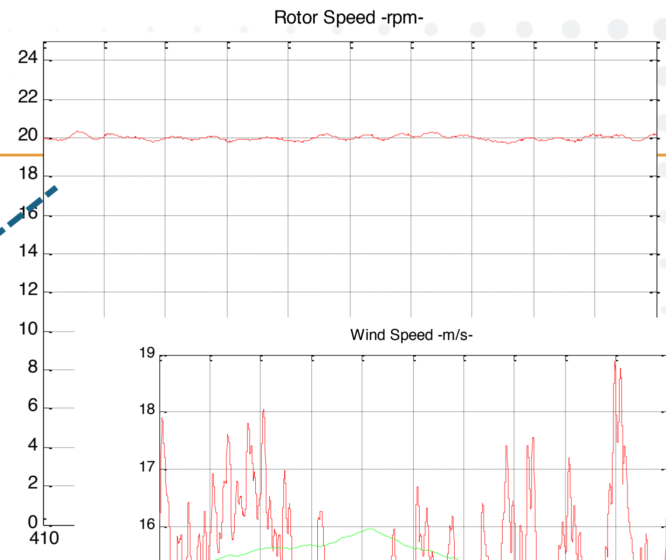
Wright brothers, 1903

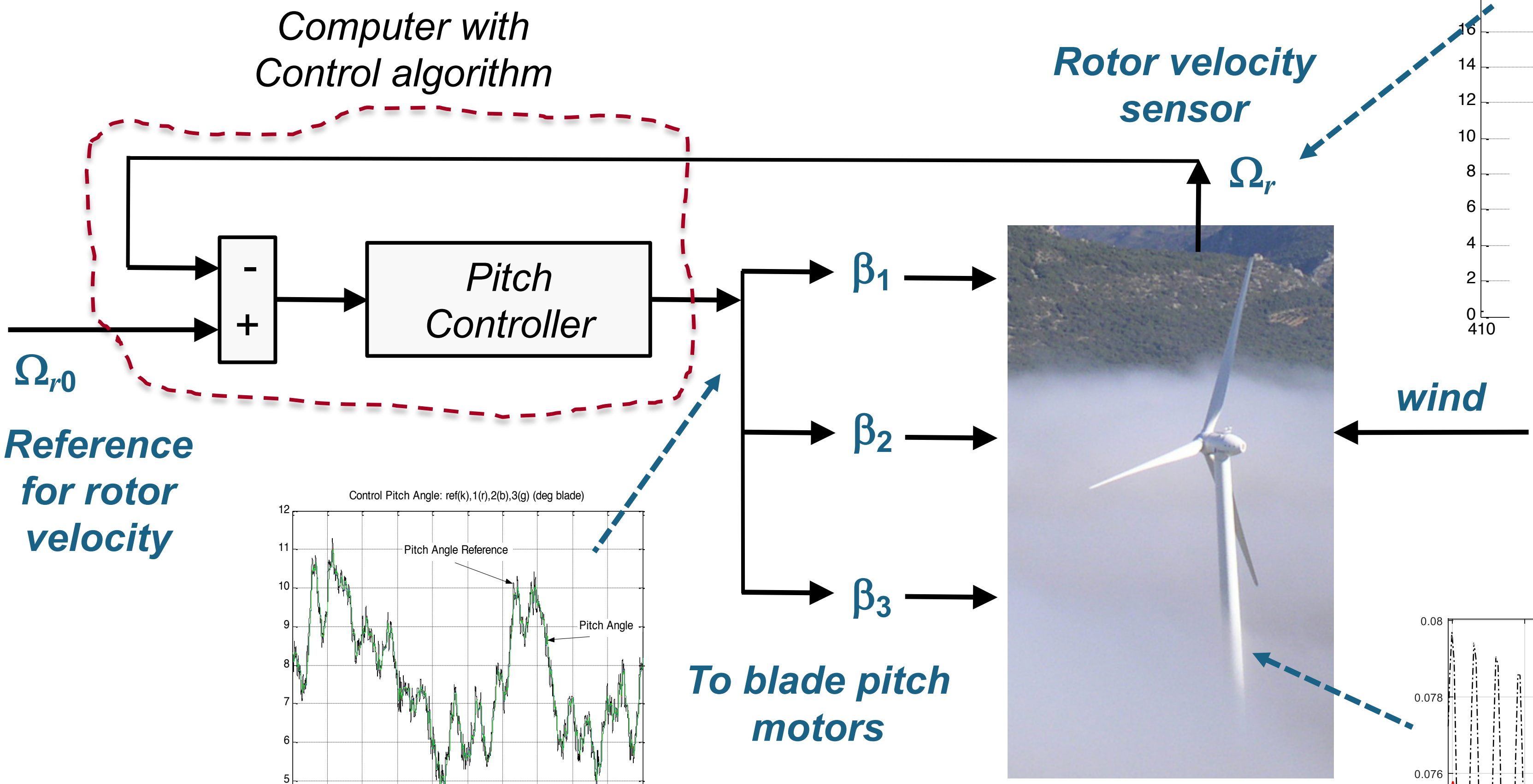
Unstable, but
fast dynamics.
It succeeded

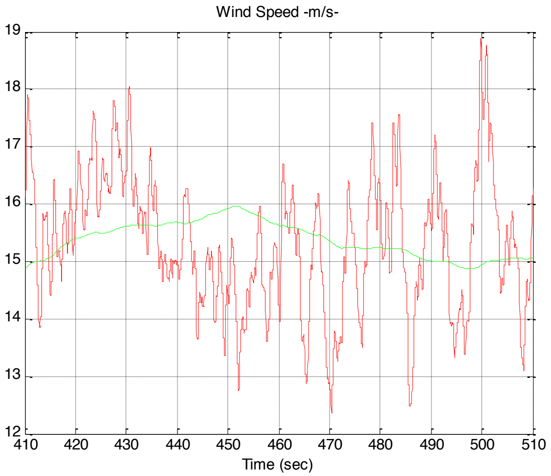


<u>*Control Co-Design*</u>:
Incorporating
control concepts
from the **start**!!!

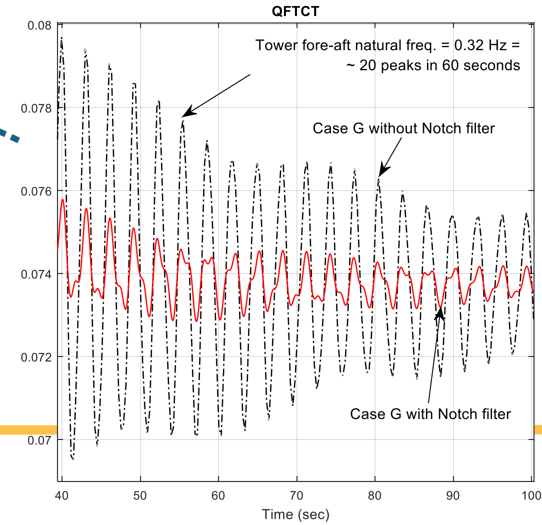
Example: *Wind turbine design*







TWT-1.65 (*)



Control to reduce Tower vibration

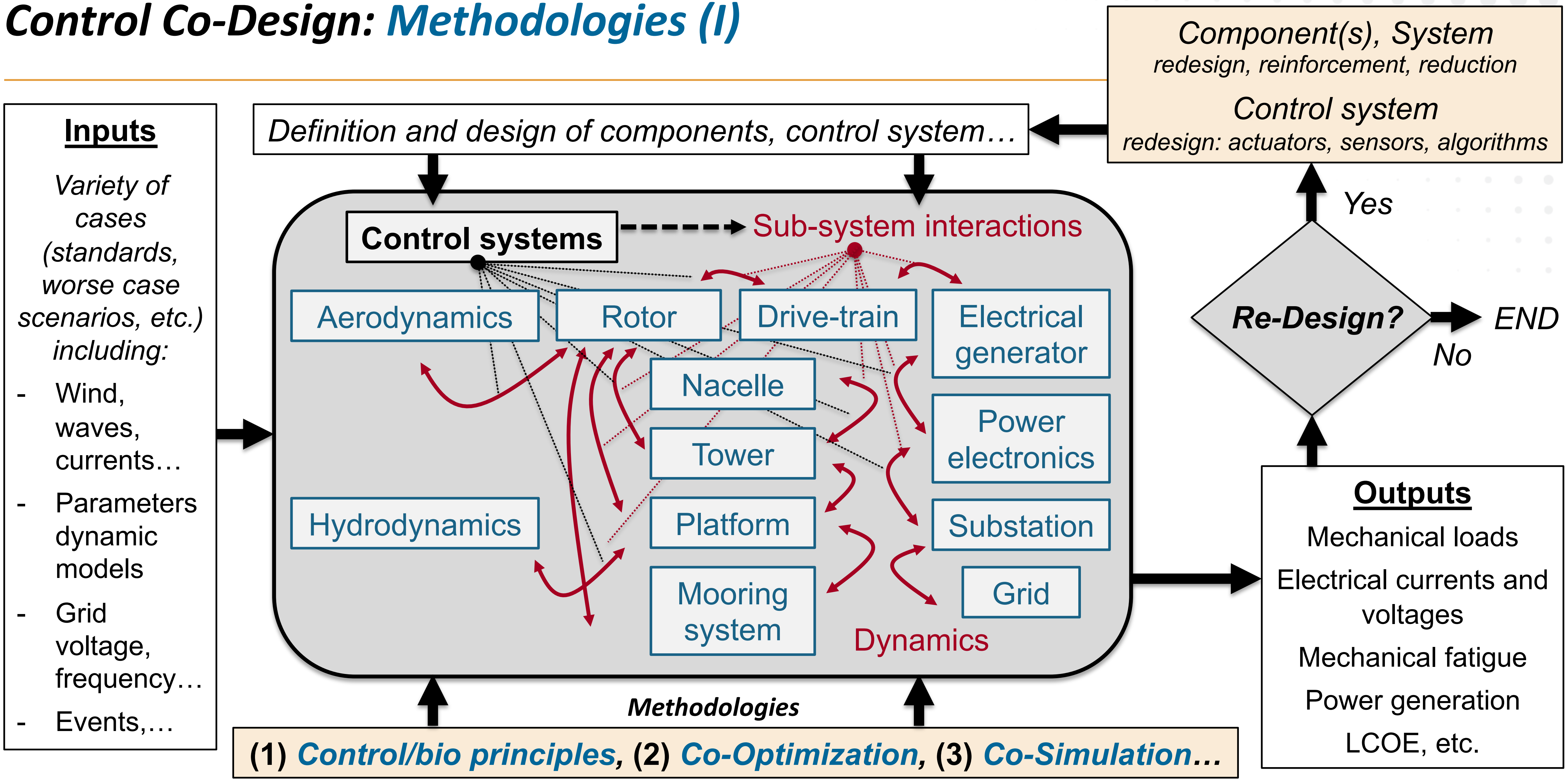
resulted in ***30%*** *less tower cost*

Rotor speed control system

varying blade pitch angle to control rotor speed

(*) Garcia-Sanz, M. *Robust Control Engineering: Practical QFT Solutions*. (Boca Raton, Florida: CRC Press, 2017), 317-342.

Control Co-Design: Methodologies (I)

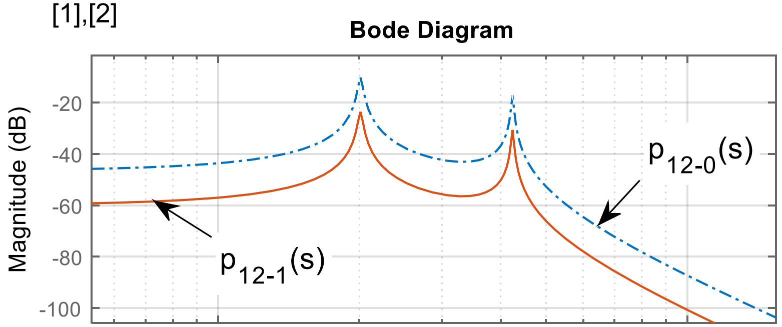


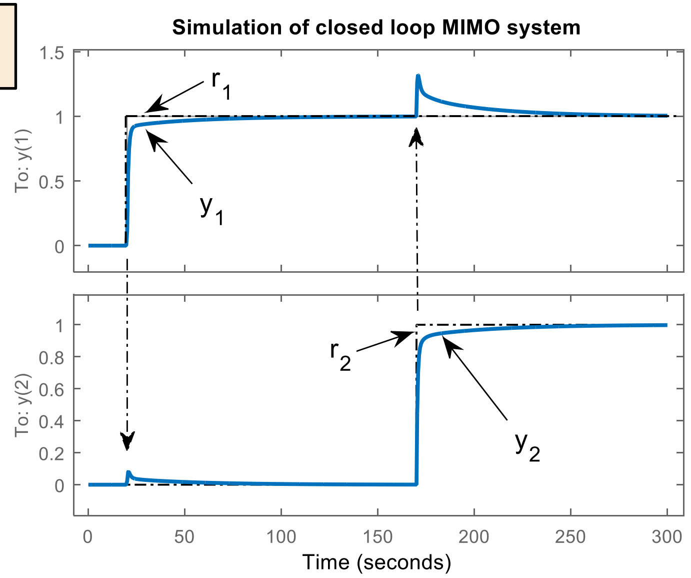
Control Co-Design: *Methodologies (II)*

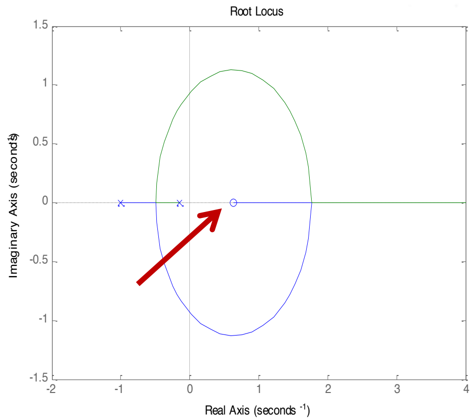
Bio-inspired control solutions *Multivariable control*
Robust control *Nonlinear control…*

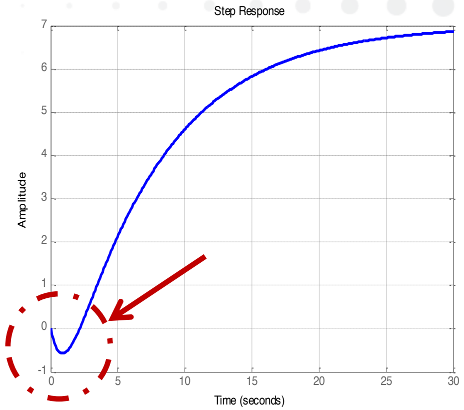
(1) *Control/bio-inspired principles*

[1],[2]









(2) *Co-Optimization*

[3],[4]

Control Design Subspace

Simultaneous Co-Design Problem Formulation:

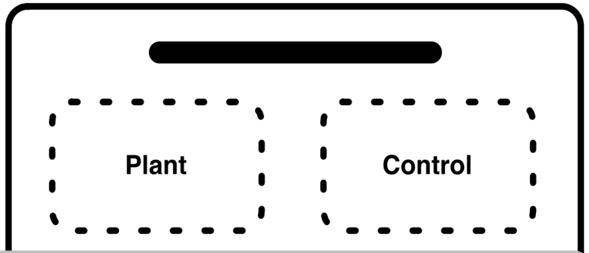
$$\min_{x_p, x_c} \quad \Psi = \int_{t_0}^{t_f} \mathcal{L}\left(t, \xi, x_c, x_p\right) dt + \mathcal{M}\left(\xi(t_0), \xi(t_f), x_c, x_p\right)$$

$$\text{s.t.} \quad \dot{\xi} - f\left(t, \xi, x_c, x_p\right) = 0$$

$$C\left(t, \xi, x_c, x_p\right) \leq 0$$

$$\phi\left(\xi(t_0), \xi(t_f), x_c, x_p\right) \leq 0$$

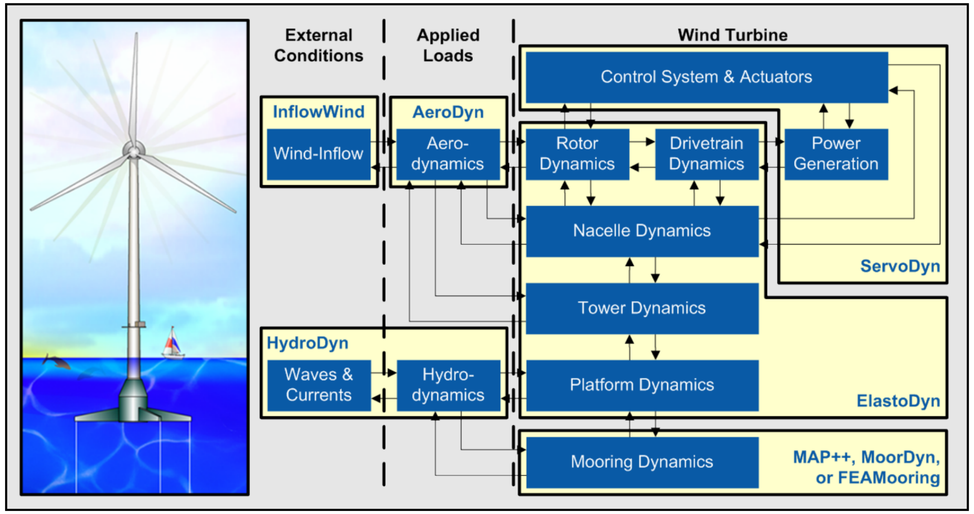
Simultaneous Co-Design



Apply the same system objective function consistently across both design domains

(3) *Co-Simulation*

[5]-[7]

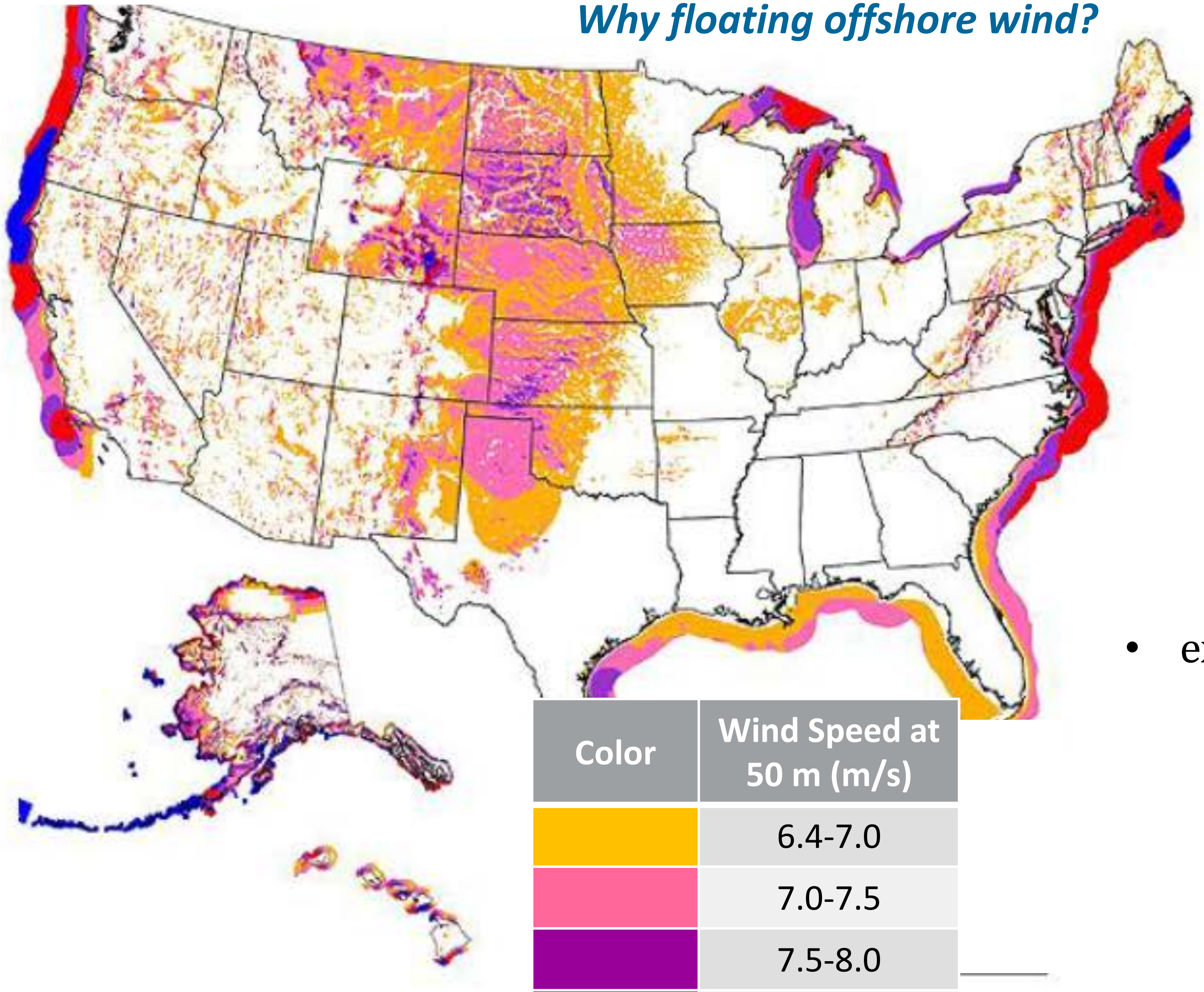


OpenFAST, Courtesy NREL

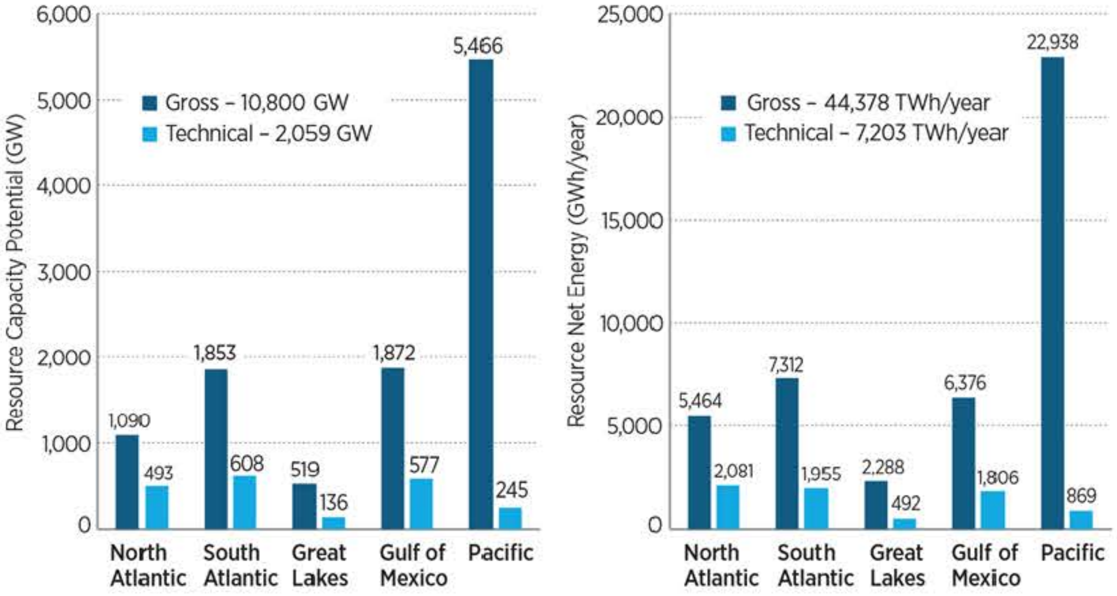
1. Mazumdar, A., Asada, H.H. (2014). *Control-configured design of spheroidal, appendage-free, underwater vehicles.* IEEE Transactions on Robotics, Vol. 30, No. 2, pp. 448-460.
2. Garcia-Sanz, M. (2017). *Robust Control Engineering: Practical QFT Solutions.* CRC Press, Boca Raton, Florida. Case Study 2, pages 317-342.
3. Allison, J.T., Guo, T., Han, Z. (2014). *Co-Design of an Active Suspension Using Simultaneous Dynamic Optimization.* ASME. Journal of Mechanical Design, Vol.136, No.8, pp. 081003.1 – 081003.14.
4. Kamadan, A., Kiziltas, G., Patoglu, V. (2017). *Co-Design Strategies for Optimal* Variable Stiffness Actuation. IEEE/ASME Transactions on Mechatronics, Vol. 22, No.6, pp. 2768-2779.
5. Kaslusky,S., Sabatino,D., Zeidner,L. (2007). ITAPS: A process and toolset to support aircraft level system integration studies. 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2007-1394, Reno, Nevada.
6. Reeve, H., Finney, A. (2008). Probabilistic Analysis for Aircraft Thermal Management System Design and Evaluation. 46th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2008-148, Reno, Nevada.
7. OpenFAST. (2018). National Renewable Energy Lab, NREL. https://nwtc.nrel.gov/OpenFAST.

3. Floating offshore wind energy

Why floating offshore wind?



Color	Wind Speed at 50 m (m/s)
	6.4-7.0
	7.0-7.5
	7.5-8.0
	8.0-8.8
	8.8-11-1



U.S. floating offshore wind resource (Technical resources)

- water depth < 1,000 m, wind speed > 7 m/s
- excluding ice regions, competing-use and environmental
- array power density of 3 MW/km^2

<u>Total technical offshore</u> = 7,203 TWh/year

- <u>Total floating</u> (>60m) = **4,178 TWh/year** > **U.S. electricity consumption** = 3,911 TWh/year (2017) which requires a small part of the gross resource area

National Offshore Wind Strategy: Facilitating the Development of the Offshore Wind Industry in the United States. U.S. Department of Energy (DOE) and the U.S. Department of the Interior (DOI). September 2016

LCOE predictions / opportunities

$LCOE_{floating} < LCOE_{fixed}$

Levelized Avoided Costs of Energy (LACE) = cost for the grid to generate the electricity that would be displaced by a new project (*Site dependent*)

Why floating offshore wind?

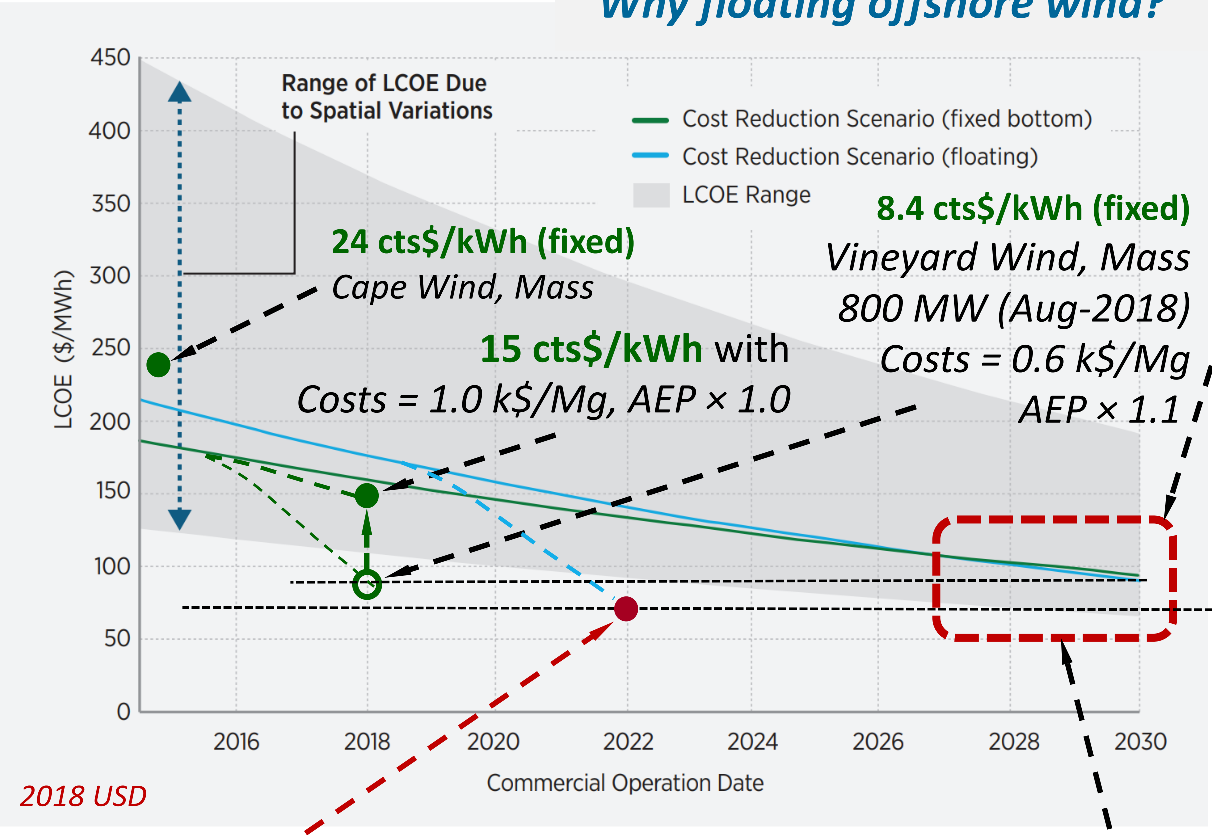


Figure 2.9. Levelized cost of electricity for potential offshore wind projects from 2015 to 2030 over technical resource area [23]

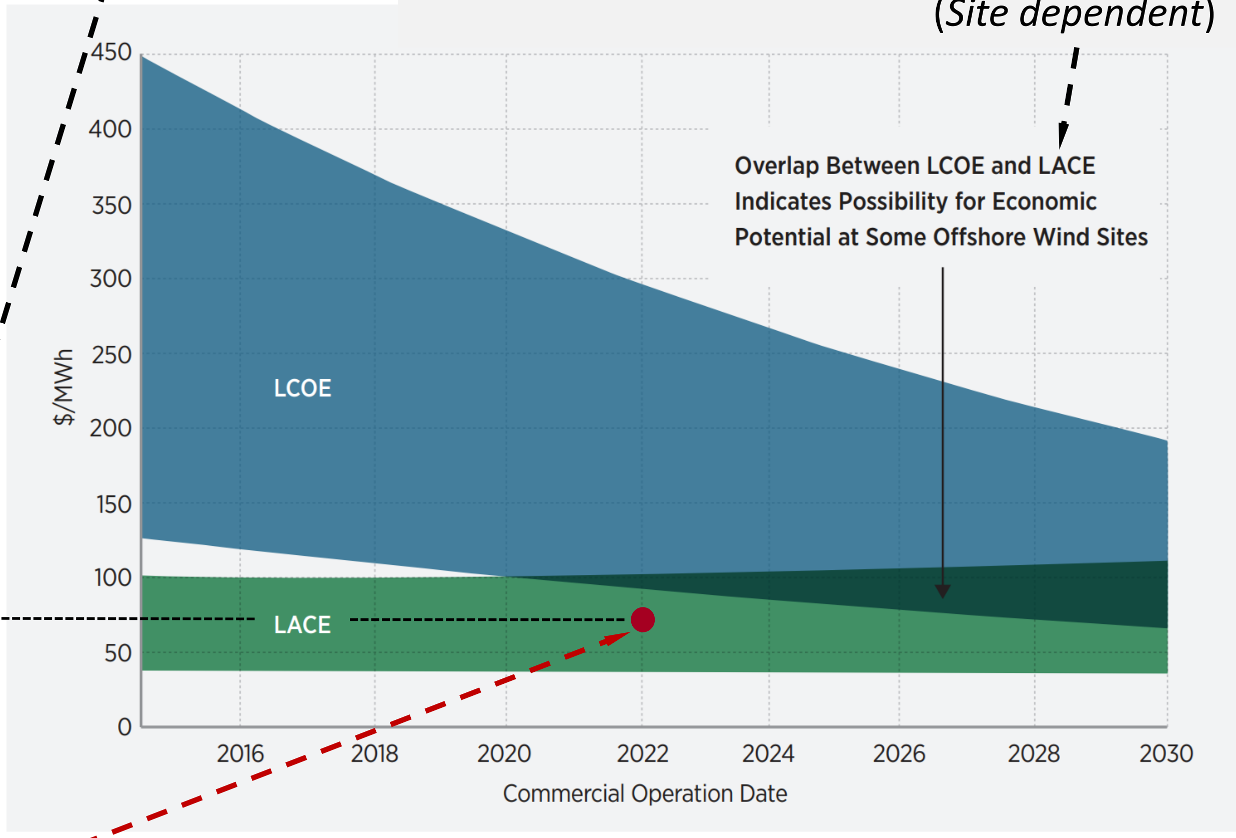
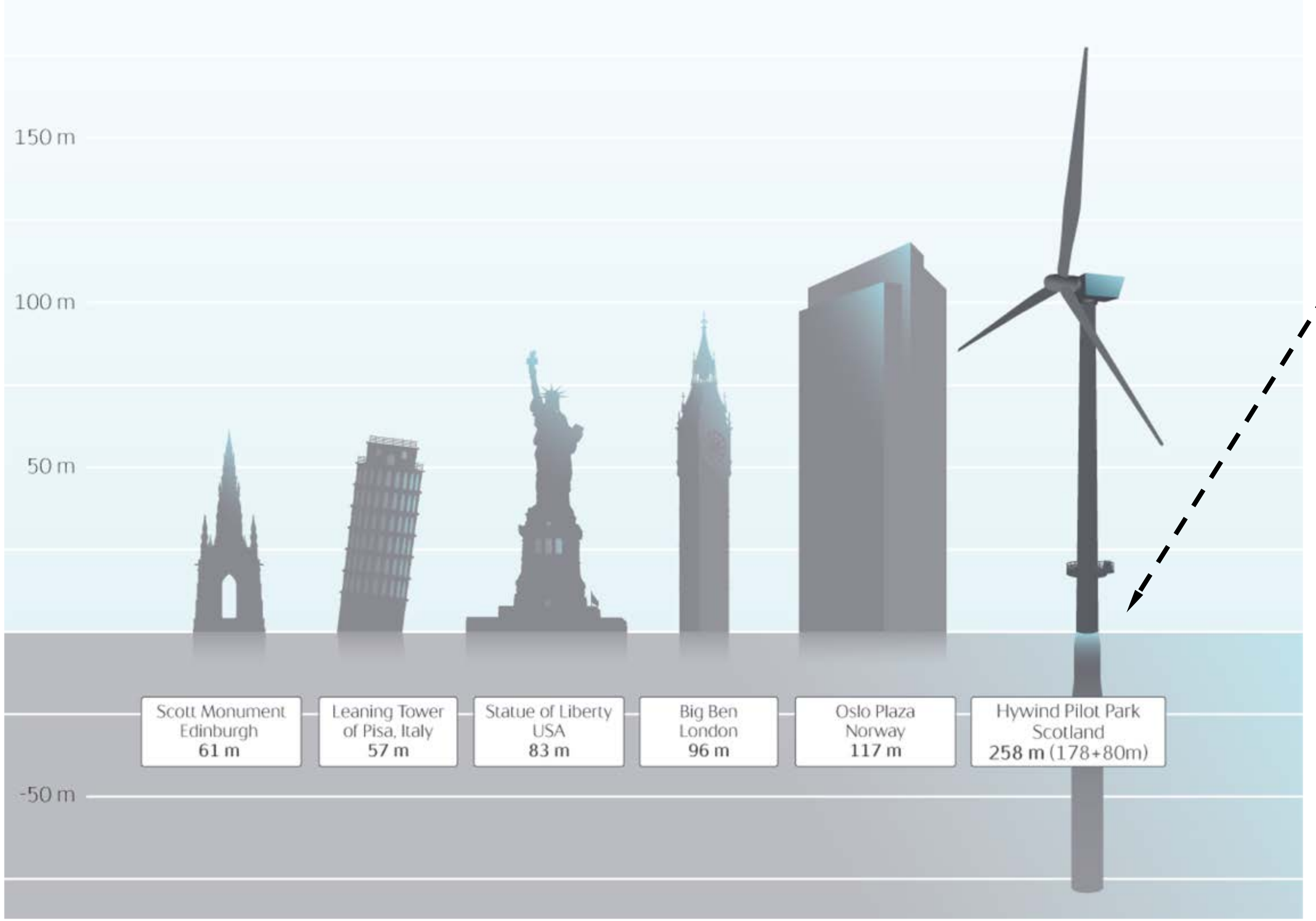


Figure 2.11. Comparison of levelized cost of energy and levelized avoided cost of energy estimates from 2015 to 2030

Envisioned program objective:
~7.5 cts$/kWh for floating for 2022

Ref. *National Offshore Wind Strategy: Facilitating the Development of the Offshore Wind Industry in the United States*. U.S. Department of Energy (DOE) and the U.S. Department of the Interior (DOI). Sept-2016.

Current vs Control Co-Design approach



***Copying* the land-based solution for floating offshore!!!!**

***= Colossal Mass* to stabilize system**

(~70% of CapEx is Floating Platform)

Control Co-Design

= Radical mass reduction

Key aspect: Sub-systems interaction

1.- Wind
moves rotor at Ω_r

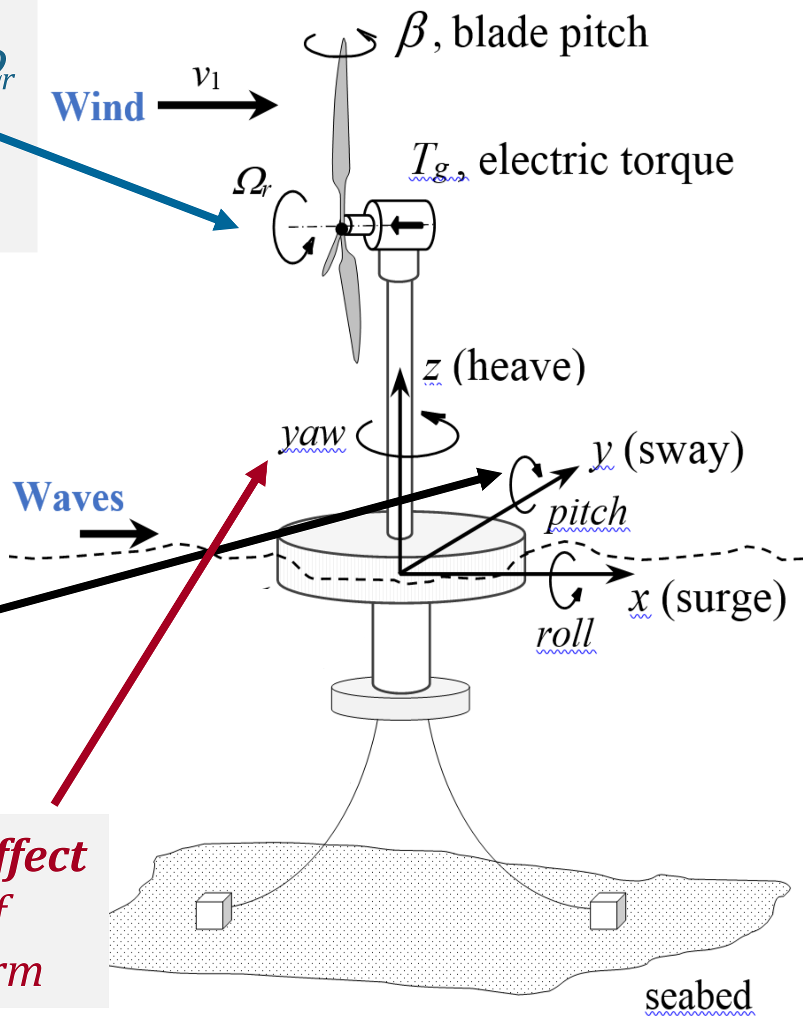
Large rotor ***inertia***

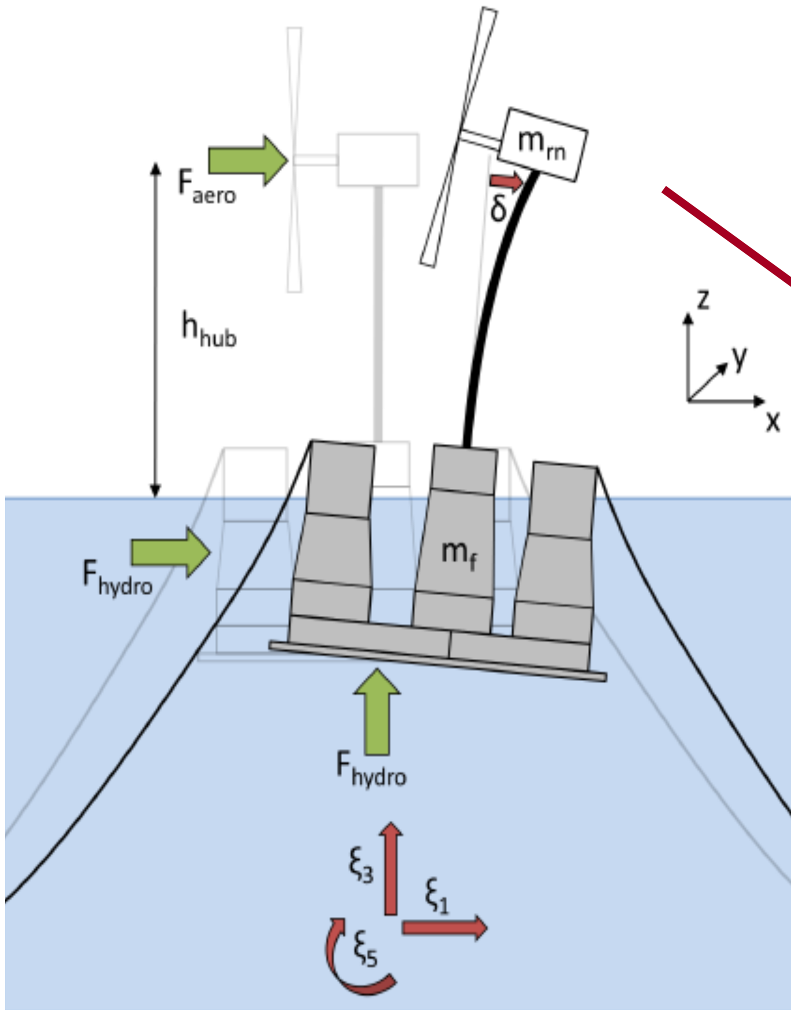
↓

2.- Waves
moves pitch of floating platform

↓

3.- Gyroscopic effect
moves yaw of floating platform





Bottom-fixed

$$\frac{\partial F_{Thrust}}{\partial V_{wind}} > 0$$

↓

Floating

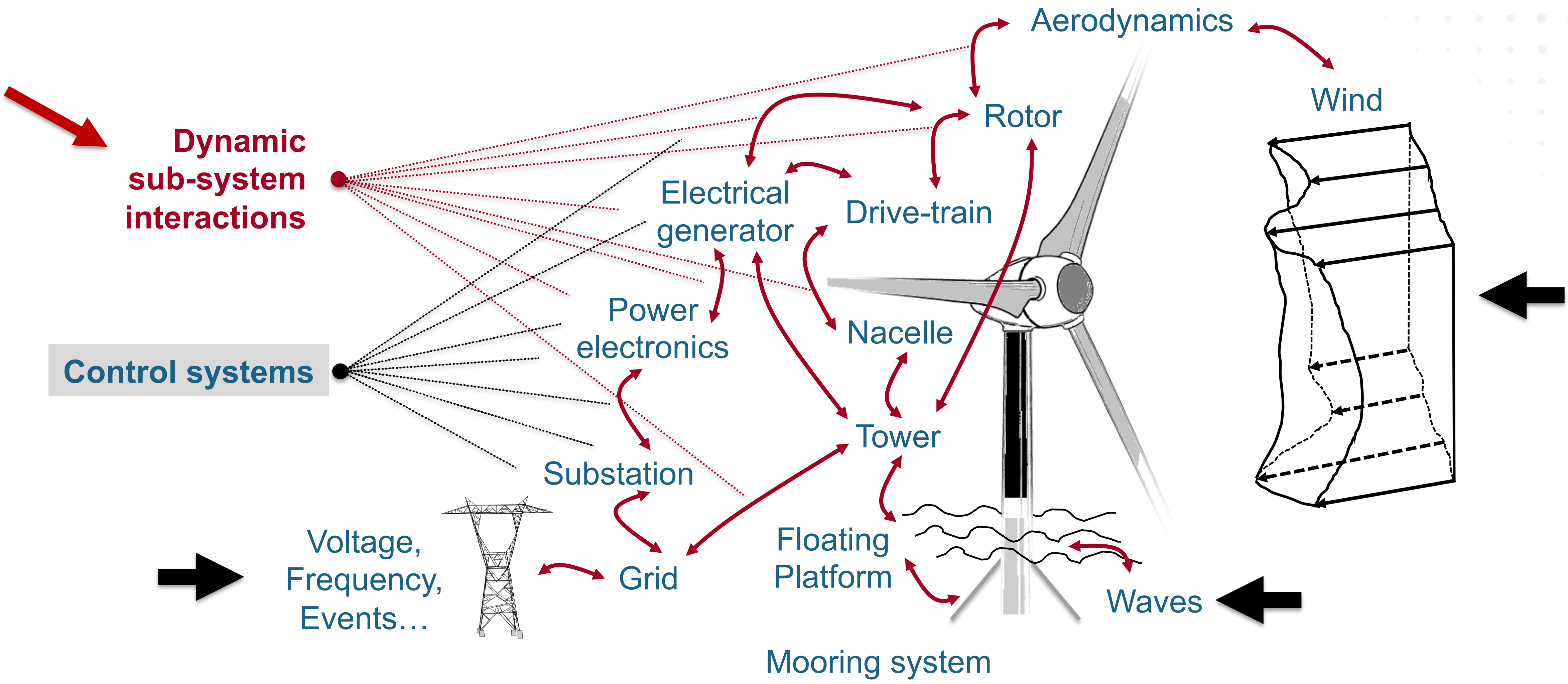
$$\frac{\partial F_{Thrust}}{\partial V_{wind}} < 0$$

↓

Unstable!!

Aero-Hydro-Servo-Elastic coupling

Key aspect: Sub-systems interaction



More **dynamic coupling** = More need of **Control Co-Design**!!!

Complex multi-dimensional optimization problem.

- Conventional design not likely to solve well.

$$LCOE = \frac{FCR\ CapEx + OpEx}{AEP}$$

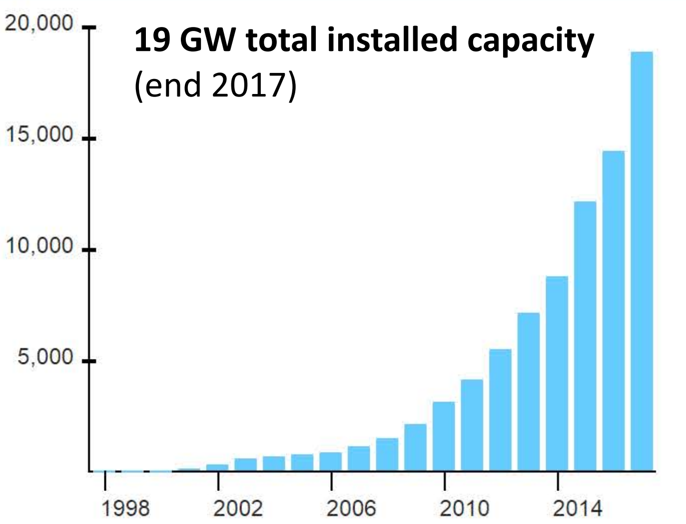
1. Mass reduction	**2. Survivability**	**3. Resiliency**	**4. Efficiency**	**5. O&M**
• Mechanical fatigue • Flexible materials • Bio-inspired materials	• Extreme weather • Wind, Waves, Ice • Maximum loads	• Fault-tolerance • Self-healing • Time to recover	• Aerodynamic • Mechanical • Electrical	• Operation costs • Maintenance costs
6. Component Replacement	**7. Performance decline**	**8. Installation**	**9. Grid integration**	**10. Off-grid opportunities**
• Time between failures • Access, costs	• Efficiency decay • Maintenance increase • Corrosion, aging…	• Vessels, cranes • Submarine work • Self-deployment	• Frequency, voltage • Active/reactive power • Ancillary services	• Remote areas • Substituting diesel • Other applications
11. Environmental friendly	**12. Subsystem interactions**	**13. New paradigms**	**14. Software development**	**15. Other…**
• Birds, fish impact • Noise reduction • Harmonics content	• Dynamic coupling • Nonlinear interactions • Control solutions	• Bio-inspired, Control, sensors, actuators... • Add. Manufacturing	• Co-Optimization • Co-Simulation • Multi-physics codes	• Experimental tests… • Hybrid systems… • …

Offshore bottom-fixed

World installed wind capacity **540 GW** (19 GW offshore)
= **5%** of the global electricity consumption (end 2017)

World's largest offshore wind farms

Wind farm	Capacity (MW)	Country	Turbines and model	Commissioned
London Array	630	United Kingdom	175 × Siemens SWT-3.6	2012
Gemini Wind Farm	600	Netherlands	150 × Siemens SWT-4.0	2017
Greater Gabbard	504	United Kingdom	140 × Siemens SWT-3.6	2012
Anholt	400	Denmark	111 × Siemens SWT-3.6-120	2013
BARD Offshore 1	400	Germany	80 × BARD 5.0 turbines	2013
Walney	367	United Kingdom	102 × Siemens SWT-3.6	2012
Thorntonbank	325	Belgium	54 × Senvion 6 MW	2013
Sheringham Shoal	317	United Kingdom	88 × Siemens 3.6	2013
Thanet	300	United Kingdom	100 × Vestas V90-3MW	2010
Meerwind Süd/Ost	288	Germany	80 × Siemens SWT-3.6-120	2014
Lincs	270	United Kingdom	75 × Siemens 3.6	2013
Horns Rev II	209	Denmark	91 × Siemens 2.3-93	2009



Wind farm: London Array (UK)

Wind turbine: Siemens 3.6 MW

Total: 630 MW.

Started operation in 10-2012

Global cumulative offshore capacity (MW).
Sources: GWEC (2011–2017)[9][10][11][2] and EWEA (1998–2010)[12]

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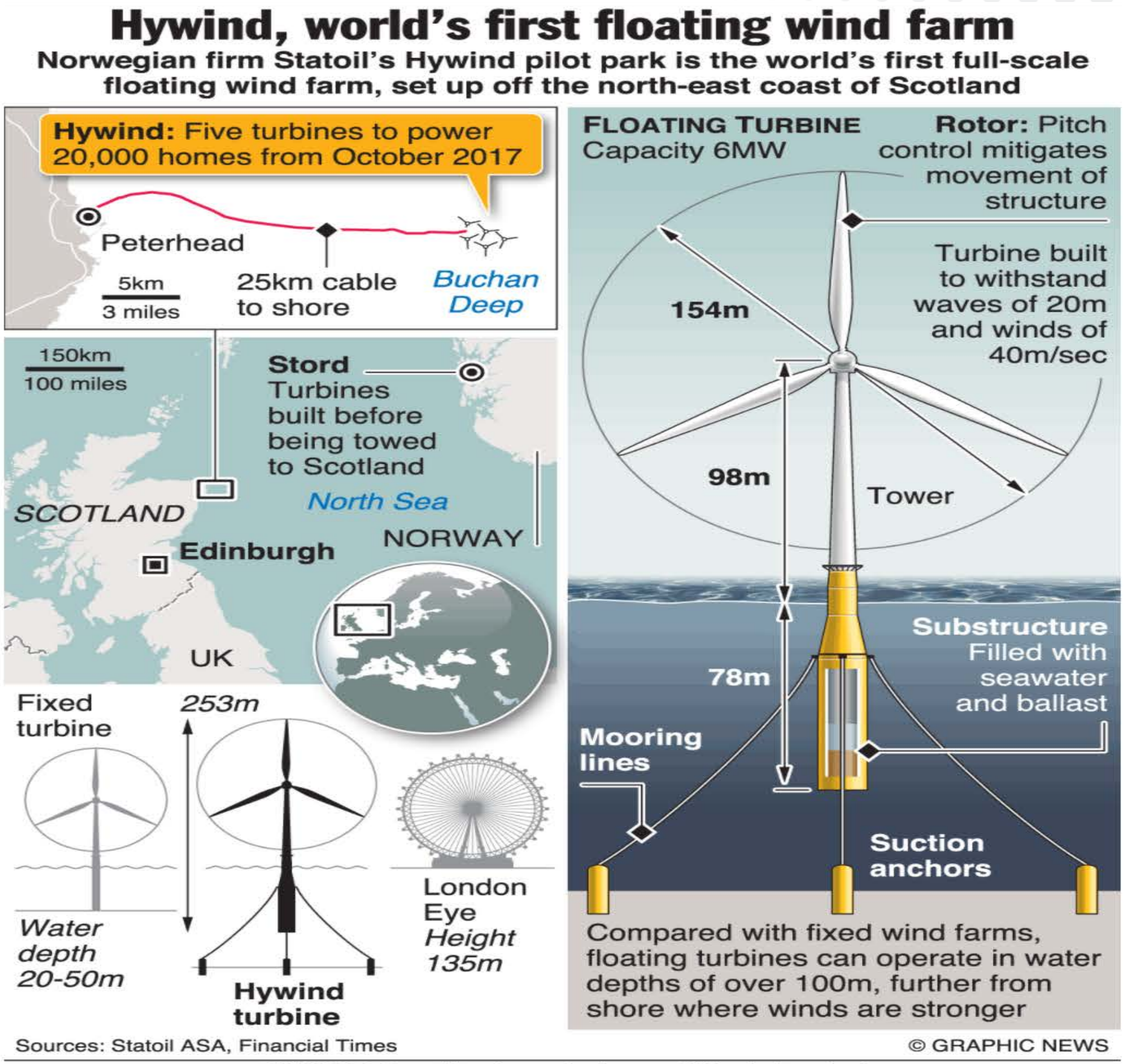
Offshore floating

Wind farm: 5 Wind turbines
Wind turbine: 6 MW, 11.5 Mkg
Project cost: $253M.
Started operation in October 2017

Courtesy Equinor (Statoil), Siemens

The Hywind Scotland floating wind farm. (Photo: Øyvind Gravås / Woldcam - Statoil ASA)



GN35693 Graphic shows features of Hywind project.

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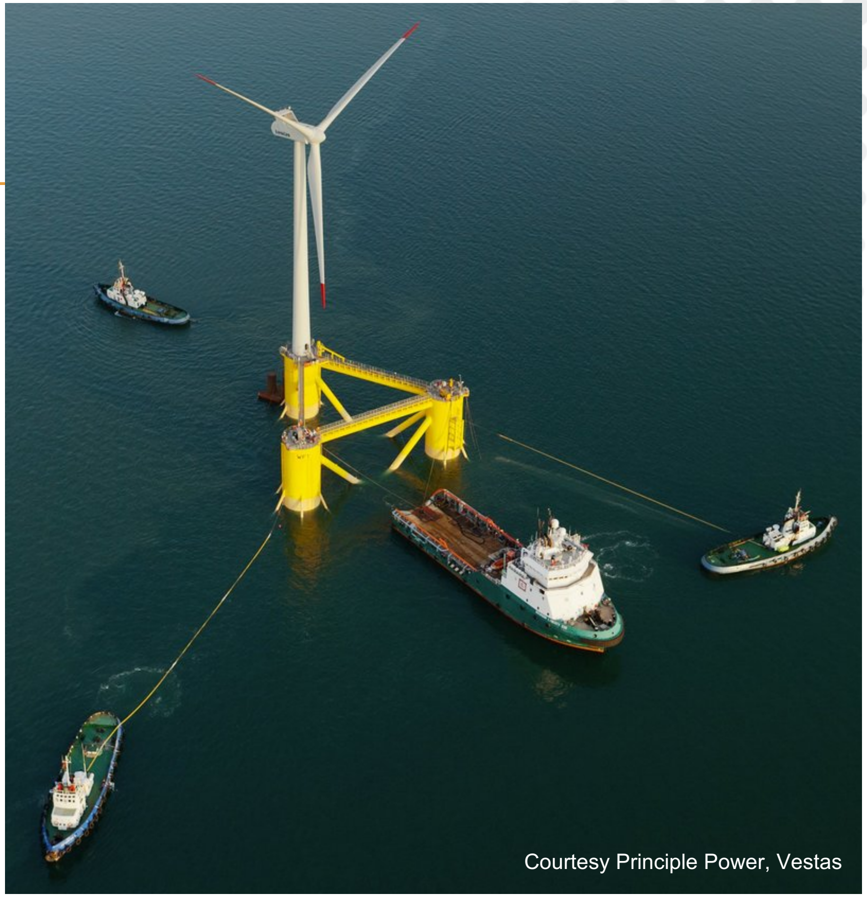
Offshore floating

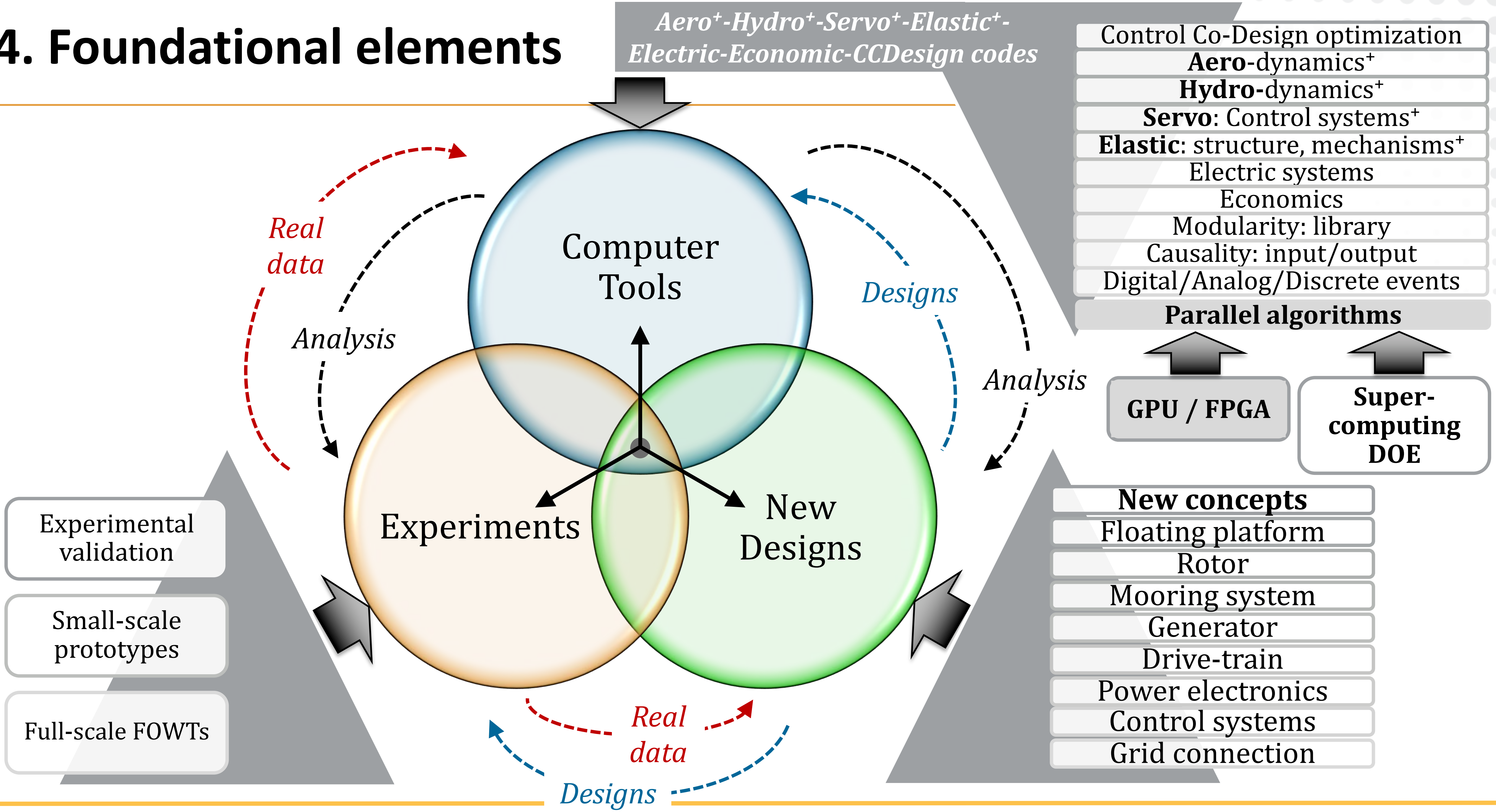
WindFloat



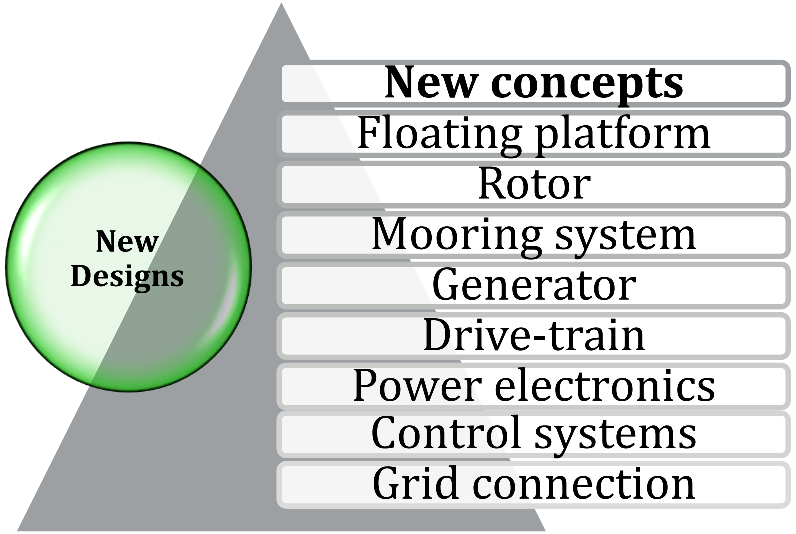
Courtesy Principle Power, Vestas

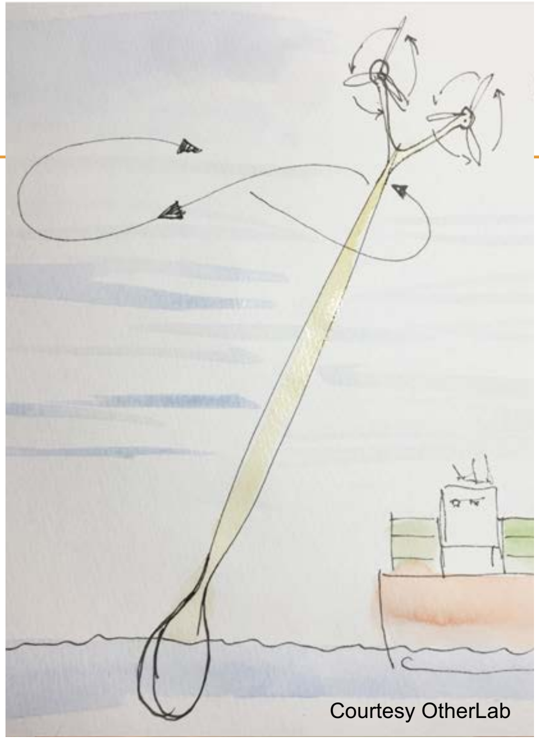
- 1 turbine, 2 MW
- 80 m rotor diameter, 78 m hub height
- Vestas, EDP, Principle Power, Repsol
- 1 prototype, 2011-2016
- Coast of Portugal

4. Foundational elements

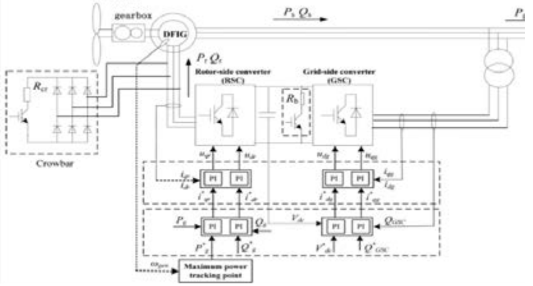


A1. New designs



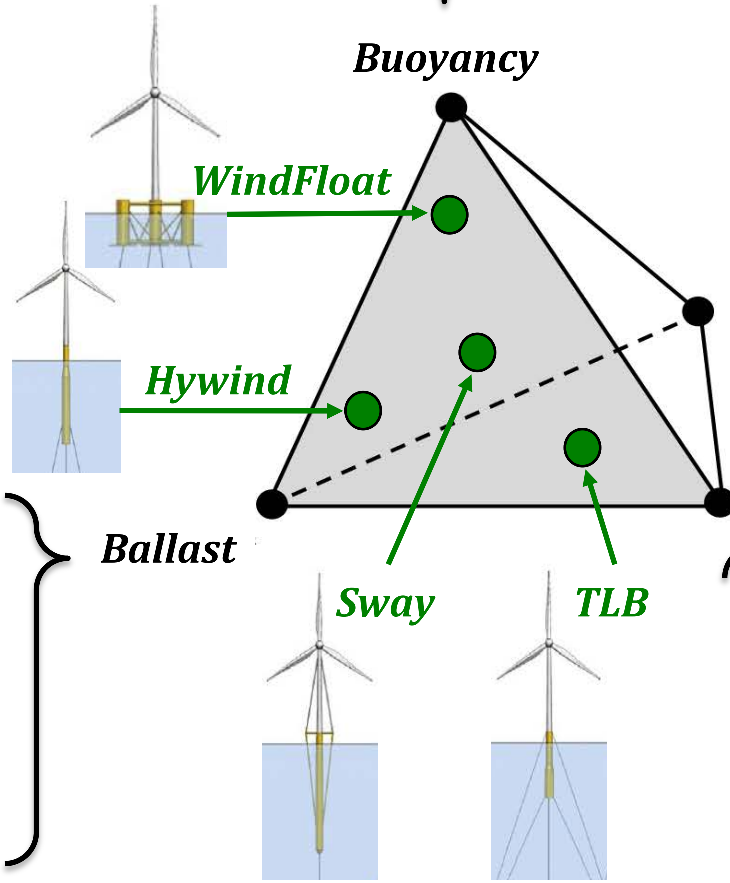


Courtesy OtherLab



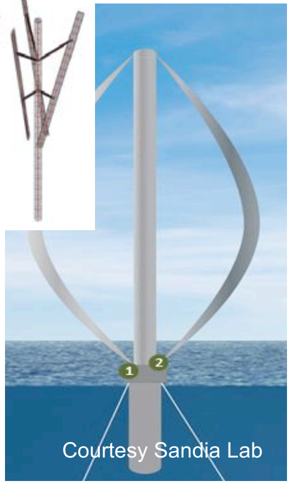
***upward acting force**, exerted by the fluid, that equals the weight of displaced fluid, (Archimedes' principle)*

*device that adds **drag** and **damping** to the structure movement*



*provides vertical separation of **center of gravity** (lower) and **center of buoyancy** (higher)*

cables**, anchors or lines that **holds** the system to the **seabed



Courtesy Sandia Lab

extra motors and actuators

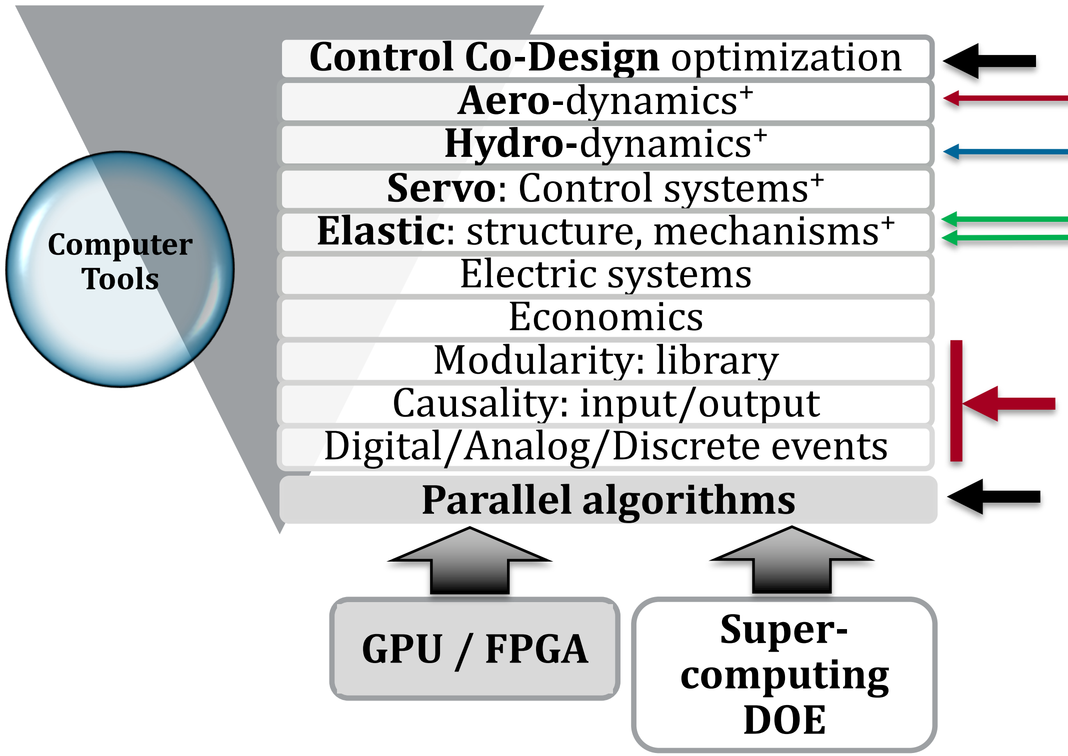
smart blades

individual pitch control

variable buoyancy, ballast, mooring tension, damping

active torque control

A2. Computer tools

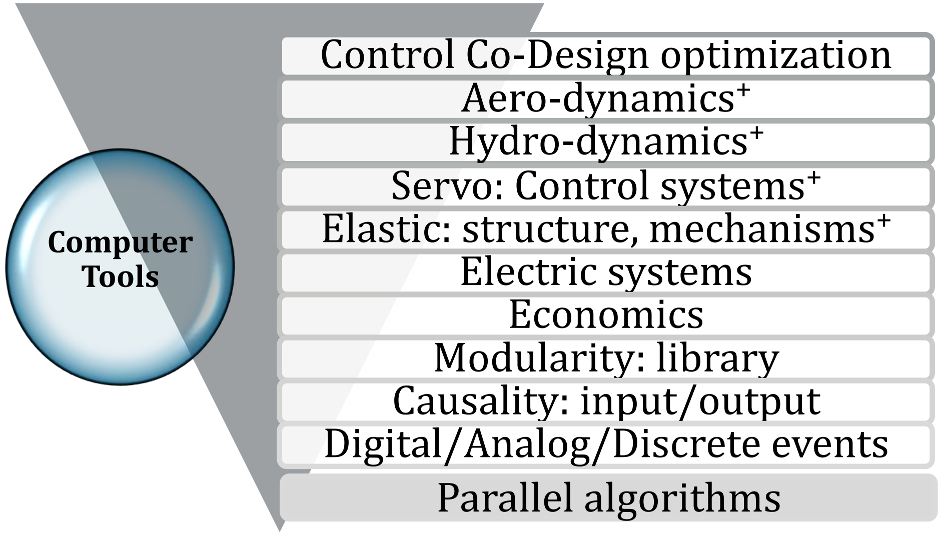


Aero⁺-Hydro⁺-Servo⁺-Elastic⁺
-Electric-Economic
Control Co-Design
Codes

Code	Structural Dynamics	Aerodynamics	Hydrodynamics	Mooring
FAST	T:Mod/MB P: Rigid	(BEM or DW)+DS	PF+QD+(QTF)	QS
FAST v8	T:Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME	QS
CHARM3D+FAST	T:Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME+(MD+NA)+(IP+IWL)	FE/Dyn
OPASS+FAST	T:Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME	LM/Dyn
UOU+FAST	T:Mod/MB P: Rigid	(BEM or GDW)+DS	PF+QD	QS
Bladed	T:Mod/MB P: Rigid	(BEM or GDW)+DS	ME+(IWL+IP)	QS
Bladed Advanced Hydro	T:Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME+(IWL)	QS
OrcaFlex	T:FE P:Rigid	BEM, GDW, or FDT	PF+ME	LM/Dyn
HAWC2	T:MB/FE P: MB/FE	(BEM or GDW)+DS	ME	FE/Dyn
Hydro-GAST	T:MB/FE P: MB/FE	BEM or FWV	PF+ME+(IP)	FE/Dyn
Simo+Riflex+AeroDyn	T:FE P:FE	(BEM or GDW)+DS	PF+ME	FE/Dyn
Riflex-Coupled	T:FE P:Rigid	BEM+FDT	PF+ME+(IWL)	FE/Dyn
3Dfloat	T:FE (co-rotated) P:FE	BEM+FDT	ME+(IWL)	FE/Dyn
SWT	T:FE+Mod/MB P:FE+Mod/MB	BEM or GDW	ME+(IWL)	FE/Dyn
DeepLinesWT	T:FE P:FE	BEM+DS	PF+ME+(MD+QTF+NA)+(IP+IWL)	FE/Dyn
SIMPACK+HydroDyn	T:Mod/MB P:Rigid	BEM or GDW	PF+QD	QS
CAsT	T:FE P:FE	BEM	ME	QS
Wavec2Wire	T:N/A P:Rigid	N/A	PF+QD	QS
WAMSIM	T:N/A P:Rigid	N/A	PF+QD	QS

Computer tools elements

To include: (e1) through (e5)



*and at least **four of the six** remaining elements, (e6) to (e11)*

(e6). **Electrical** and **economic** modules,

(e7). **Analog/digital/discrete-event/probabilistic** models,

(e8). **User-friendly standard interfaces**, intuitive and reliable,

(e9). Input/output **causality-free** codes,

(e10). **IEC-61400 standard inputs**, including all operational modes,

(e11). **Parallel algorithms** to speed up the calculations.

(e1). **CCD optimization methodologies** for both, individual turbine and wind farm level, and with dynamic/control simulation capabilities and techno-economic estimates,

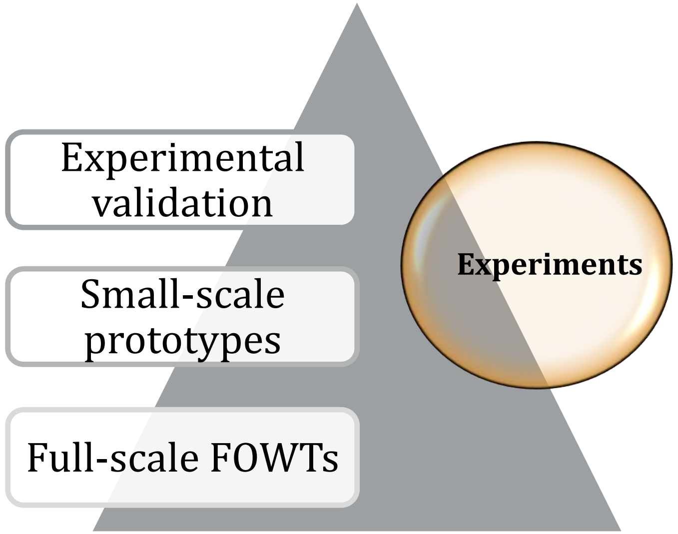
(e2). New **aero-, hydro-, elastic-, servo-** mathematical models that incorporate nonlinear dynamics, multi-disciplinary analysis and optimization beyond the OCx programs,

(e3). Libraries of **modular functions** to allow designers to simulate new ideas,

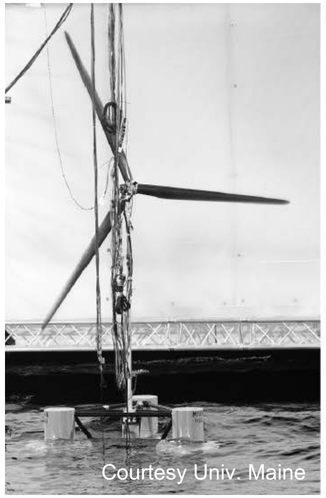
(e4). Tools that run under a **standard software** environment, like Matlab, Simulink or similar,

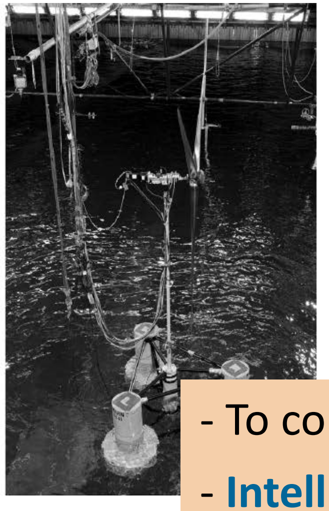
(e5). **Linearization capabilities** with the ability to derive reduced control-oriented models,

A3. Experiments




Courtesy Sandia Lab


Courtesy Univ. Maine



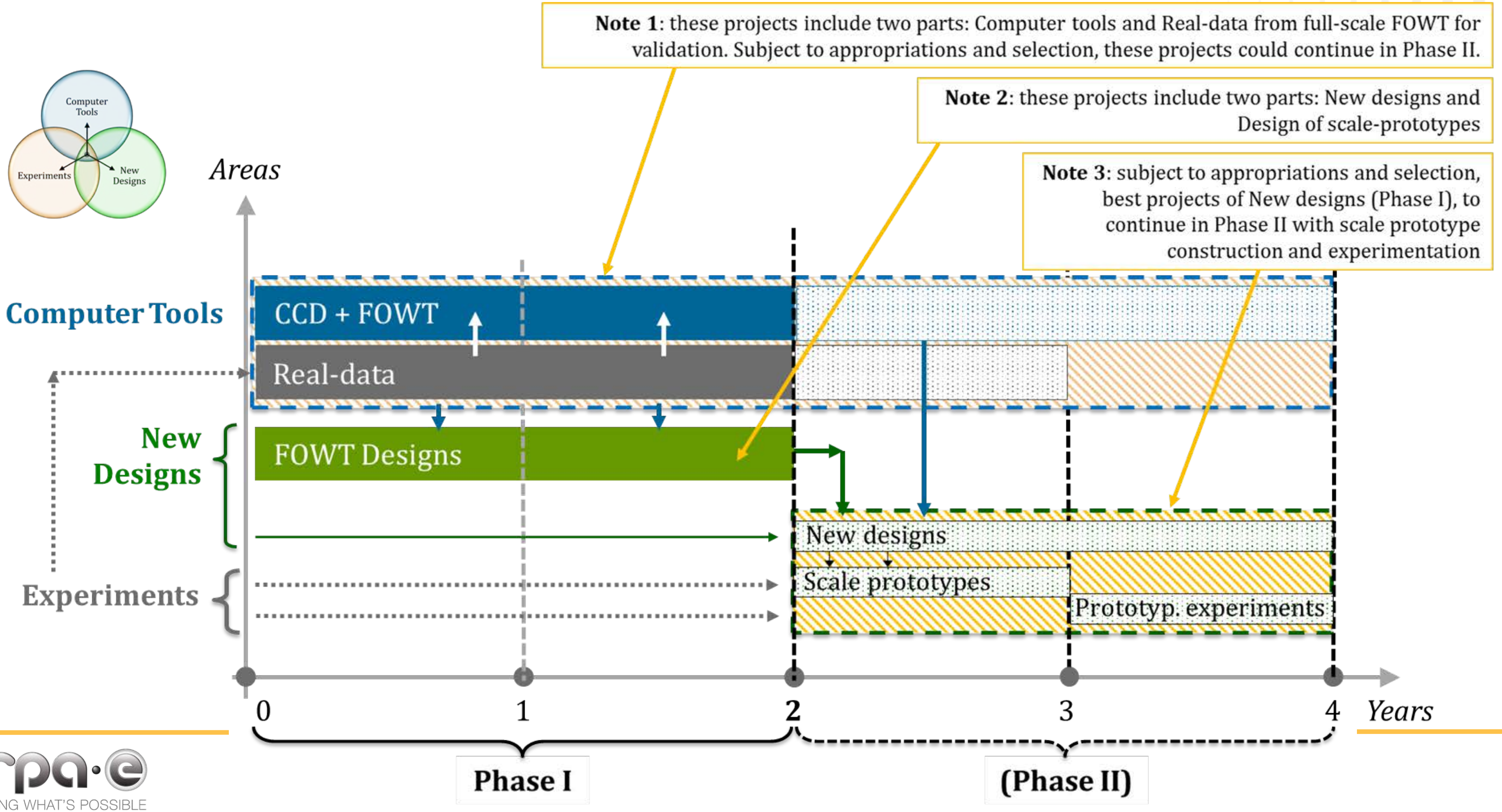

Courtesy Navy


Courtesy GE

- To collect **real-data** from full and lab-scale FOWTs

- **Intelligent real-time systems** with new sensors and network of sensors, advanced data-fusion, observer, learning and classification algorithms, dynamic models and communication devices

5. Potential program structure. *Schedule and costs*

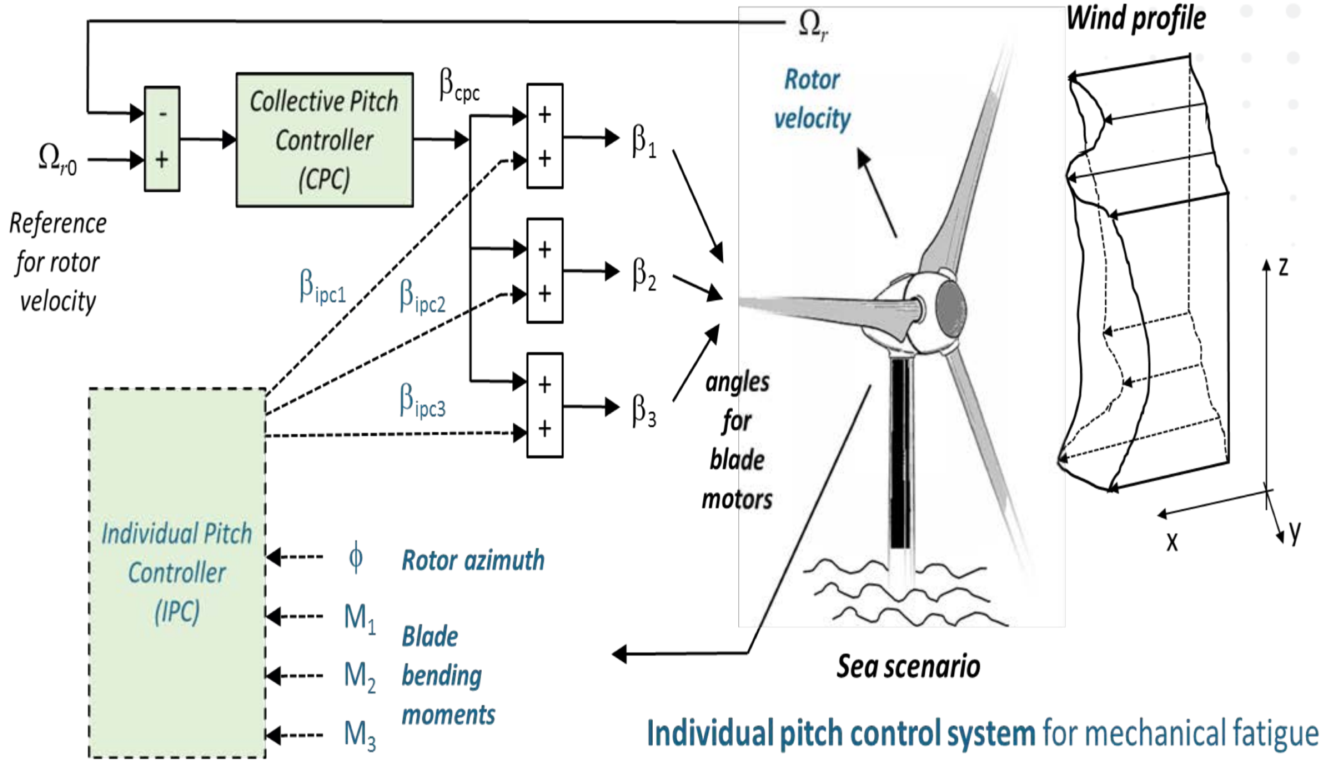


ATLAS competition

Look our **website**:
https://arpa-e.energy.gov/?q=site-page/atlas-competition

Launched *on*
January 11th, 2019

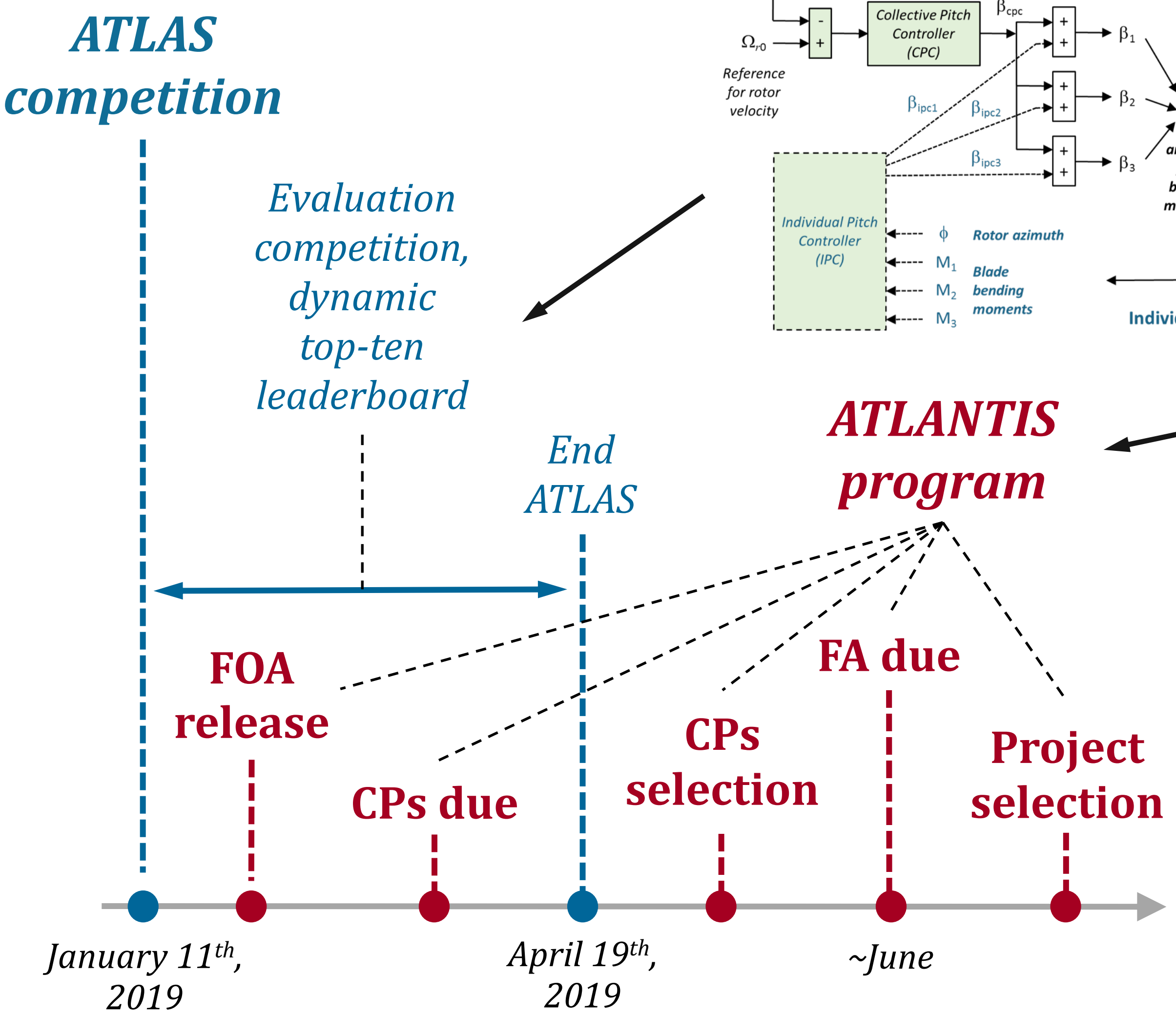
ATLAS COMPETITION
Aerodynamic **T**urbines with **L**oad **A**ttenuation **S**ystems

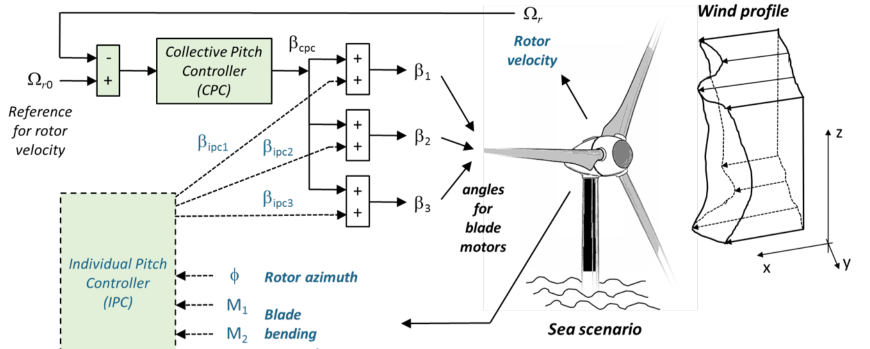


Individual pitch control system for mechanical fatigue minimization in **offshore floating wind turbines**

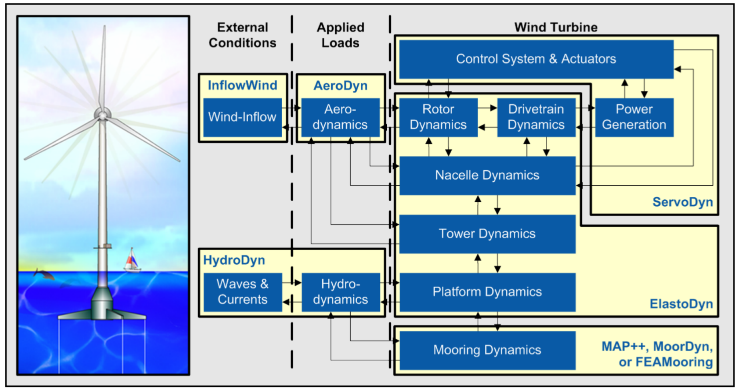
The Advanced Research Projects Agency – Energy (ARPA-E) of the U.S. Department of Energy is challenging the research and industrial communities to discover, develop, and test innovative and disruptive Control Co-Design solutions for critical wind energy challenges. The ATLAS (Aerodynamic Turbines with Load Attenuation Systems) Competition is the first ARPA-E effort associated with this advanced design methodology.

Coordination. *Tentative schedule*

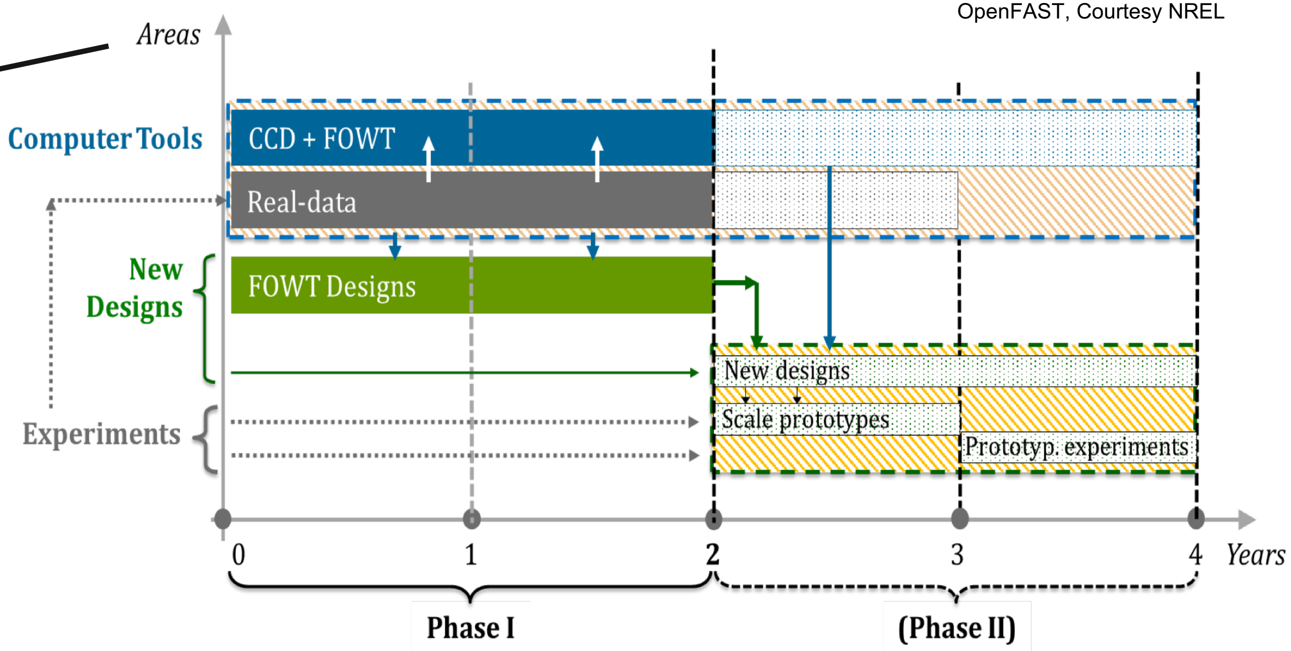




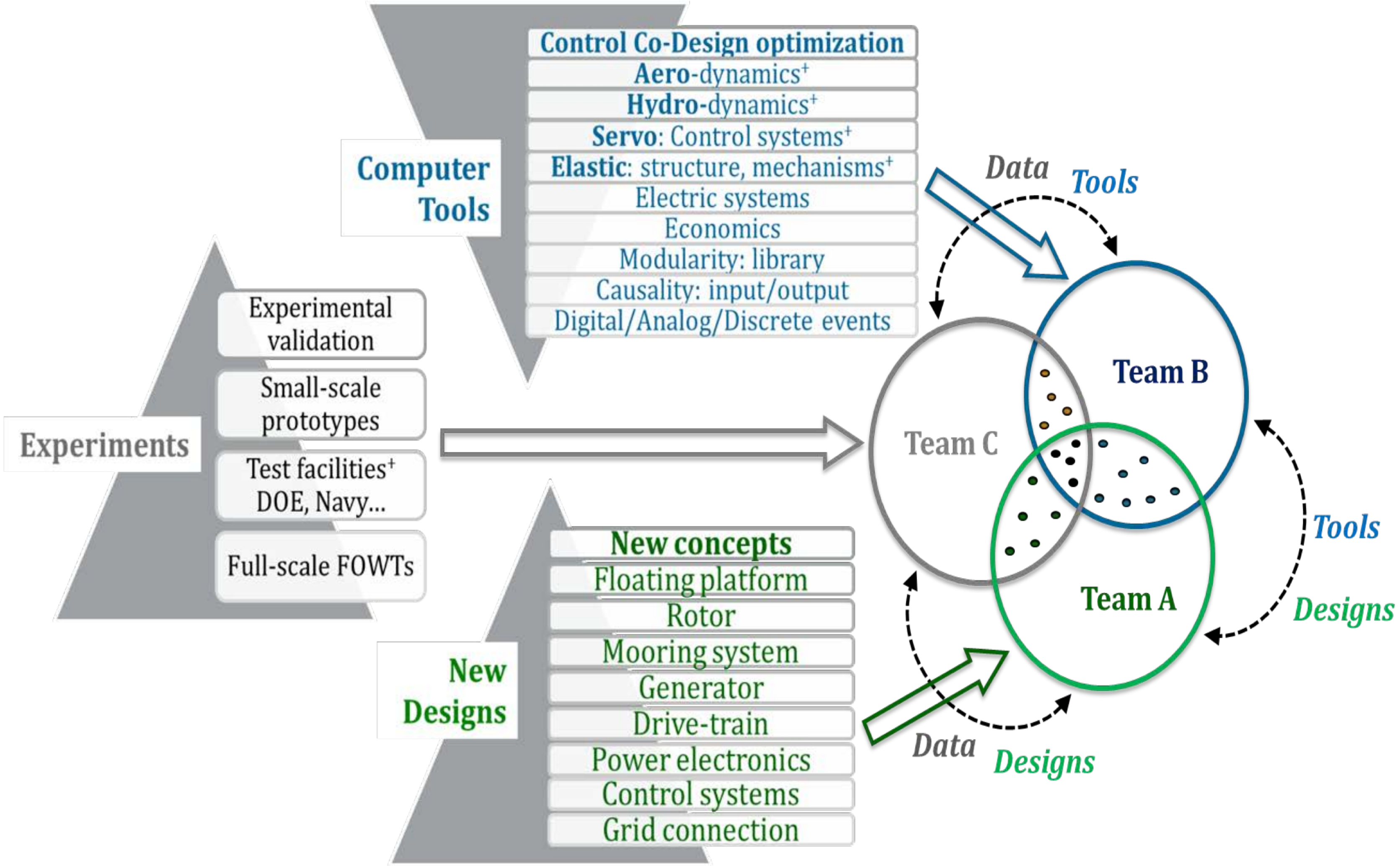
Individual pitch control system for mechanical fatigue minimization in offshore floating wind turbines



OpenFAST, Courtesy NREL



Multi-disciplinary team/program collaboration



1. **Models** or discussion specifying how the project teams will facilitate successful collaborations.
2. **New designs projects**, encouraged to describe main characteristics and challenges of the new designs to teams of other two areas.
3. **Computer tools projects**, encouraged to make the new simulation tools available to the teams of other two areas.
4. **Experiments projects**, encouraged to make the real-world FOWT data available to the teams of other two areas.

THANKS!!

The ATLANTIS team