Control Co-Design of Floating Offshore Wind Turbines

The ARPA-E ATLANTIS Program

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1. Control Co-Design (CCD)

Sequential

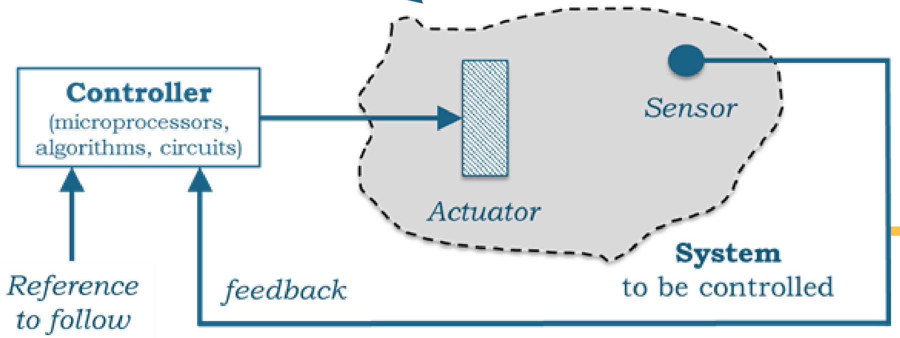
Each step limits the next one

- The increasing **complexity** of technology has changed the way we study engineering.

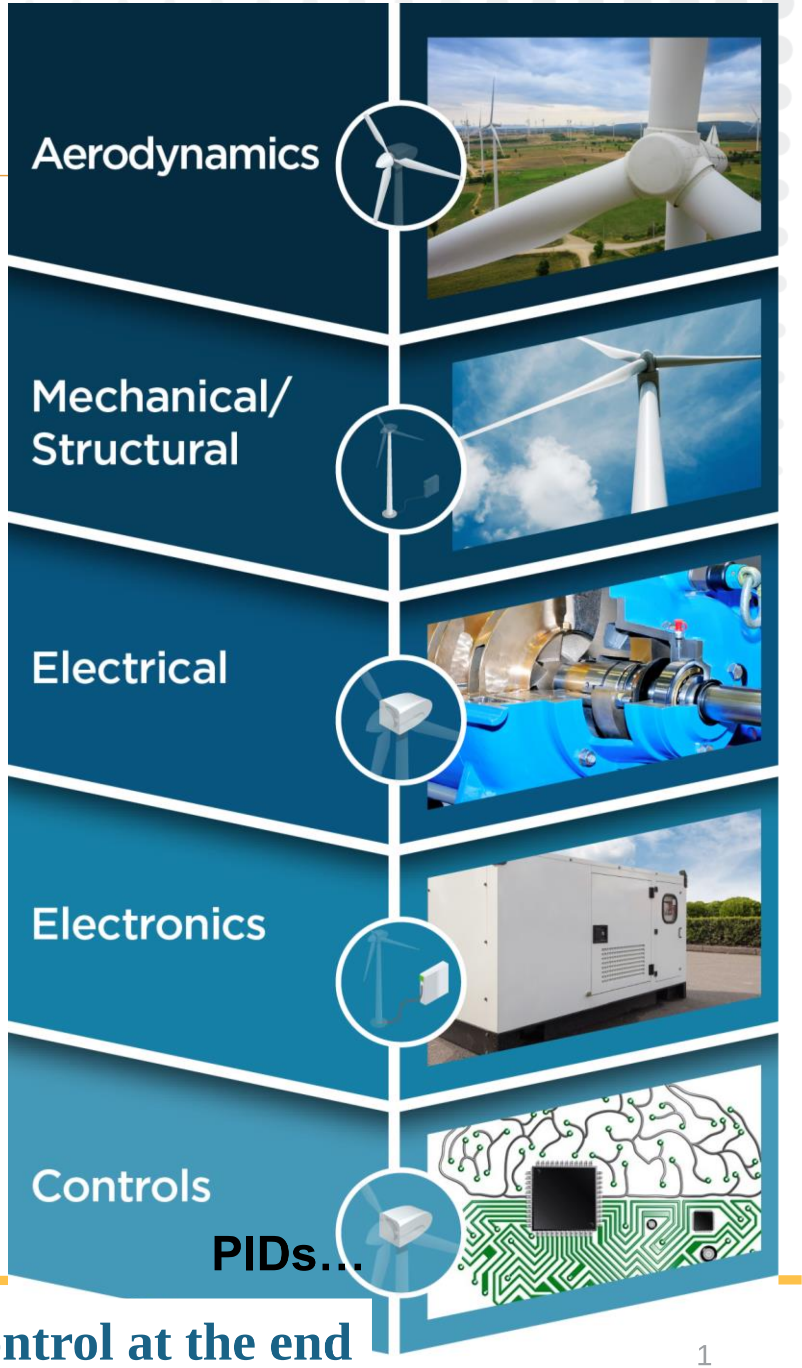
  Engineering **careers** are now much more **specialized**.

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

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

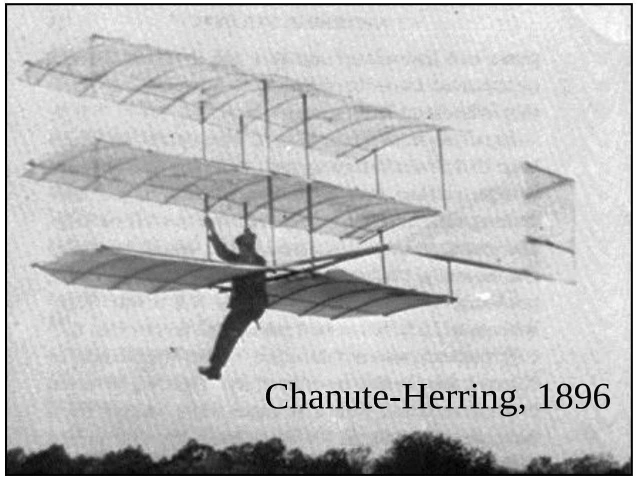


- This sequential approach **<u>limits</u>** the **<u>possibilities</u>** of the design.



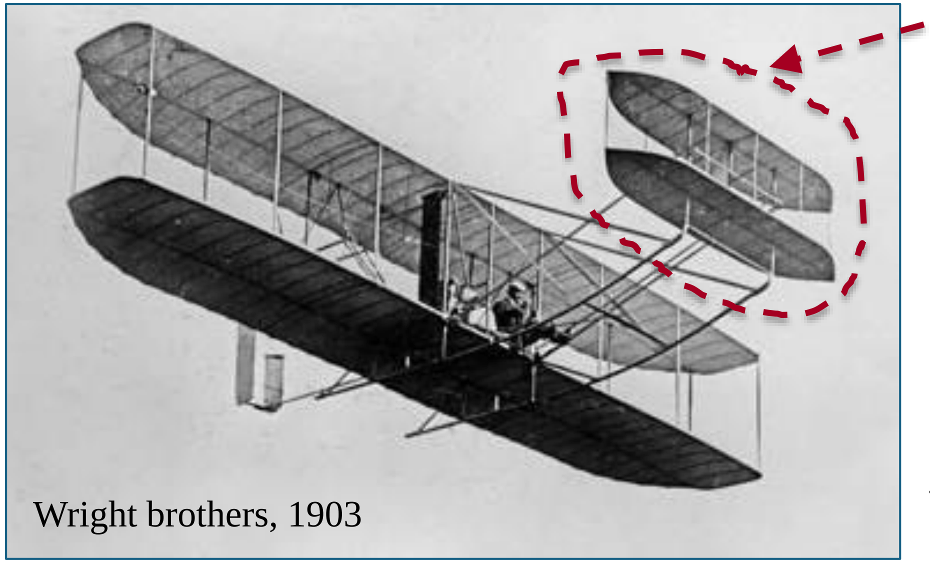
Control at the end

Control Co-Design



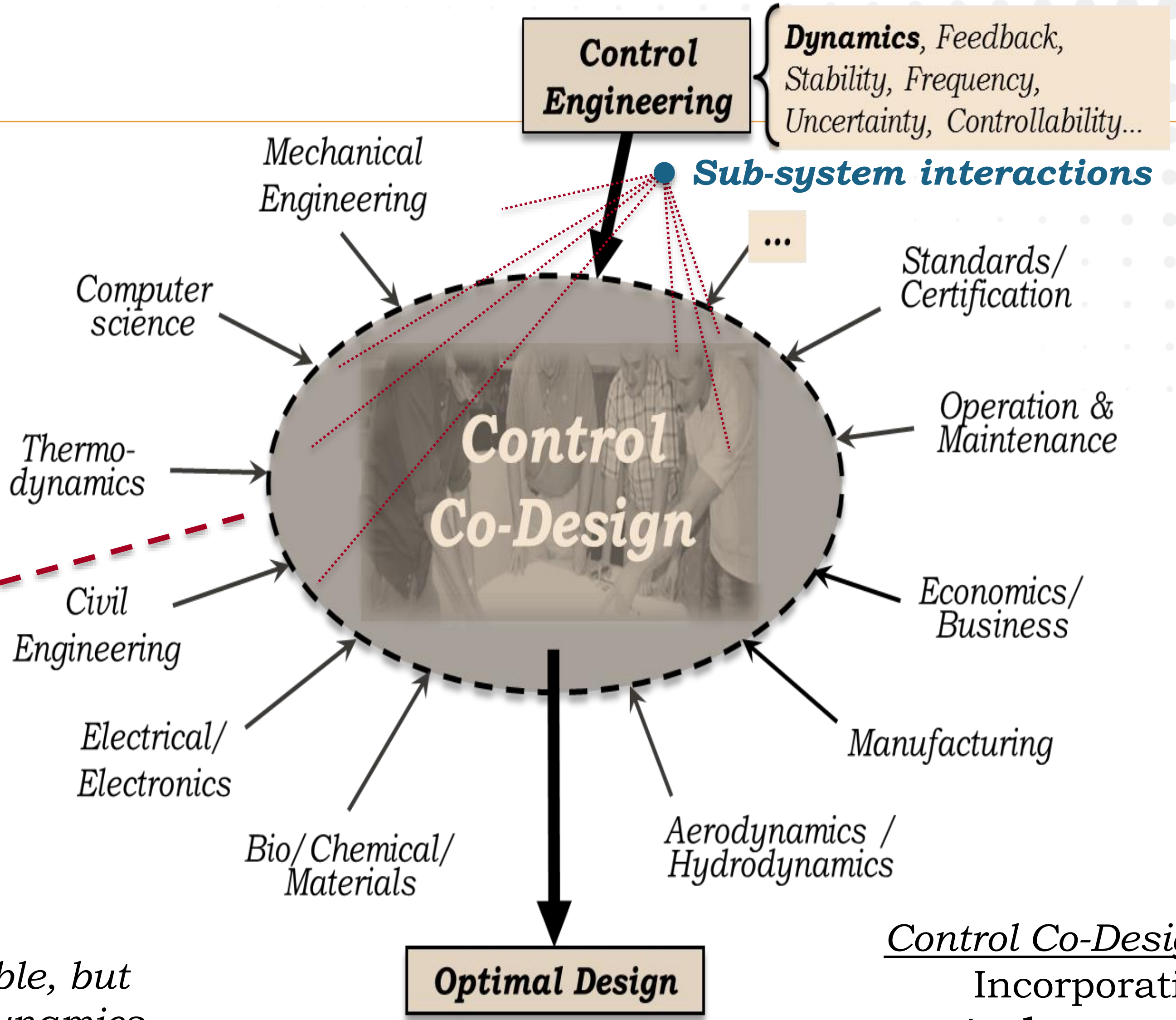
Chanute-Herring, 1896

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**!!!

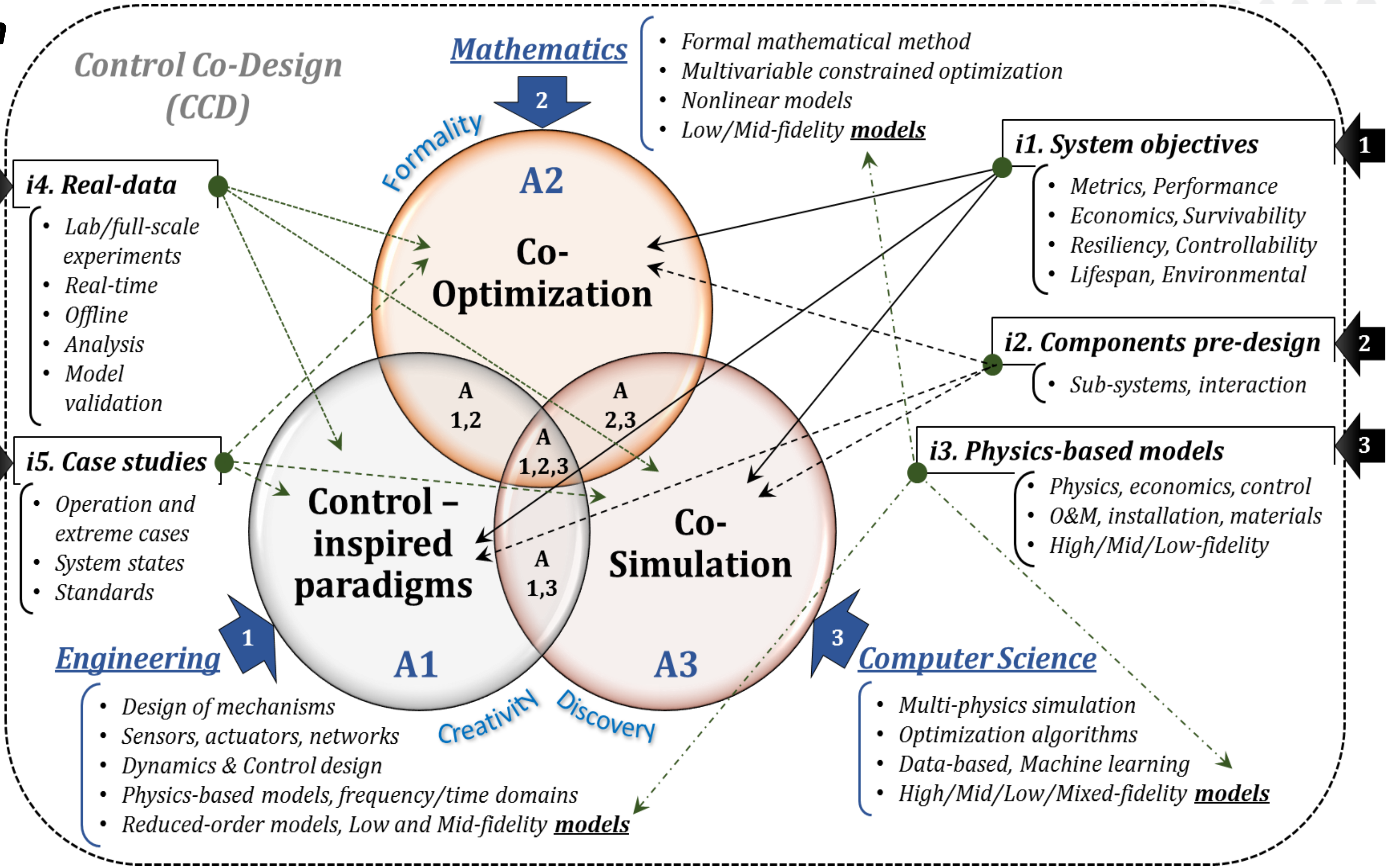
Control Co-Design

Five Inputs:

i1 to i5

Three Areas:

A1 to A3



Garcia-Sanz M. (2019). *Control Co-Design: an engineering game changer*. Advanced Control for Applications, Wiley, Vol. 1, Num. 1. https://doi.org/10.1002/adc2.18

2. New Metric Space

Garcia-Sanz M. (2019). *A Metric Space with LCOE Isolines for Research Guidance in Wind and Hydrokinetic Energy Systems*. Wind Energy, Wiley;1–21. https://doi.org/10.1002/we.2429.

LCOE

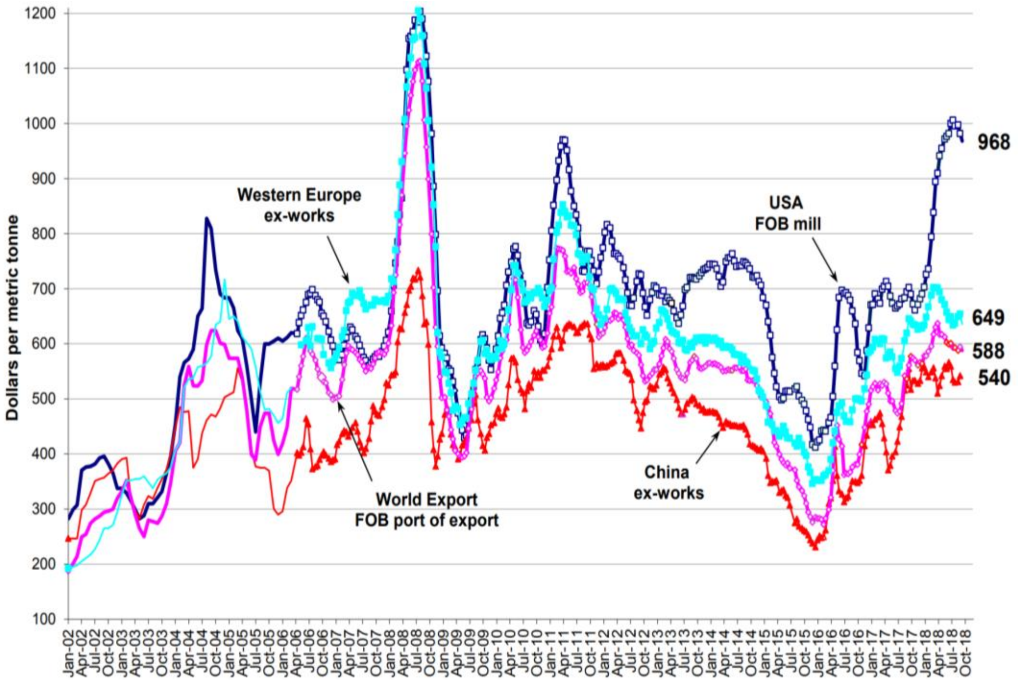
Wind projects are calculated in terms of the ***Levelized Cost Of Energy*** (*LCOE*), as dollars per MWh, or cents of dollar per kWh, and is a function of:

- the *capital expenditures* or ***CapEx*** of the turbine (in $), which includes the cost of the blades, nacelle, tower, electrical generator, gearbox, pitch and yaw systems, power electronics, floating platform, mooring system, anchor system, etc.;
- the *fixed charge rate* or ***FCR*** (in 1/year), which includes the cost of money, taxes and amortization;
- the *operation and maintenance expenditures* or ***OpEx*** (in $/year);
- the *annual energy production* or ***AEP*** (in kWh), which depends on the site wind characteristics.

$$LCOE = \frac{FCR\ (\sum_{k=1}^{n} CapEx(k)) + \sum_{k=1}^{n} OpEx(k)}{\sum_{k=1}^{n} AEP(k)} = \left[\frac{\$/year}{kWh/year}\right]$$

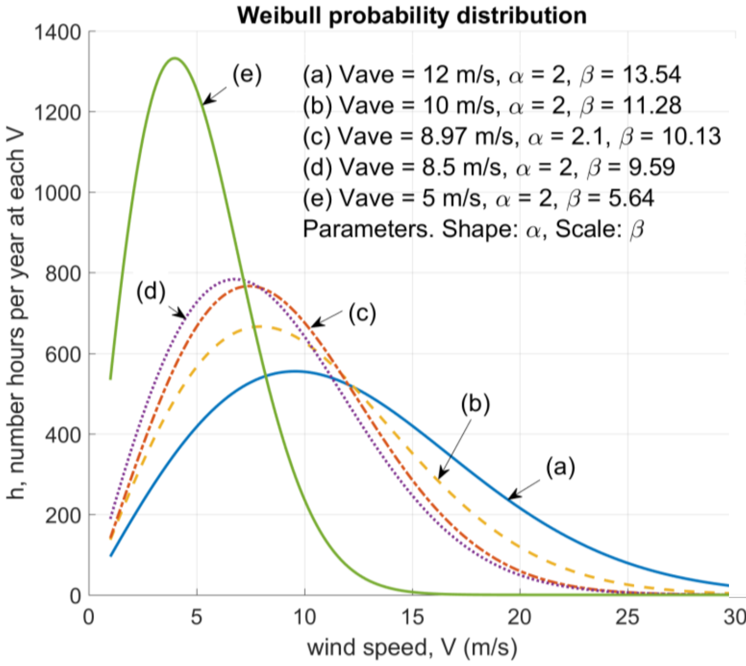
LCOE dependences

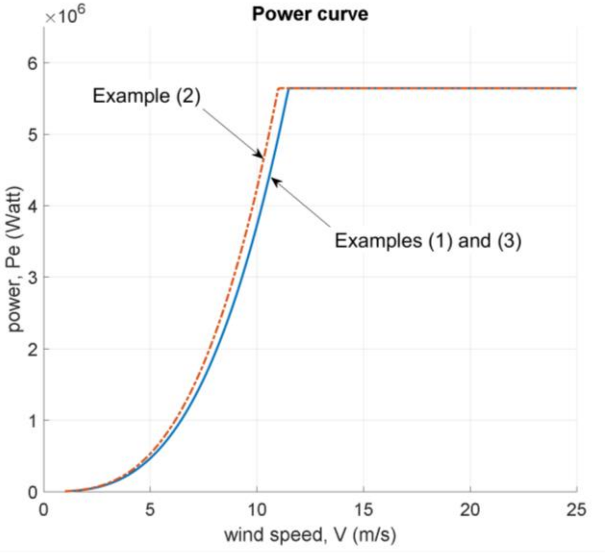
LCOE cost of steel dependence



CapEx ($) $= f(Cost\ of\ steel)$

LCOE site dependence





AEP (kWh) $= P_e * h$ = $\left(0.5\, \rho\, A\, C_p\, \mu\, V^3\right) * h$

New metric space: *first metric*

Based on internal properties

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

$$\boxed{\boldsymbol{M_1} = \left.\frac{\sum_{k=1}^{n} P_{e1}(k)}{\sum_{k=1}^{n} P_{w1}(k)}\right|_{at\ V_1} = \sum_{k=1}^{n}\Big(w(k)\ C_p(k)\ \mu(k)\Big)}$$

$$P_{e1}(k) = \frac{1}{2}\ \rho\ A_r(k)\ C_p(k)\ \mu(k)\ V_1^3$$

$$P_{w1}(k) = \frac{1}{2}\ \rho\ A_r(k)\ V_1^3$$

$$w(k) = \frac{A_r(k)}{\sum_{k=1}^{n} A_r(k)}$$

$$C_p(k) = C_{pmax}(k)$$

$$\mu(k) = \big(1 - L_g(k)\big)\ \big(1 - L_{dt}(k)\big)\ \big(1 - L_w(k)\big)\ \big(1 - L_e(k)\big)\ \big(1 - L_o(k)\big)\ A_v(k)$$

where:

→ n = number of WTs in the farm,

→ ρ = 1.225 kg/m^3 is the density of the air,

→ $A_r(k) = \pi R^2$ is the swept area of the k WT rotor in m^2,

→ V_1 is the selected undisturbed upstream below-rated wind velocity (for example = 8 m/s),

→ $C_p(k)$ = aeropdynamic efficiency of k WT,

→ $\mu(k)$ = efficiency of k WT, including (all in per unit):

- L_g: generator losses,
- L_{dt}: drive-train (gearbox and power electronics) losses,
- L_w: wake effect losses due to the aerodynamic interaction of turbines in the farm,
- L_e: electrical losses (substation and electrical lines, intra-wind-farm and farm-to-shore),
- L_o: other losses,
- A_v: wind turbine availability.

New metric space: second metric

Based on internal properties

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

$$\boxed{\boldsymbol{M_2} = \frac{\sum_{k=1}^{n} A_r(k)}{\sum_{k=1}^{n} M_{eq}(k)}}$$

$$M_{eq}(k) = \sum_{j=1}^{z} m_j(k)$$

$$m_j(k) = f_{tj}(k)\left(1 + f_{mj}(k) + f_{ij}(k)\right) m_{cj}(k)$$

where:

→ n = number of WTs in the farm

→ $A_r(k) = \pi R^2$ is the swept area of the k WT rotor in m^2,

→ f_t = material factor = cost original material ($/kg) / cost steel of reference ($/kg)

→ f_m = manufacturing factor = cost manufacturing of component ($/kg) / cost original material of the component ($/kg)

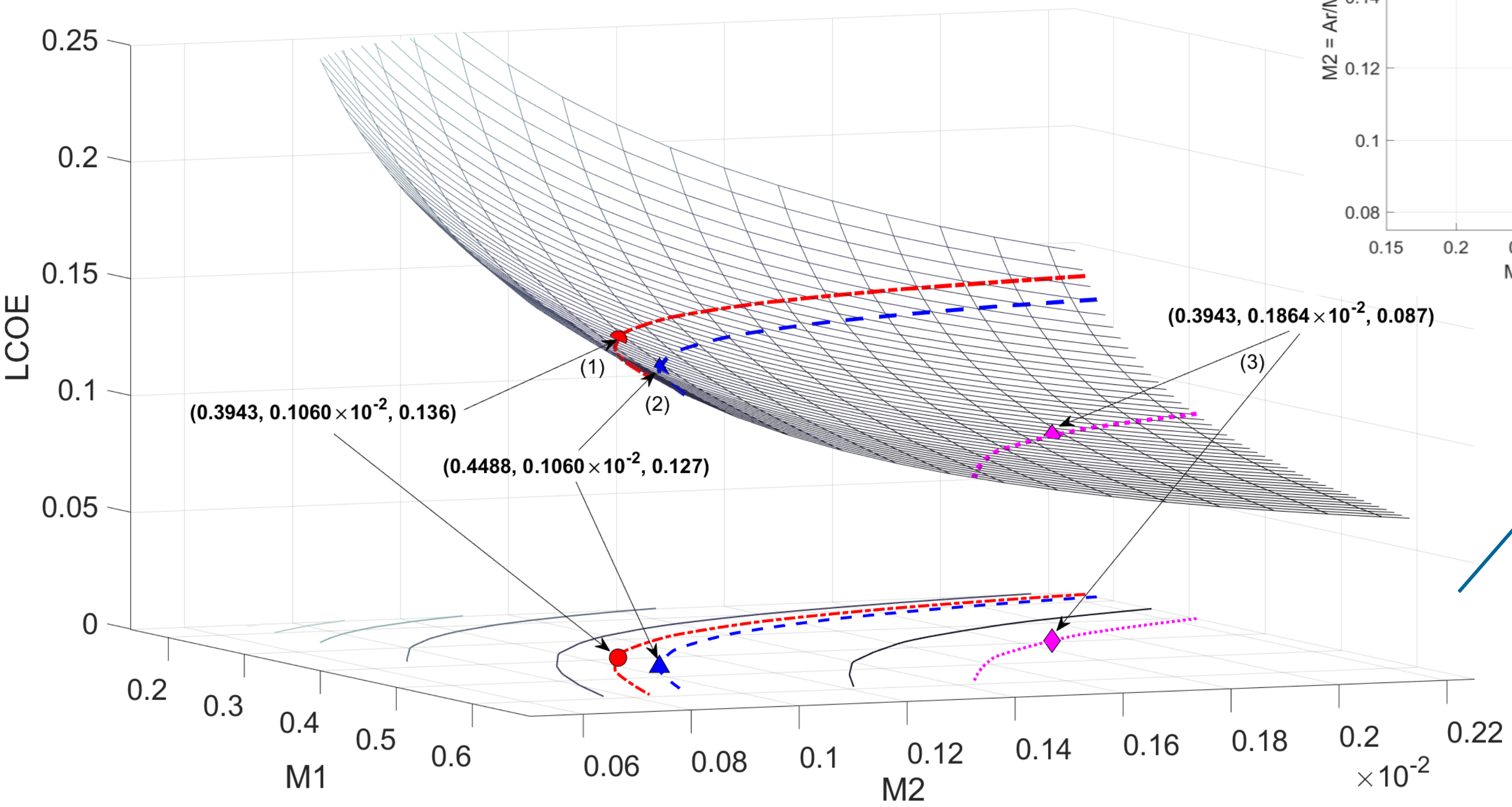
→ f_i = installation factor = cost installation of component ($/kg) / cost original material of the component ($/kg)

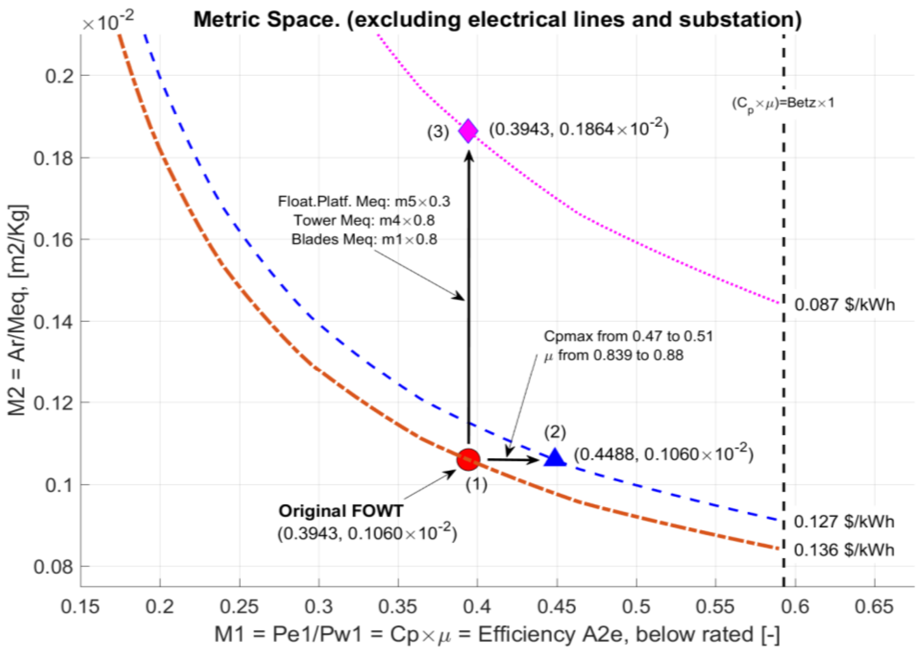
→ m_c = mass of each major component of the FOWT (kg)

→ z = number of main components of the k WT

New metric space: *LCOE isolines*

Combining M1 and M2, and fixing external properties, the LCOE appears in a third dimension

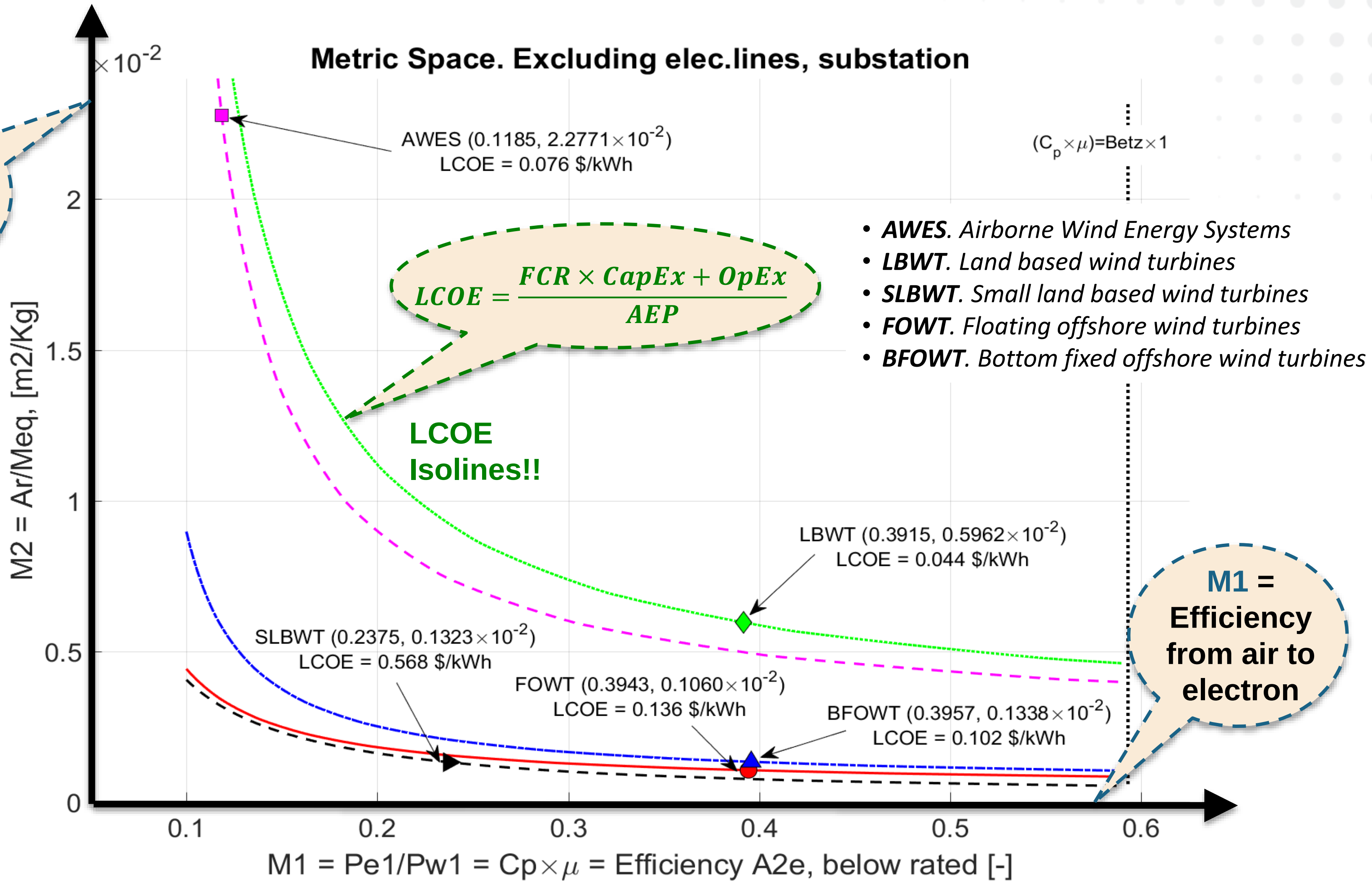




2D Projection

New metric space: *WT technologies*

M2 = Swept Area / Mass-eq



One WT case

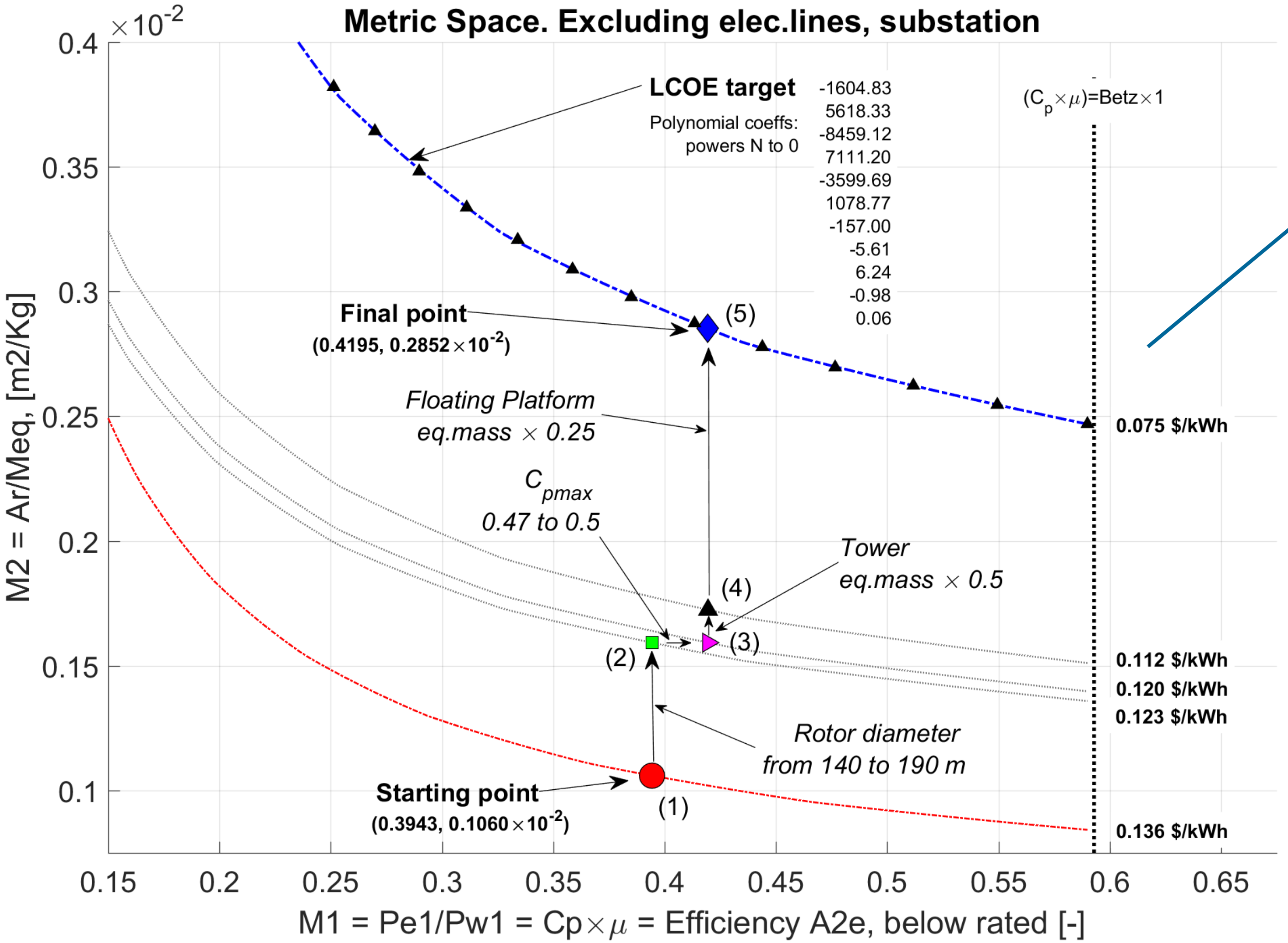
$$M_1 = \frac{P_{e1}}{P_{w1}}\bigg|_{at\ V_1} = C_p\,\mu$$

$$M_2 = \frac{A_r}{M_{eq}}$$

$$M_{eq} = \sum_{j=1}^{Z} m_j$$

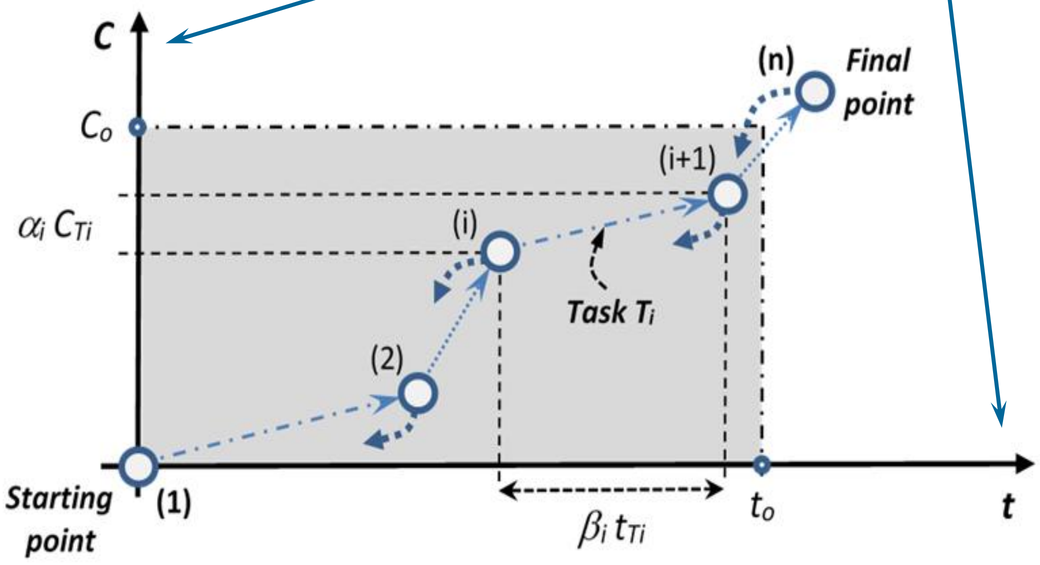
$$m_j = f_{tj}\left(1 + f_{mj} + f_{ij}\right) m_{cj}$$

New metric space: *research guidance*



***Tasks** (T_i) and*

*associated **Cost** (C) and **Time** (t)*



3. ARPA-E ATLANTIS Program

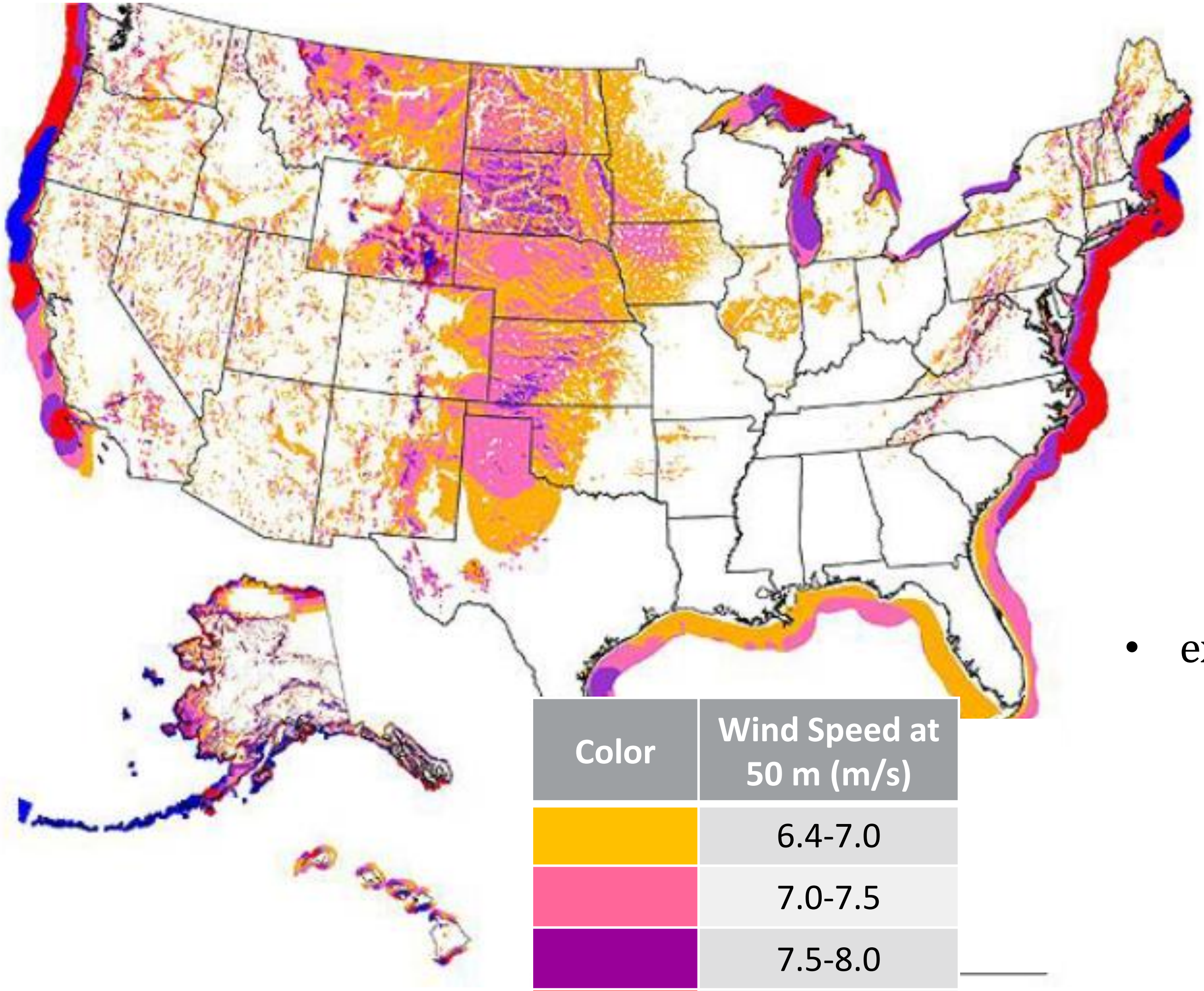
Aerodynamic **T**urbines **L**ighter and **A**float with **N**autical **T**echnologies and **I**ntegrated **S**ervo-control

Program Director Dr. Mario Garcia-Sanz

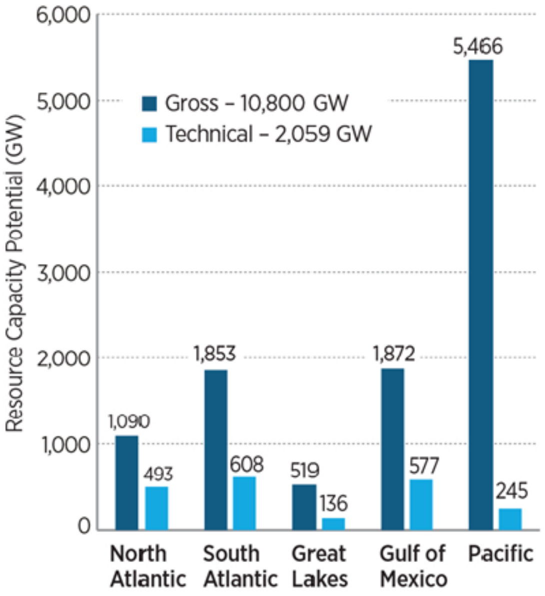
Application of Control Co-Design methodologies
that integrate dynamics and control engineering at the start of the design process, enabling **optimal FOWT** solutions that are not achievable otherwise.

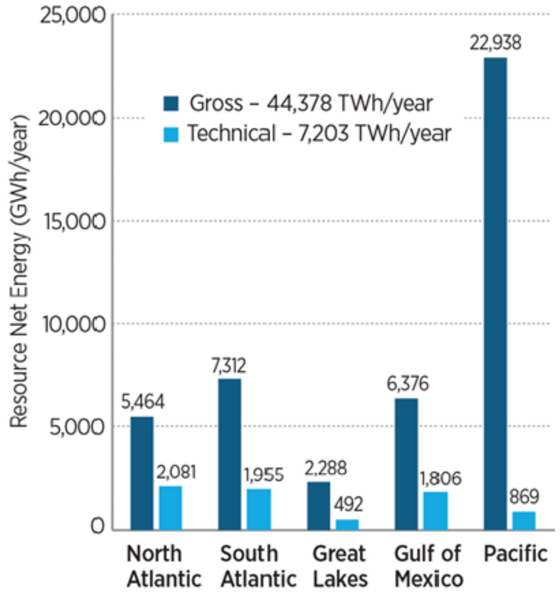
Floating Offshore Wind Turbines (FOWT)

ATLANTIS Program: U.S. resources



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

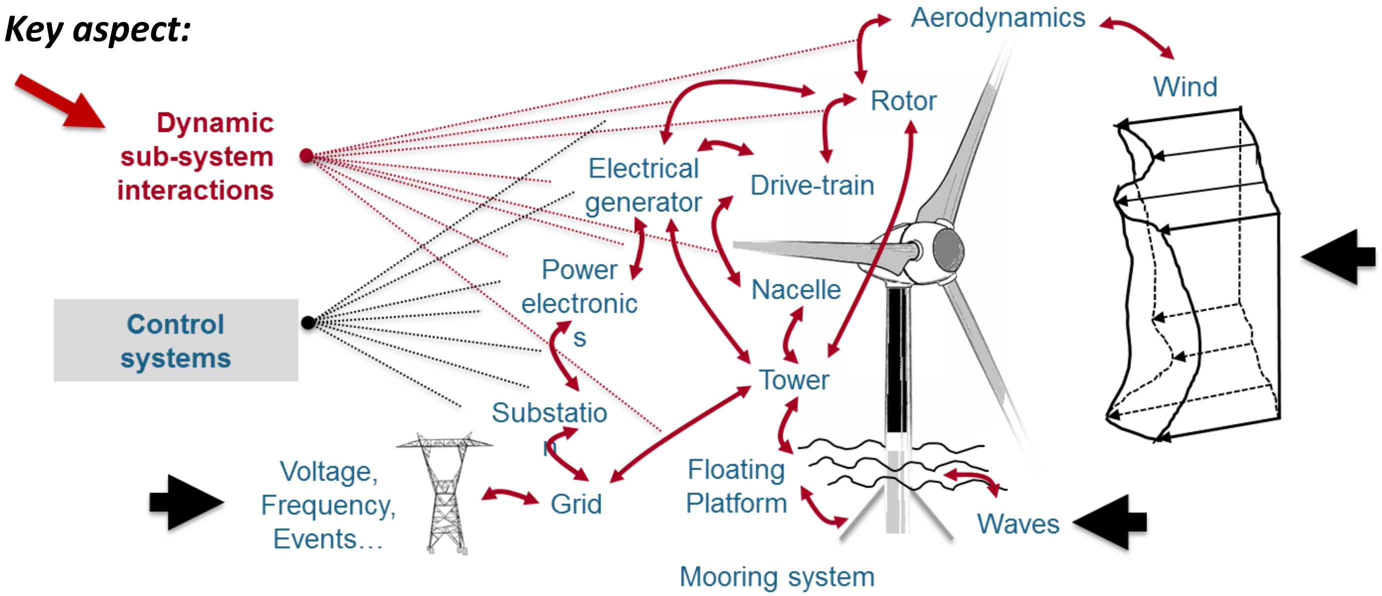
Total technical offshore = 7,203 TWh/year

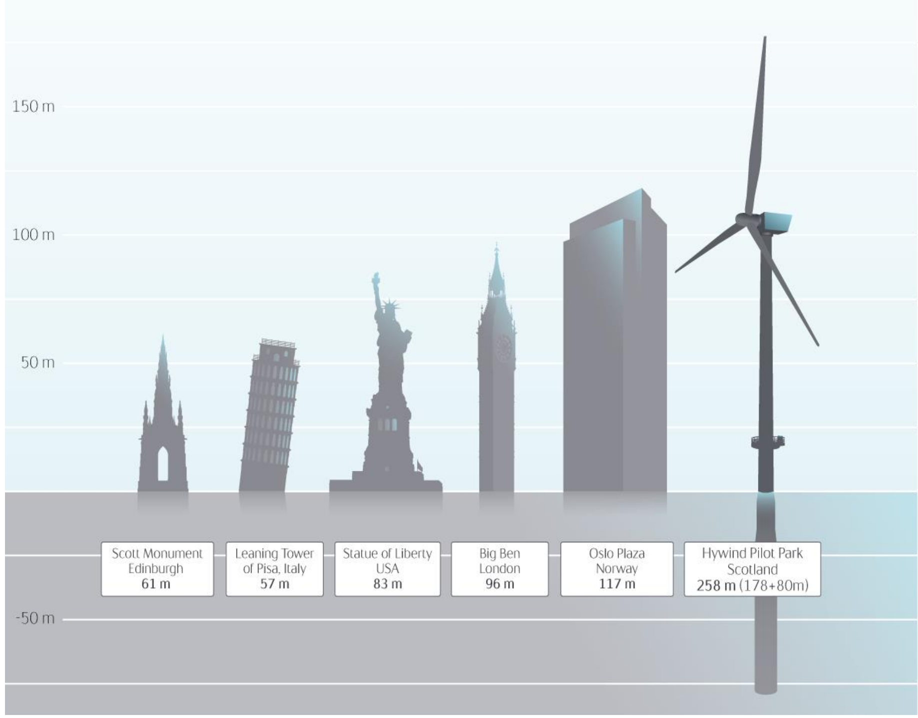
- Total floating (>60m) = **4,178 TWh/year** > **U.S. electricity consumption** = 3,911 TWh/year (2017) which requires a small part of the gross resource area

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

ATLANTIS Program: Control Co-Design

Key aspect:





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

Control Co-Design
= Radical mass
reduction

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

= Colossal Mass to stabilize system
(~70% of CapEx is Floating Platform)

ATLANTIS Program: Objective in Metric Space

Metrics:

$$M_1 = \left.\frac{P_{e1}}{P_{w1}}\right|_{at\ V_1} = C_p\ \mu$$

$$M_2 = \frac{A_r}{M_{eq}}$$

$$M_{eq} = \sum_{j=1}^{z} m_j$$

$$m_j = f_{tj}\left(1 + f_{mj} + f_{ij}\right) m_{cj}$$

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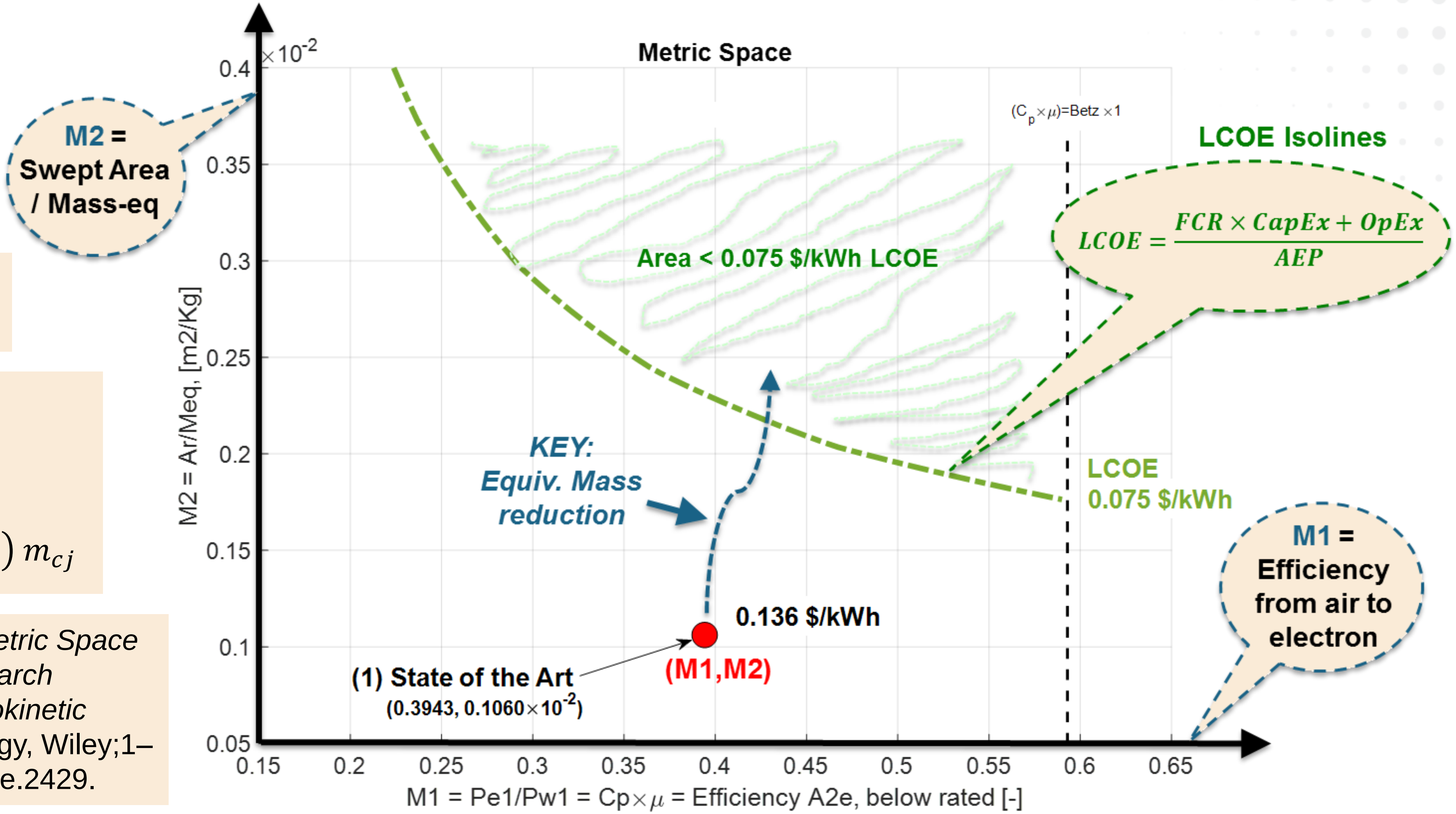


ATLANTIS Program: Areas

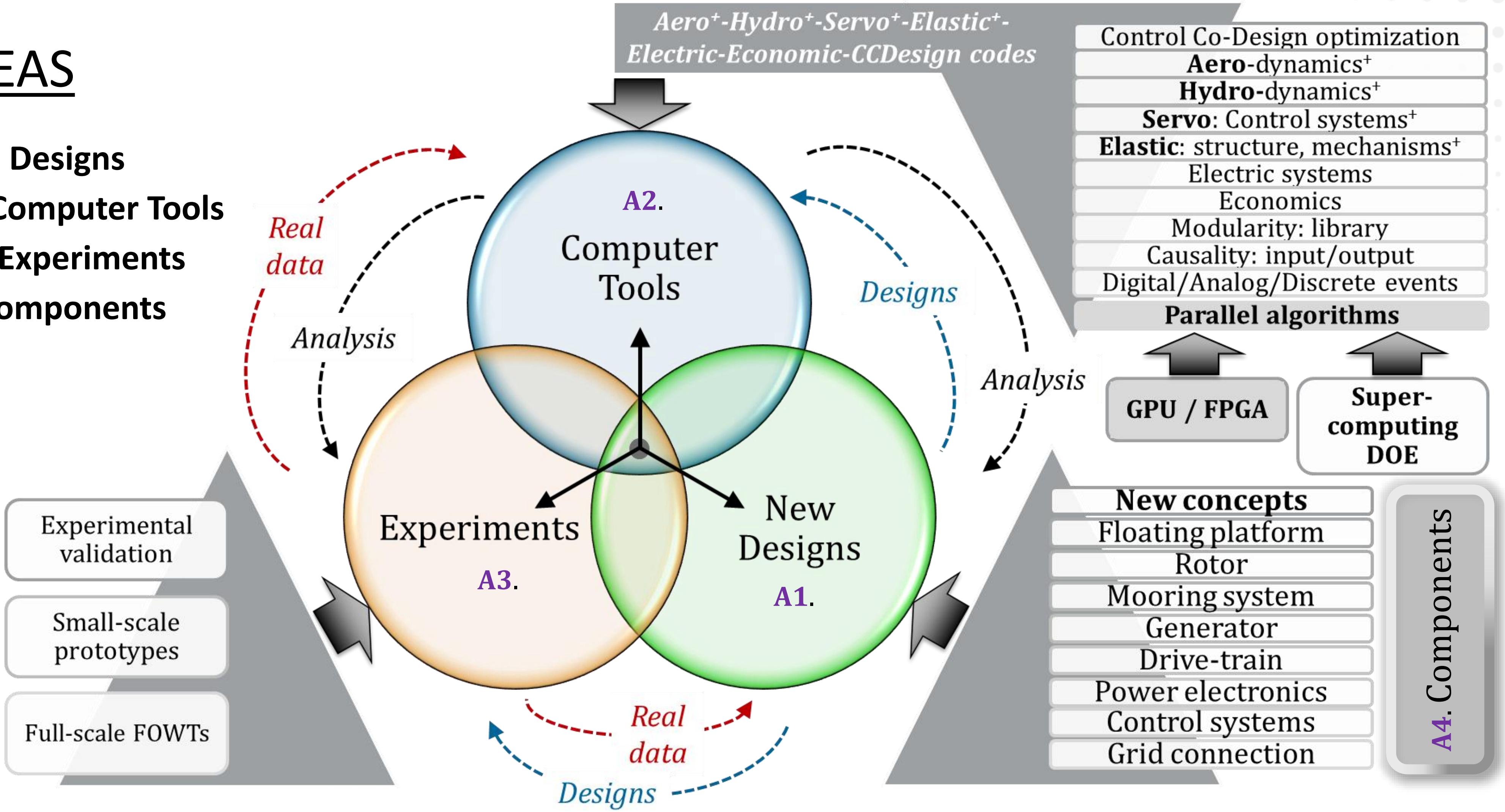
AREAS

A1. New **Designs**

A2. Enhanced **Computer Tools**

A3. Physical **Experiments**

A4. Extra **Components**



ATLANTIS Program: ***Projects***

ARCUS Vertical-Axis Wind Turbine.
Sandia Lab, Keppel, ABS

A Low-Cost Floating Offshore Vertical Axis Wind System. **U.T. Dallas, Aquanis, UIUC, VLO, XFlow, NREL**

Ultra-light Concrete Floating Offshore Wind Turbine with NASA-developed Response Mitigation Technology.
U. Maine, NASA, NREL, HOE, ABS

Design and Develop Optimized Controls for a Lightweight 12 MW Wind Turbine on an Actuated Tension Leg Platform. **GE, Glostein**

USFLOWT: Ultra-flexible Smart Floating Offshore Wind Turbine.
NREL, CSM, CU, UIUC, Sandia Lab

AIKIDO - Advanced Inertial and Kinetic energy recovery through Intelligent (co)-Design Optimization.
Otherlab, Bronberg

Wind Energy with Integrated Servo-control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems.
NREL, UIUC

Model-Based Systems Engineering and Control Co-Design of Floating Offshore Wind Turbines. **UCF**

A Co-Simulation Platform for Off-Shore Wind Turbine Simulations.
U.Mass.Am., Sandia Lab

Computationally Efficient Atmospheric-Data-Driven Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis.
Rutgers U., U.Mich., NREL, Brigham Young U., DAR

The Floating Offshore-wind and Controls Advanced Laboratory (FOCAL) Experimental Program.
NREL, U.Maine, DNV-GL

Scale Model Experiments for Co-Designed FOWTs Supporting a High-Capacity (15MW) Turbine.
WS Atkins, MARIN, ABS, NREL, NASA

DIGIFLOAT: Development, Experimental Validation and Operation of a DIGItal Twin Model for Fullscale FLOATing Wind Turbines.
Principal Power, Akselos, ABS, EDP, NSWC, UBC, UW

50 MW Segmented Ultralight Morphing Rotors for Wind Energy.
UVA, NREL, CSM, CU, UIUC, Sandia Lab

Megawatt-scale Power-Electronic-Integrated Generator with Controlled DC Output. **UIUC**

Active Aerodynamic Load Control for Wind Turbines. **Aquanis, U.T. Dallas, Sandia Lab, TPI**

A1. New FOWT **Designs** | A2. Enhanced **Computer Tools** | A3. Physical **Experiments** | A4. Extra **Components**

arpa·e CHANGING WHAT'S POSSIBLE

THANKS!!

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