# Opportunities in Control Co-Design for Wind Systems

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National Renewable Energy Laboratory

ARPA-E Workshop on Control Co-Design for Wind and Marine-hydro-kinetic Energy Systems

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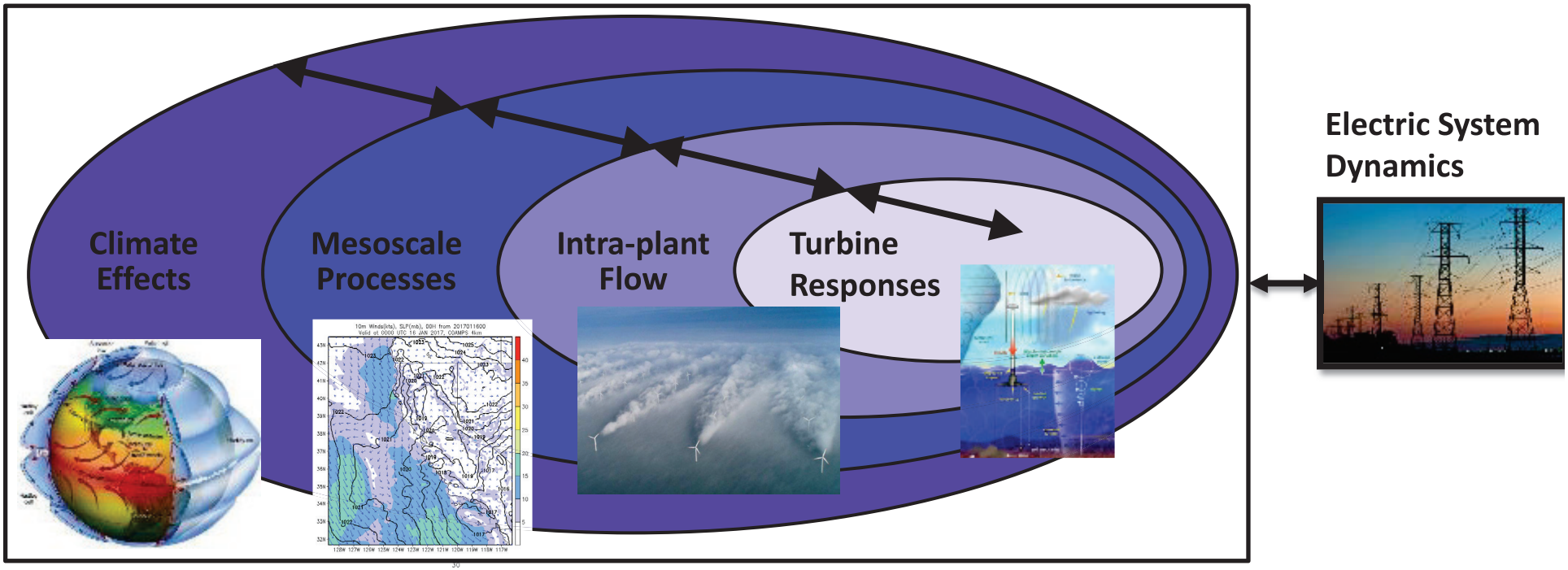
# Challenges and Complexity in Wind System Physics

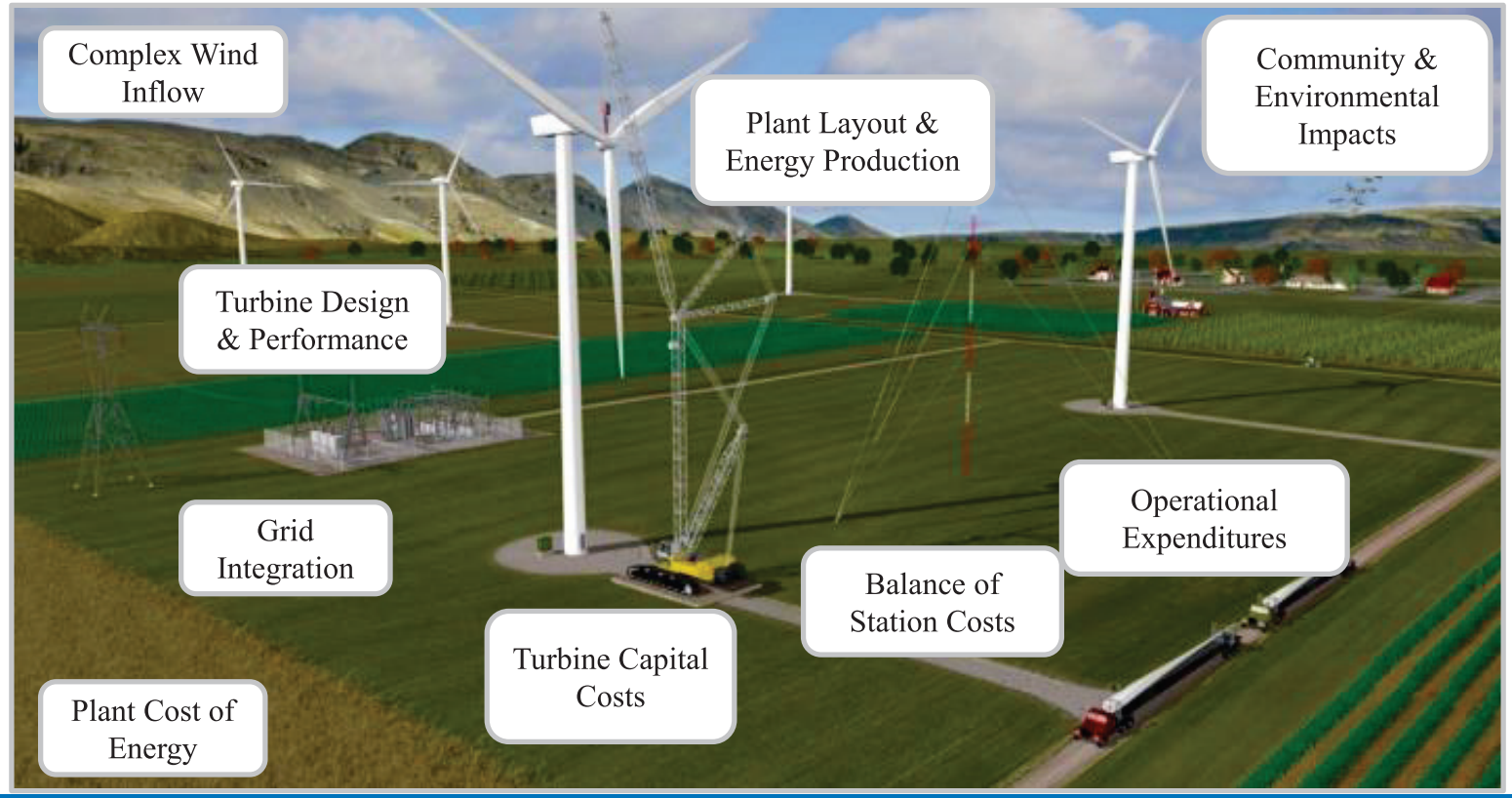
Uncertainty and scientific challenges for wind energy system physics persist and affect ability to further drive down costs

It's all about coupling!



# Challenges and Complexity in Wind System Design

Wind turbine and power plant design, development and control are partitioned across a large industry between sub-sectors resulting in sub-optimal system-level performance and cost

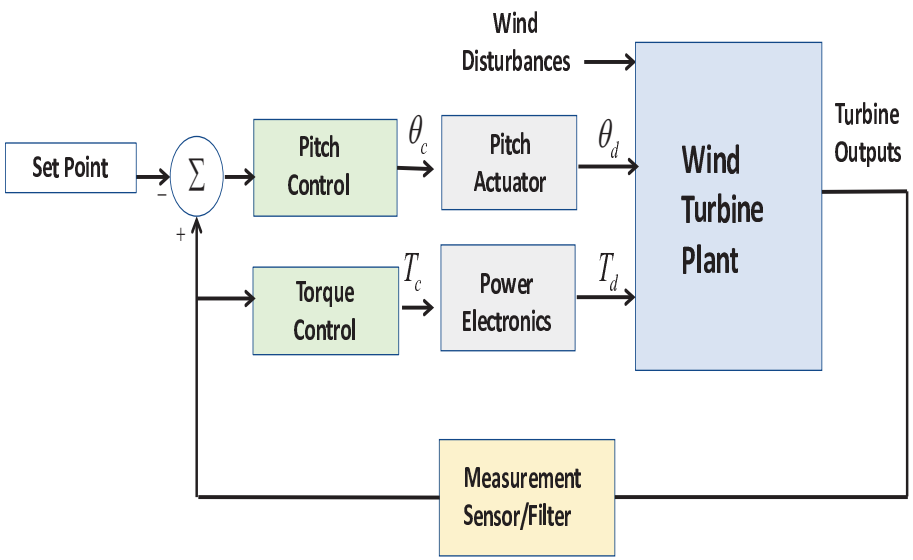



*A full wind plant involves stakeholders and large technical complexity*
*Graphic: Al Hicks, NREL*

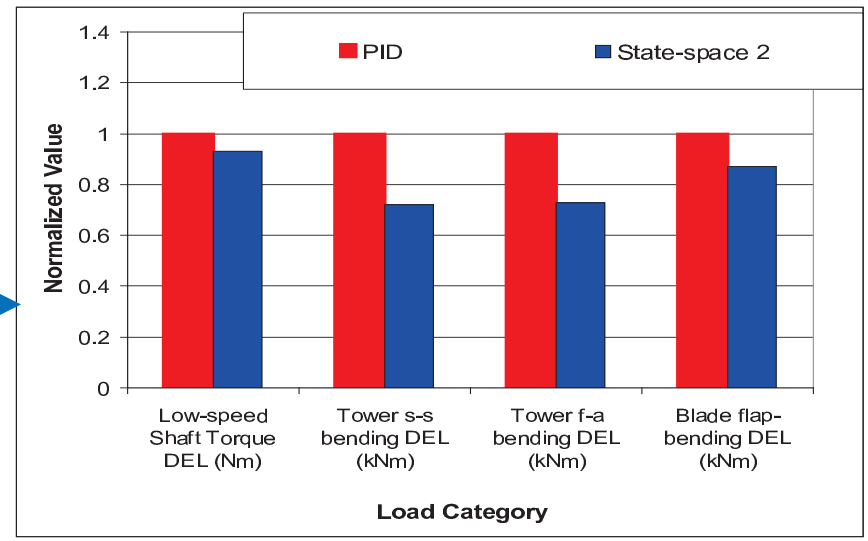
# Co-Design Opportunities for Wind Turbines

# Past Control Design Practice:

## Control Loops




## Load Reduction Results




## Sensors

**Strain gages**

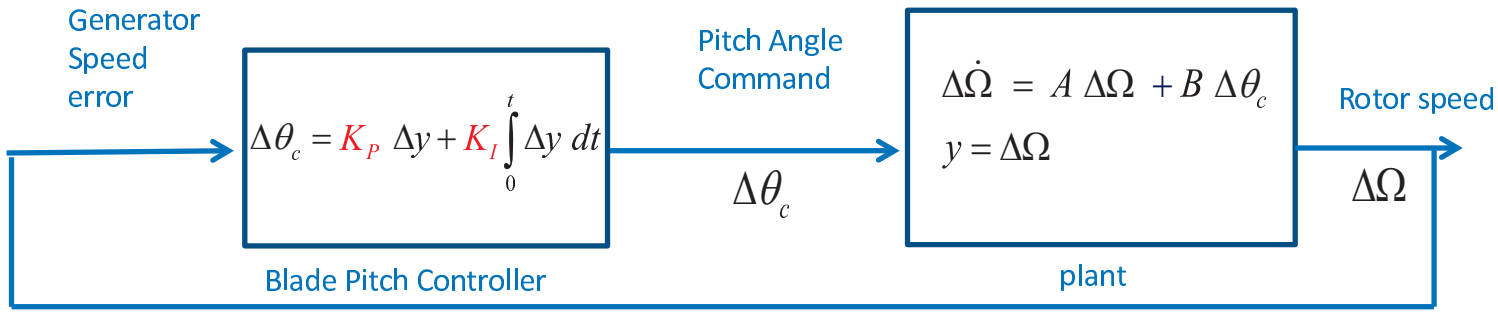
**Accelerometers**

**Speed sensors**

Control designed for existing turbine!

# Opportunities for Control Co-Design

## PI pitch control for speed regulation




## Closed-loop equation

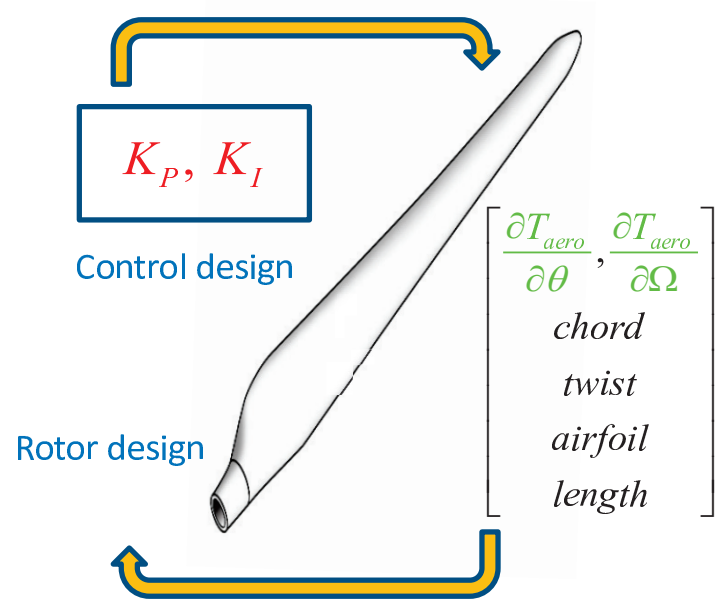
$$\Delta\ddot{\phi} + (-A + B\ K_P)\ \Delta\dot{\phi} + (-B\ K_I)\ \Delta\phi = 0,$$

$$A = \frac{1}{I_{rot}}\left(\frac{\partial T_{aero}}{\partial \Omega}\right),\ B = \frac{1}{I_{rot}}\left(\frac{\partial T_{aero}}{\partial \theta}\right),\quad \left(\Delta\phi = \int_0^t \Delta\Omega\ \mathrm{dt}\right)$$

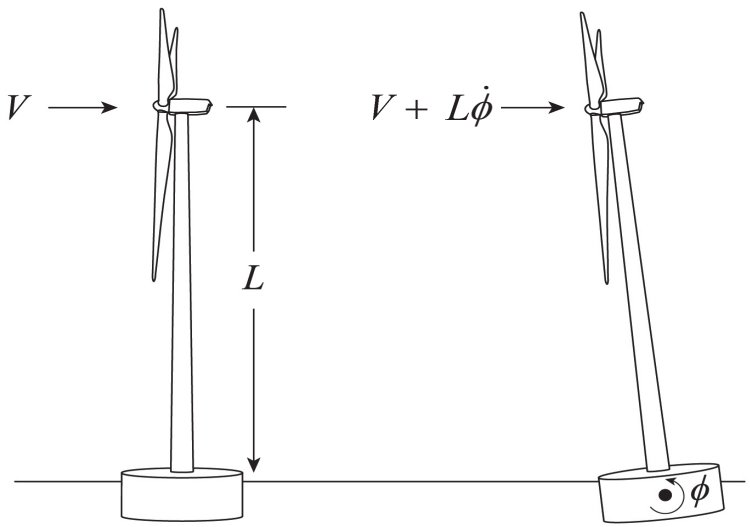
$T_{aero}$ - rotor aerodynamic torque

$I_{rot}$ - total rotational inertia (generator, rotor, etc.)

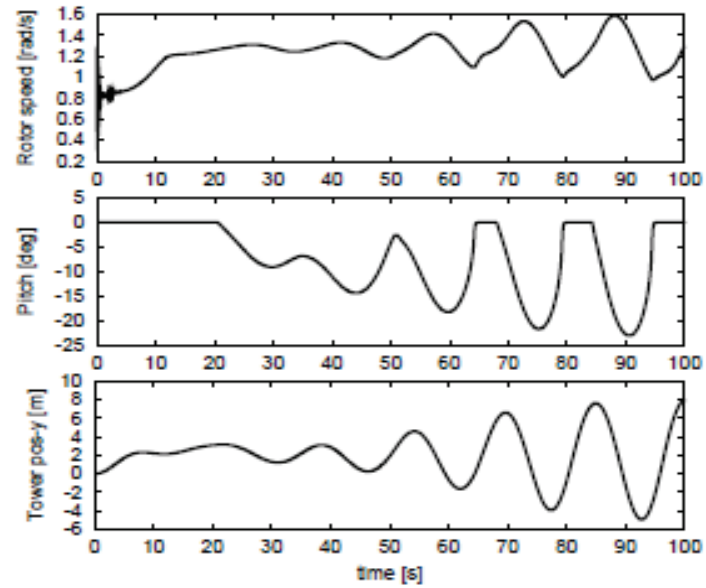
## Co-design process:



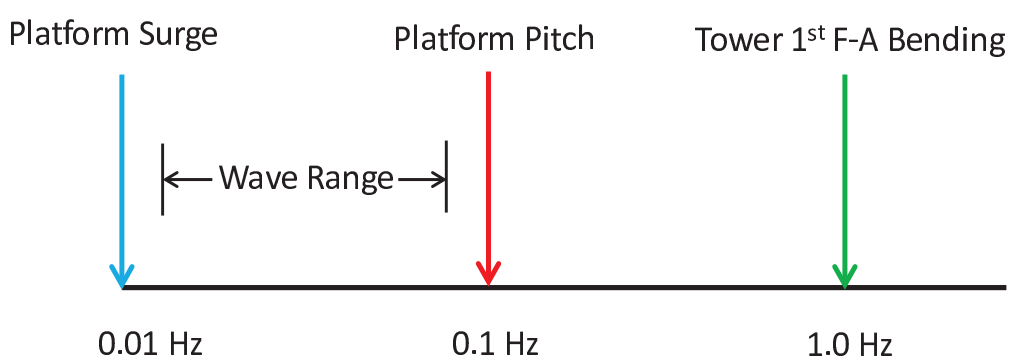
# Special Issues: Offshore Floating Controls




**Platform-Pitch Instability**




**Blade pitch controller drives instability** *

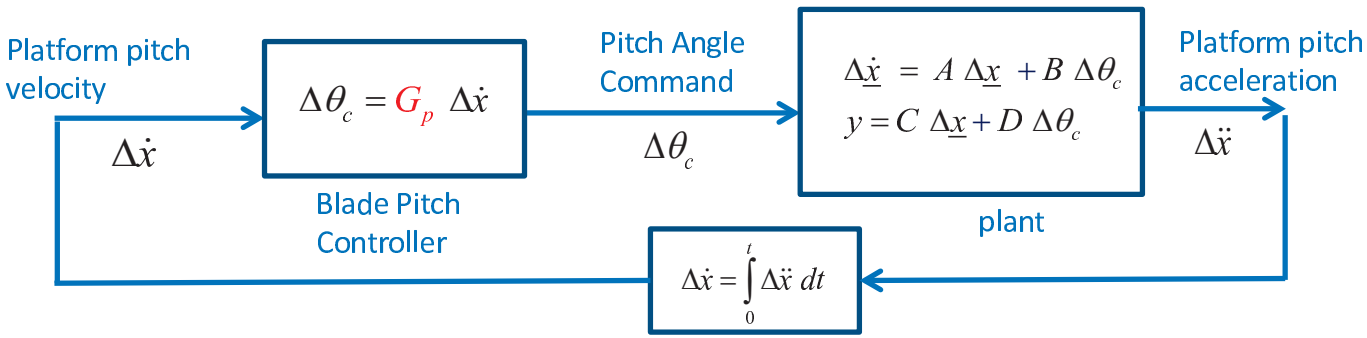



**Lack of pitch authority to mitigate wave loads**

* From: Larsen, T. and Hanson, T. "A Method to Avoid Negative Damped Low Frequent Tower Vibrations for a Floating, Pitch Controlled Wind Turbine." *Journal of Physics. J. Phys.: Conf. Ser. 75 012073.* 2007.

# Opportunities for Control Co-Design (floating)

## pitch control for platform damping




### Closed-loop equation

$$(M_{platform})\Delta\ddot{x} + (C_{platform} + \frac{\partial T_{thrust}}{\partial v} - G_p \frac{\partial T_{thrust}}{\partial \theta_c})\ \Delta\dot{x}$$
$$+ (K_{platform})\ \Delta x = 0,$$

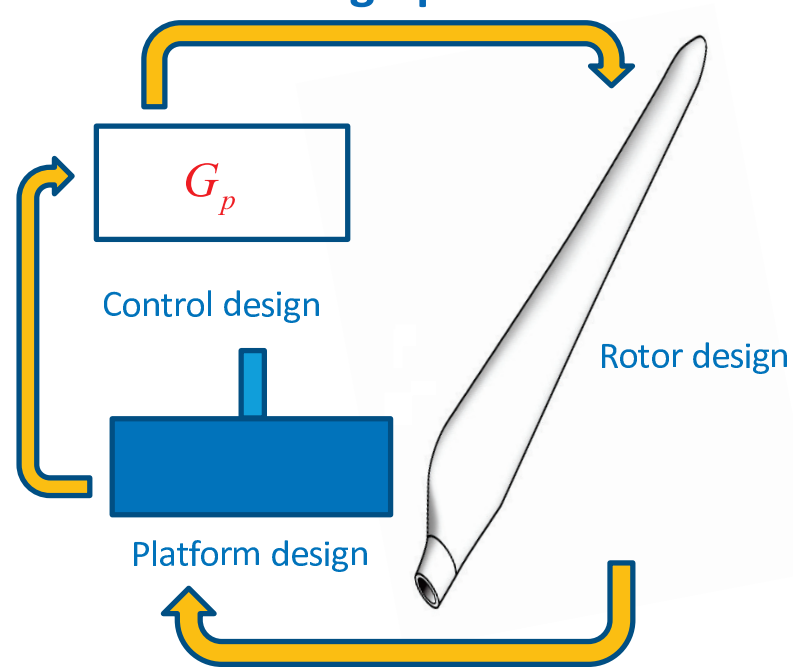
Platform parameters: $M_{platform}, C_{platform}, K_{platform}$

Rotor parameters: $\frac{\partial T_{thrust}}{\partial v}, \frac{\partial T_{thrust}}{\partial \theta_c}$

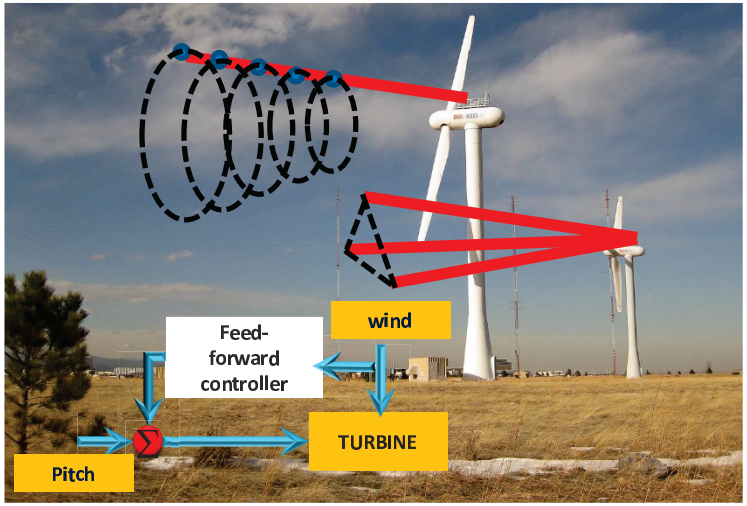
Controller gain: $G_p$

($v$: rotor effective wind speed)

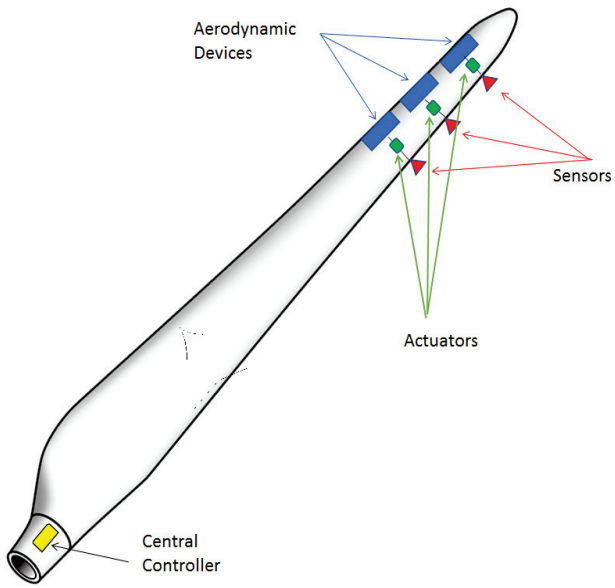
### Co-design process:



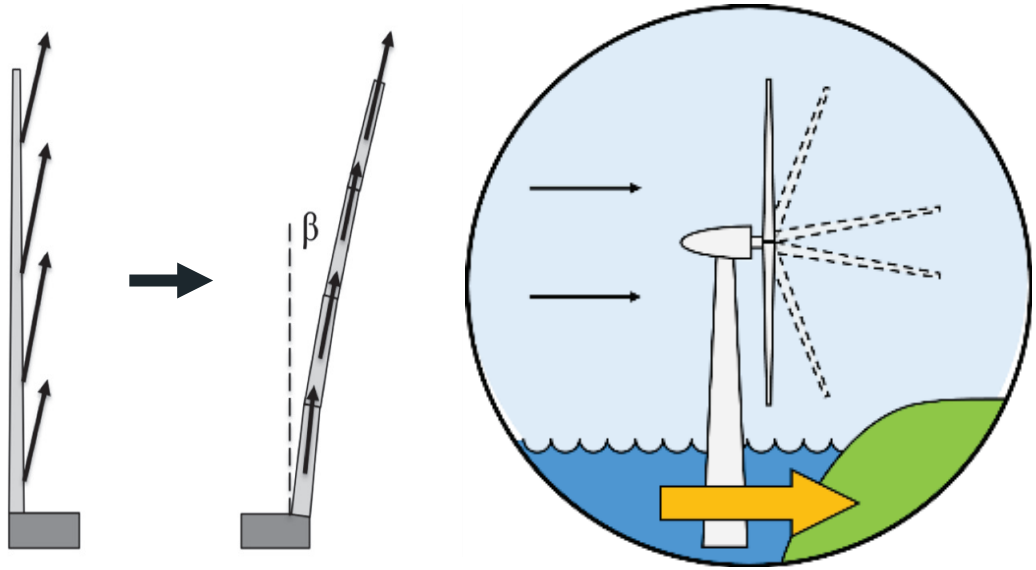
# Recent Control Advancements:




**Lidar feed-forward control**



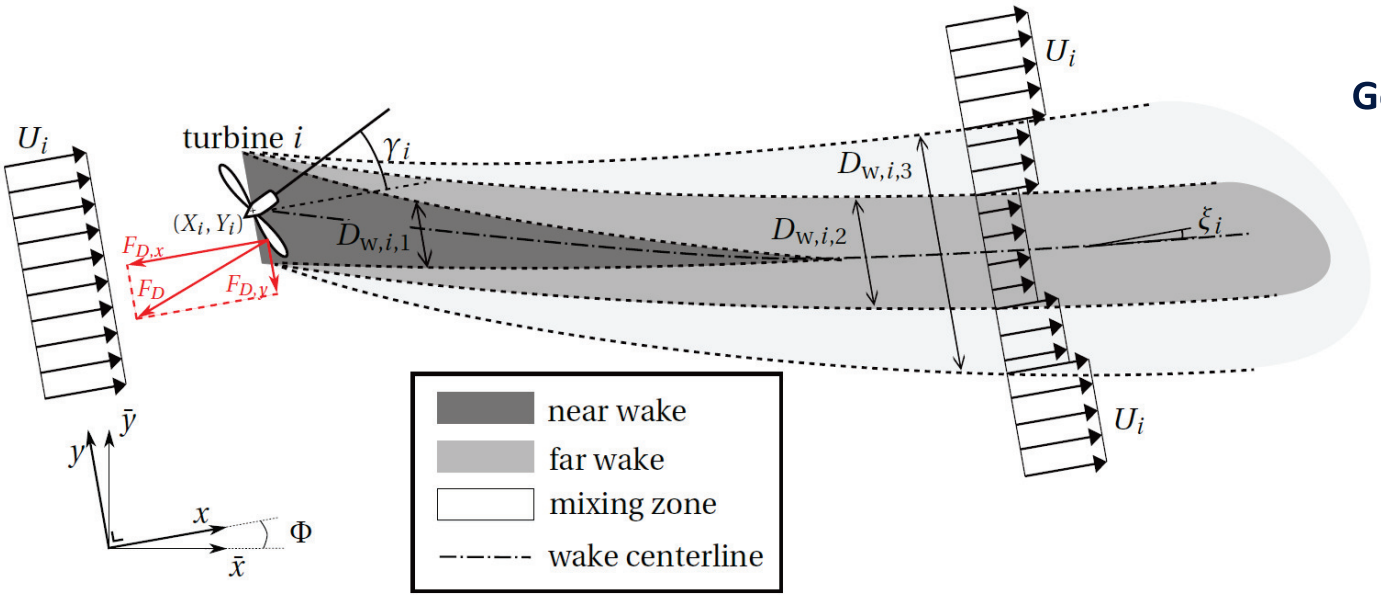

**"Smart" rotor control**




**Control to enable novel turbine configurations such as the ultra-flexible, downwind ARPA-E SUMR-D**

# Co-Design Opportunities for Wind Plants

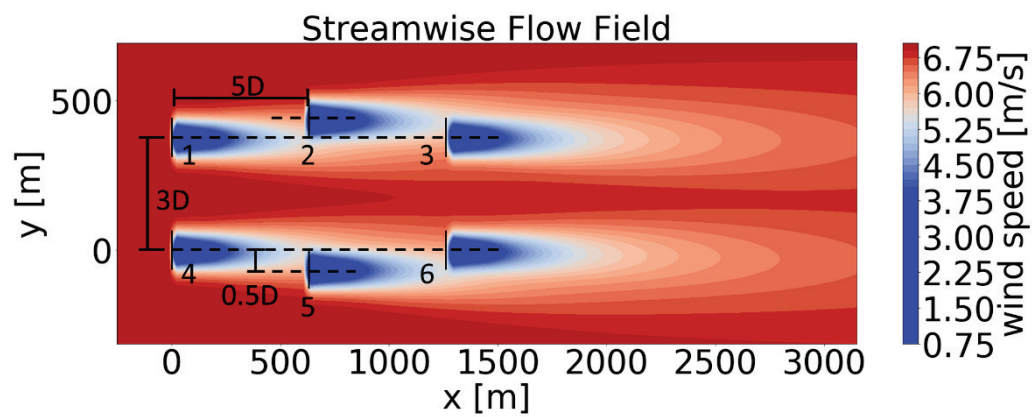
# Wind Plant Control Advancements with NREL FLORIS




**Gebraad, (2014)**

## Opportunities with existing configurations: Wake Steering

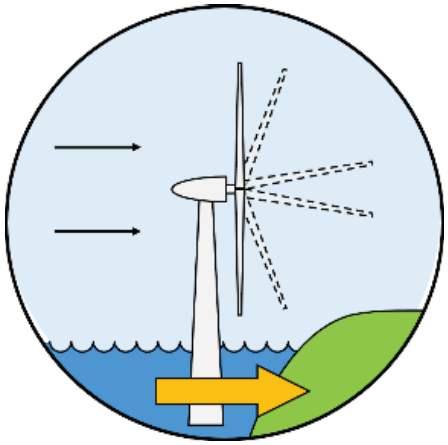
- Controls inspired models driving advancements in wind plant operations




**Bay, (2018)**

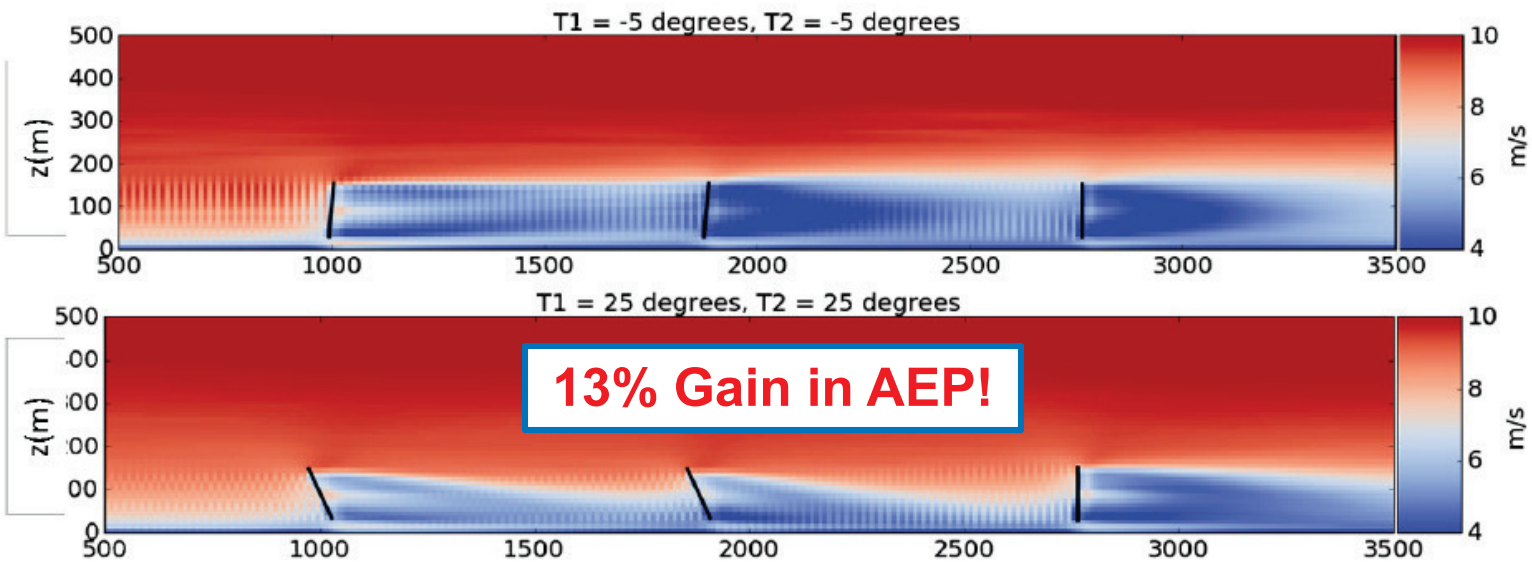
## Co-Design Opportunities with Novel Configurations

- Vertical wake steering brings higher speed winds to downstream turbines
- Enabled by downwind turbines



ARPA-E SUMR

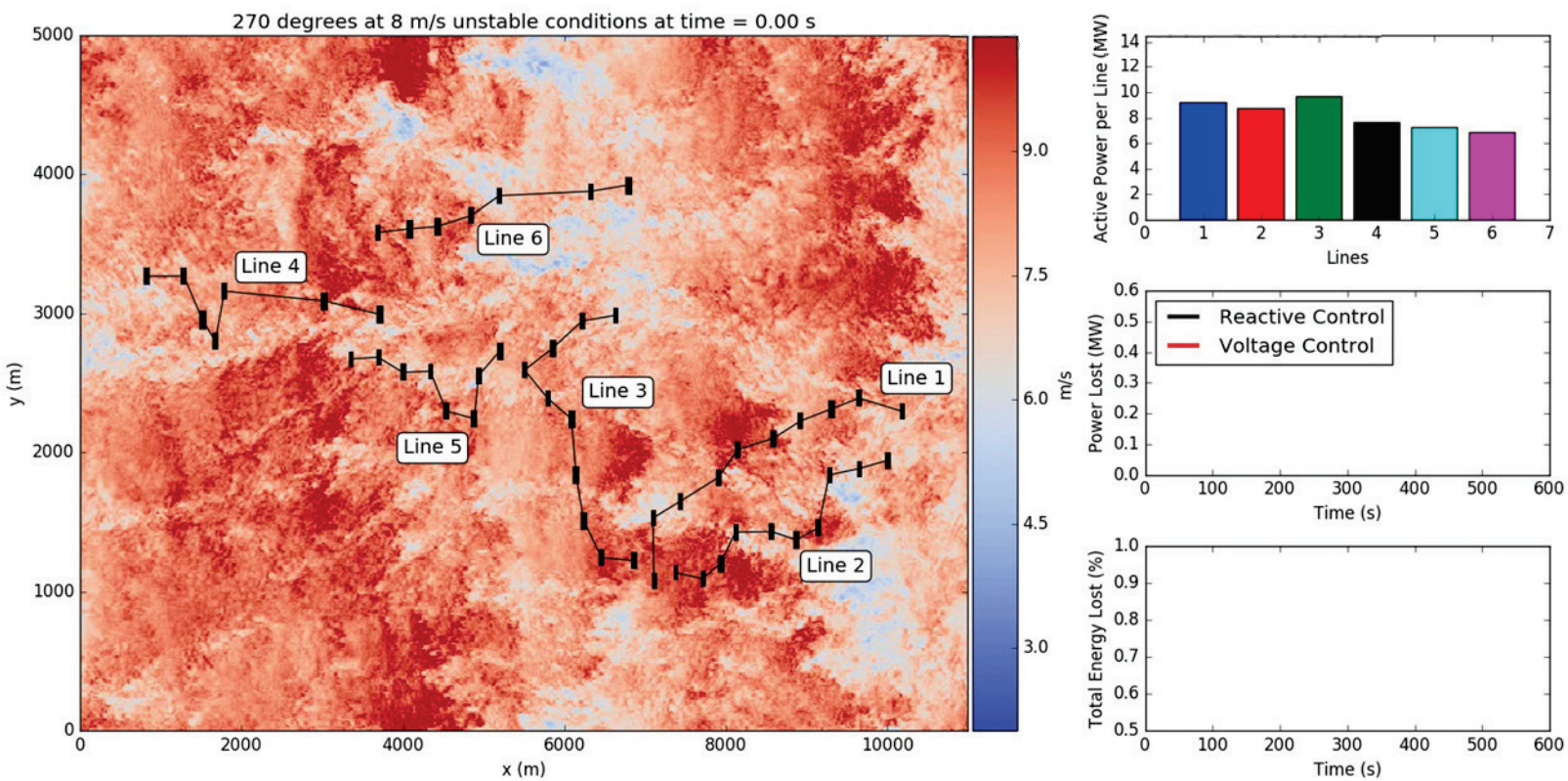
Annoni, (2017)



# Wind Plants of the Future and Support for the Grid

Controllable, dispatchable, and predictable grid support services:

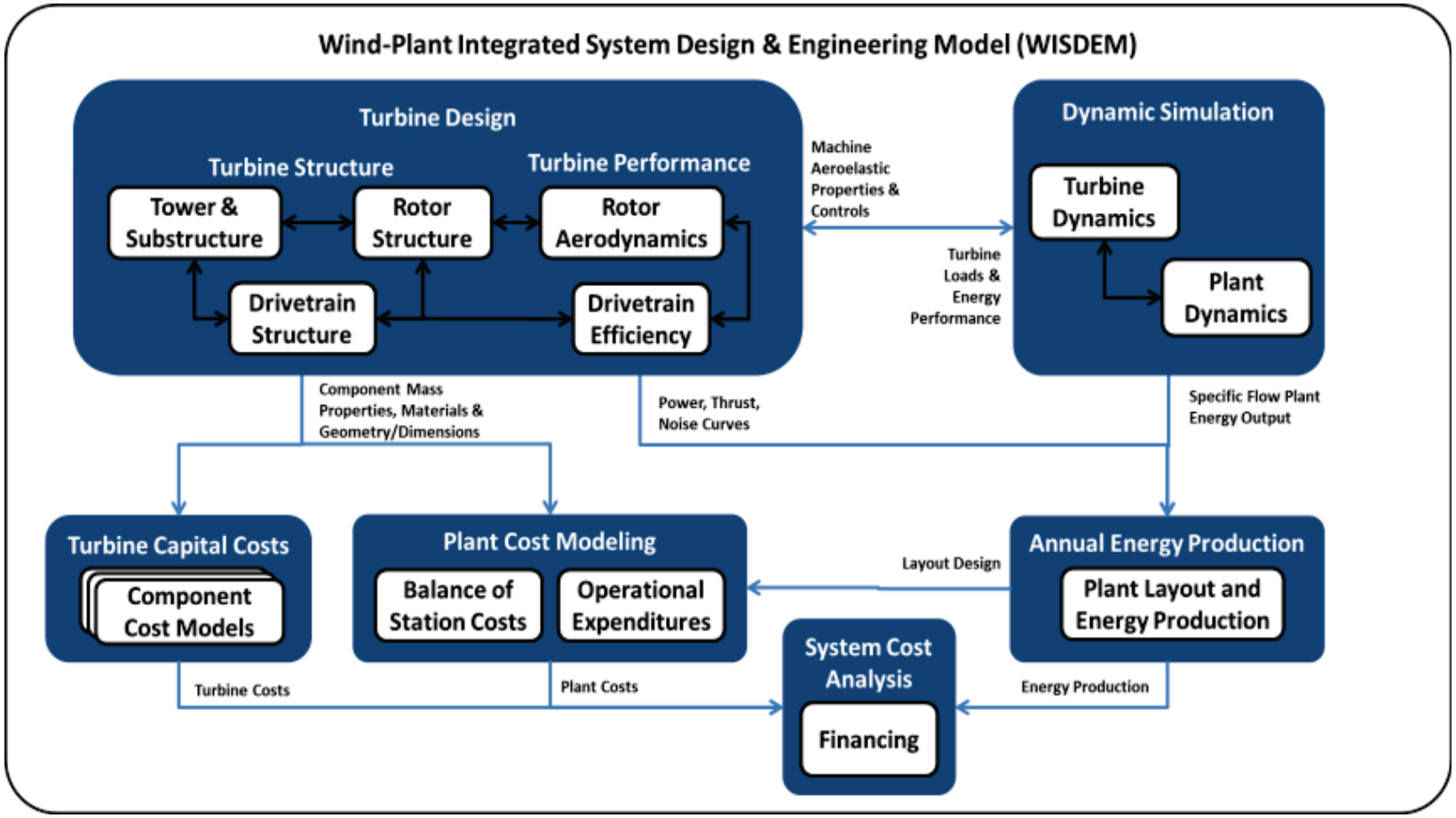
- Advanced frequency and voltage management systems for real time grid interaction and dispatchability.



# Co-Design Opportunities for Integrated Wind Energy Systems

# NREL Wind-Plant Integrated System Design & Engineering Model

WISDEM™ creates a virtual, vertically integrated wind plant from component design to operations and control.

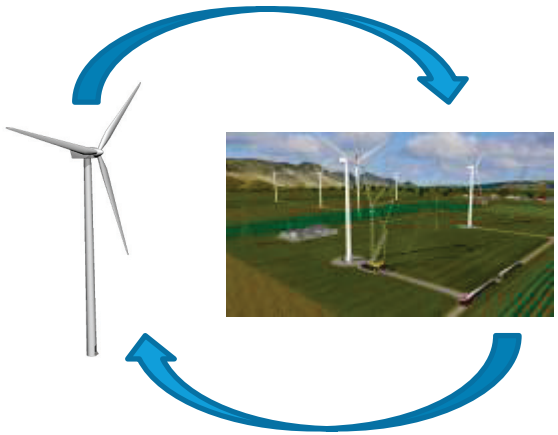



http://nwtc.nrel.gov/WISDEM

# MDAO Research for Wind Energy & Co-Design

## Integrated modeling capability allows for investigation of co-design at all system levels:

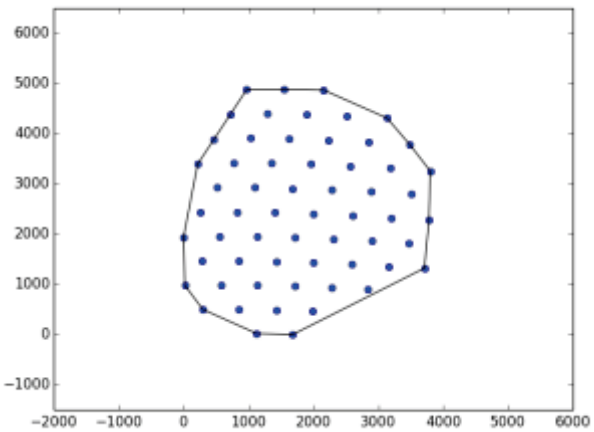
- Integrated turbine design (rotor aero-structure, full turbine optimization including controls co-design)
- Integrated plant design and operations (wind plant layout and hub height, layout and support structure, plant controls co-design)
- Integrated turbine and plant optimization (multi-turbine layout designs, integrated turbine-plant co-design)



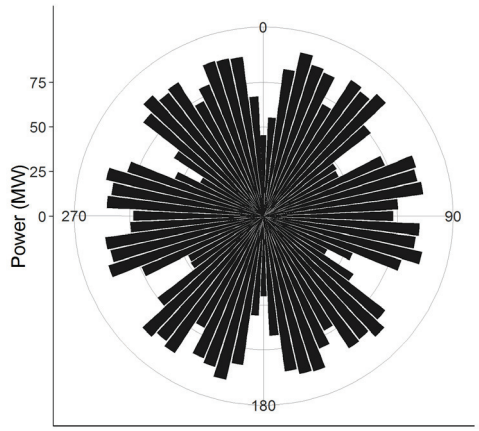
# Wind Plant Co-Design Example

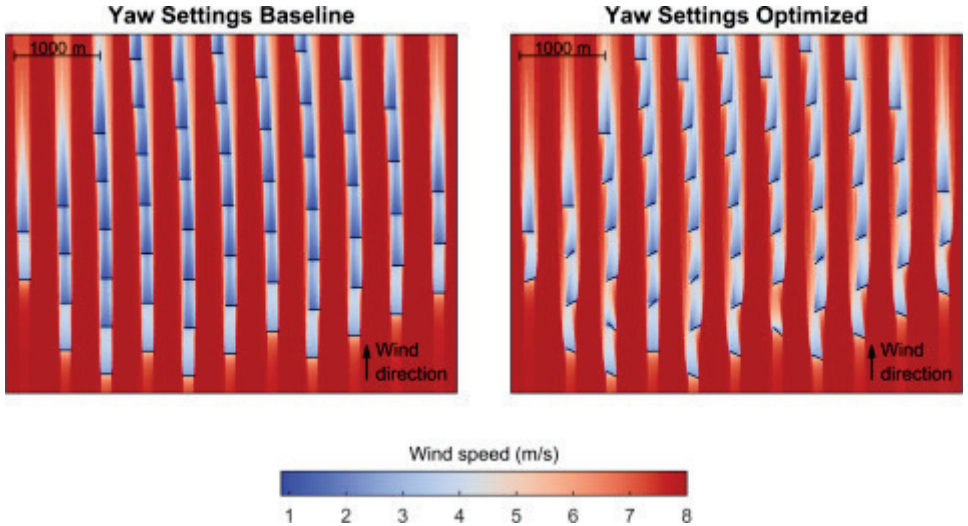
WISDEM-FLORIS COUPLING:
1. Real-time AEP optimization (O&M)
2. Wind Plant layout optimization (Development and Engineering)

Baseline Layout



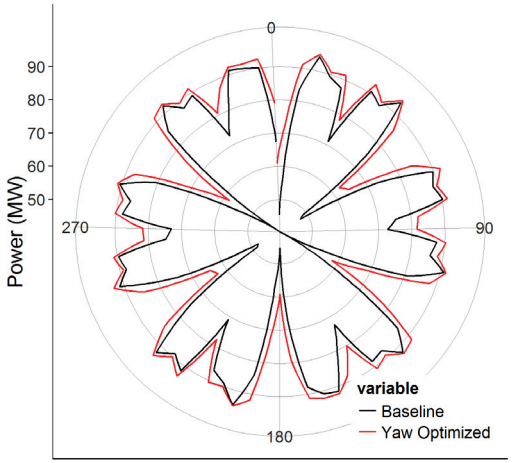

Baseline Power Production



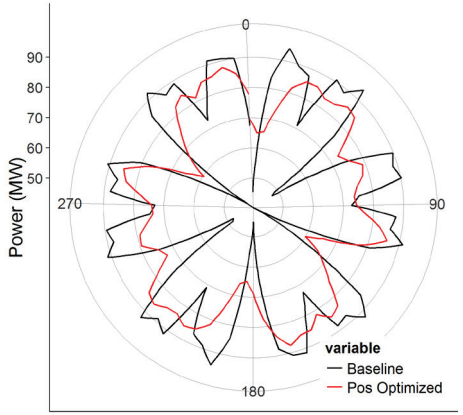




- **Baseline**: fixed (original) positions, turbines all yawed in mean wind direction
- **Optimized yaw**: fixed (original) positions, turbines optimally yawed for each wind direction
- **Optimized location**: position optimized, turbines all yawed in mean wind direction
- **Combined optimization**: simultaneously optimized position and yaw for each wind direction.

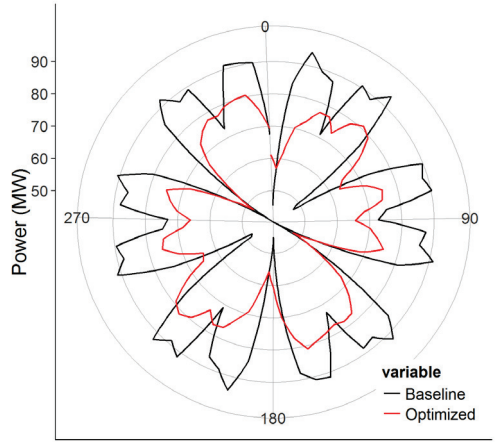
# WISDEM™ -FLORIS – CASE STUDY Results

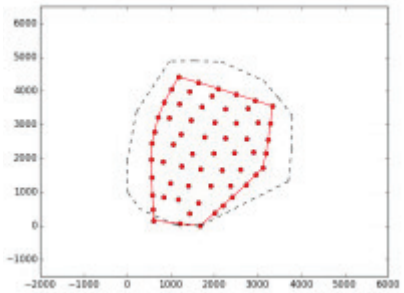



Yaw Optimized




Position Optimized



Combined

| | Baseline | YawOpt | PosOpt | Combined |
|---|---|---|---|---|
| Mean power (MW) | 78.86 | 84.91 | 78.86 | 78.84 |
| Area ($km^2$) | 14.53 | 14.53 | 12.45 | 8.96 |
| Power density ($W/m^2$) | 5.43 | 5.84 | 6.33 | 8.80 |
| AEP(GWh) | 1040.3 | 1094 (+5.2%) | 1055.8 (+1.5%) | 1095 (+5.3%) |

# Opportunities for R&D in Wind Energy Co-Design

# Opportunities for R&D in Wind Energy Co-Design

- Wind energy has relatively low LCOE but further reductions are necessary to maintain competitiveness; what can co-design do to further drive down turbine and power plant costs and increase performance to keep wind competitive with solar / gas / other energy sources?

- Floating offshore wind energy is still nascent – dynamics are more complex than past systems and coupling with controls is more pronounced than ever; what can co-design do to help us design reliable and low cost floating wind turbines?

- Wind energy systems are extremely complex, making them difficult to design and model; what can co-design illuminate in terms of gaps and opportunities in controllability (novel actuators?) and observability (novel sensors?) for these systems?

- Plant operations today lack sophistication – controls are simplistic and maintenance strategies are reactive; what can co-design do to help us create the "smart" wind power plants of the future?

- Wind plants of tomorrow will need to provide more and more services to the grid (both energy on demand and reliability services); what can co-design do to help us design an integrated wind energy system that serves the grid on-demand at all time-scales of interest?