2024 Sandia Blade Workshop

JOHNS HOPKINS
RALPH O'CONNOR SUSTAINABLE ENERGY INSTITUTE

Yaw augmented frequency regulation

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- **Vision:** We see a world fueled by carbon-free energy abundance where no individual or community lacks access to these resources.
- **Mission:** Research, Education and Translation for the Energy Transition.
- **Values:** Innovation, Education, Equity, Community
- **Founded**: Earth Day 2021


HUB

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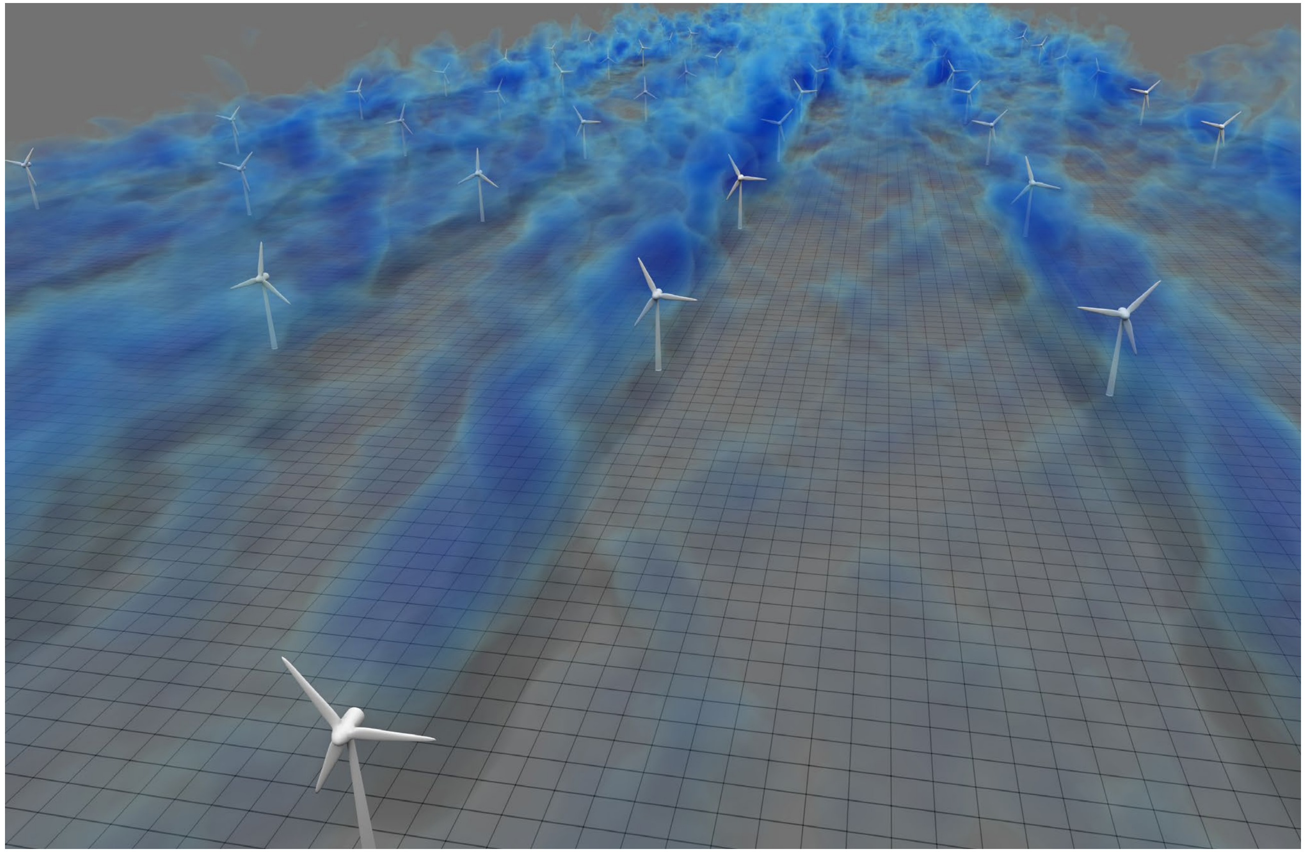
The establishment of the Ralph S. O'Connor Sustainable Energy Institute is part of a 10-year, $75M investment by the university in energy-related research and education

Hub staff report / Apr 22, 2021

MEDIA INQUIRIES

With a $20 million gift from the estate of trustee emeritus and alumnus Ralph S. O'Connor, the Johns Hopkins University and its Whiting School of Engineering today announced the establishment of the Ralph S. O'Connor Sustainable Energy Institute (ROSEI) to serve as the university's interdisciplinary home for ongoing research and education aimed at creating clean, renewable, and sustainable energy technologies.

ROSEI team: wind energy



In-silico wind farm Large-Eddy-Simulations using the JHU-LES code
Simulation details: Stevens, R. J., Gayme, D. F., & Meneveau, C. (2016).
Wind Energy, *19*, 359-370. Visualization: D. Brock (Extended Services, XSEDE)

Related Expertise	ROSEI Faculty
Wind power grid integration, markets, systems modeling	**Yury Dvorkin**, Elec Eng | Civil & Systems Eng.
Wind farm modeling and control, grid integration	**Dennice Gayme**, Mech. Eng.
Wind power grid integration, markets	**Ben Hobbs**, Env. Eng.
Wind farm simulation, wake modeling	**Charles Meneveau**, Mech. Eng.
Atmospheric modeling, metocean modeling	**Julie Lundquist** Earth & Planetary Sci./MechE
Wind harvesting, flow physics, fluid-structure interaction	**Rajat Mittal**, Mech. Eng.
Wind tower structures, design and optimization	**Ben Schafer**, Civil & Systems Eng.
Wind tower reliability, uncertainty quantification ML	**Michael Shields**, Civil & Systems Eng.
Wind policy, social acceptance, int'l markets	**Johannes Urpelainen**, Political Science

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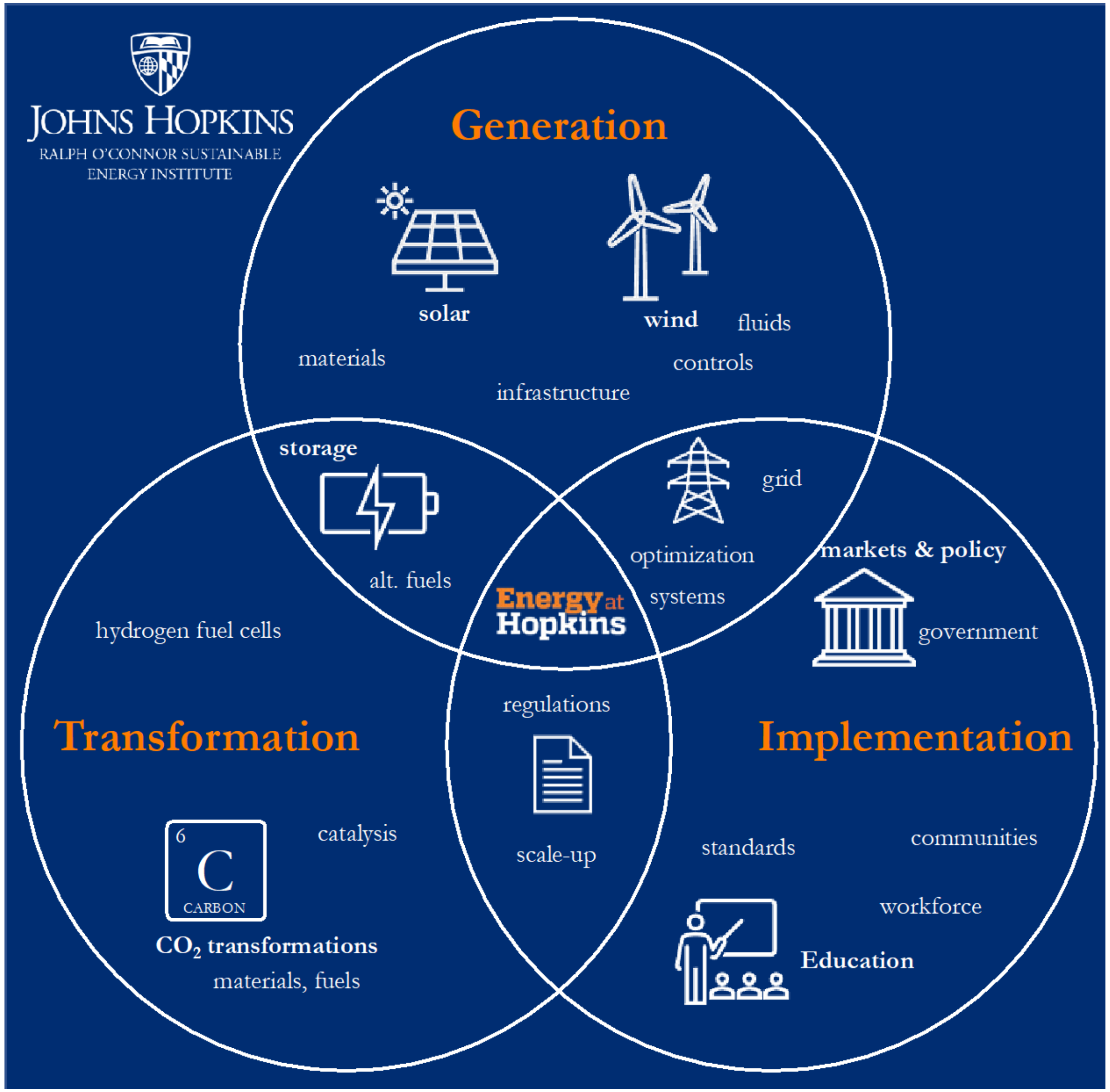
Broad view of ROSEI Faculty Expertise:

Engineers
Chemical Eng, Materials Science, Electrical Eng., Mechanical Eng., Civil Eng., Systems Eng., Env. Eng., App. Math
Scientists
Chemistry, Earth Sciences, Physics
Social Scientists
Economics, Political Science, Sociology, Anthropology



ROSEI Research Pillars and Cross-Cutting Areas

Community

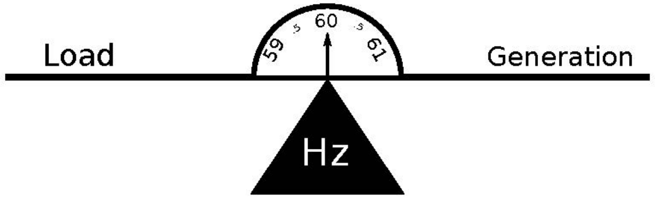
Education

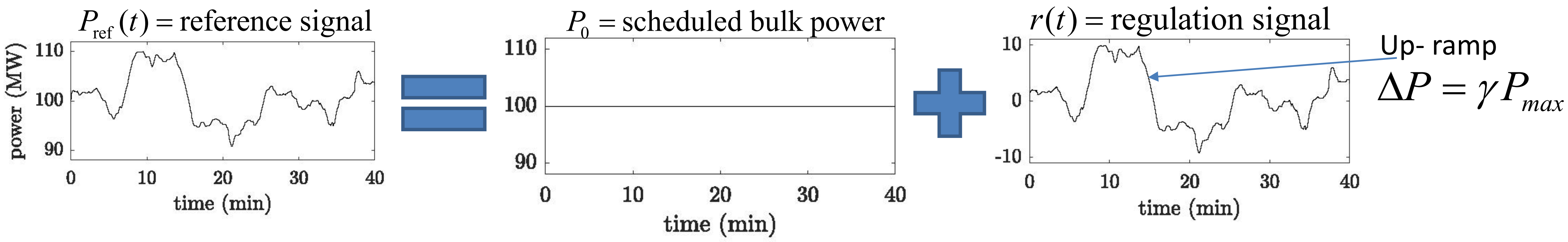
Policy

Translation

Wind farm power tracking

- Secondary frequency regulation is an important grid service that requires power tracking

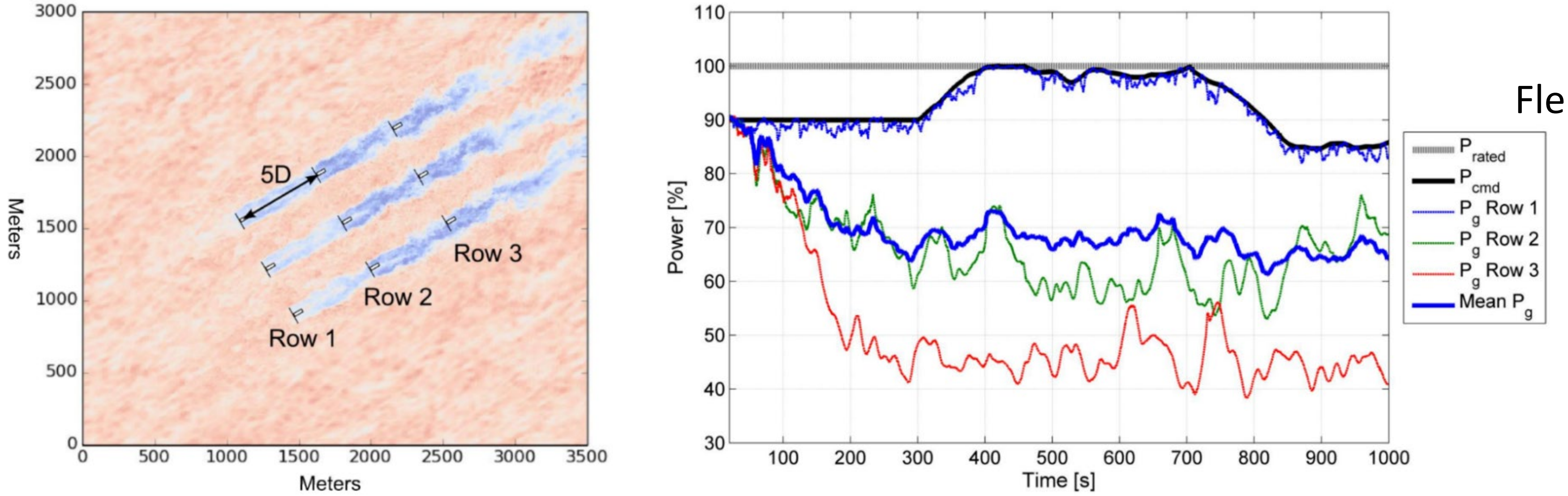




- Reduce bulk power supply (i.e. do not maximize power output) $P_0 = (1-\alpha)P_{max}$
  - Derate the turbine by some percentage $\alpha \times 100\%$
- Ideally up-ramp capability (upramp) $\gamma > \alpha$ (derate)

Frequency regulation: Challenges

- Direct economic trade-off between bulk power supply and regulation
  - Ideally up-ramp capability $\gamma > \alpha$ (derate) *Not possible with a single turbine*
- Individual turbine control (i.e., failure to take wake effects into account) even with $\gamma = \alpha$ fails even in small farms (except if $\gamma << \alpha$ e.g., van Wingerden et al. 2017)



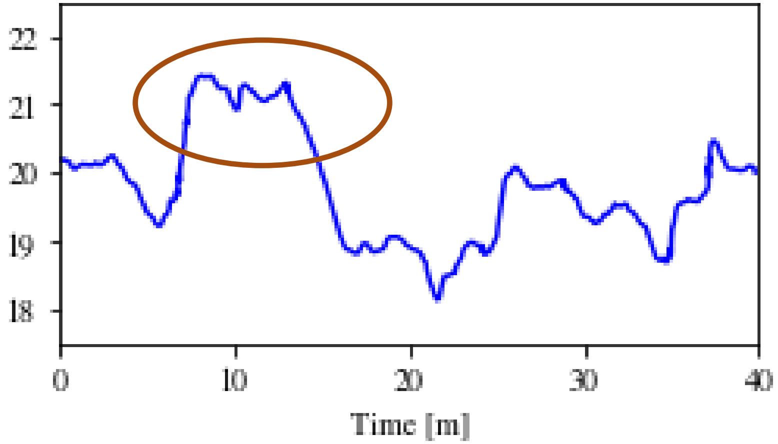
Fleming et al 2016

- Previous work using dynamic models that account for wake propogation have reduced required derates e.g., Shapiro et al. 2017, 2018, 2019; Vali et al 2018

Power tracking control

- Previous work using dynamic models that account for wake propogation have reduced required derates e.g., Shapiro et al. 2017, 2018, 2019; Vali et al 2018
- Pitch control can saturate in power tracking applications due to finite control authority

Genevieve Starke



Yawing turbines

- Yawing turbines has been shown to increase power output
  e.g. Howland et al. 2019, 2022 , Fleming et al. 2017, Gebraad et al. 2016, Campagnolo et al. 2016

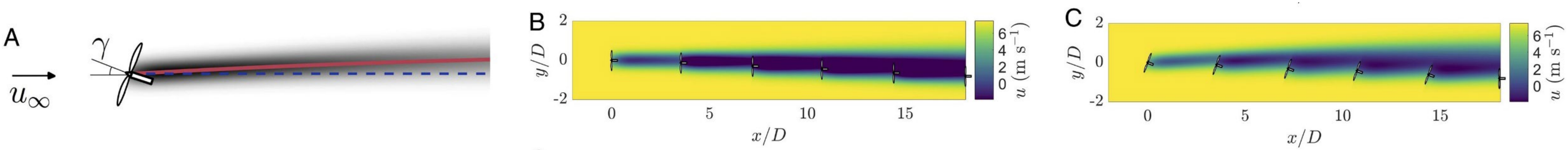
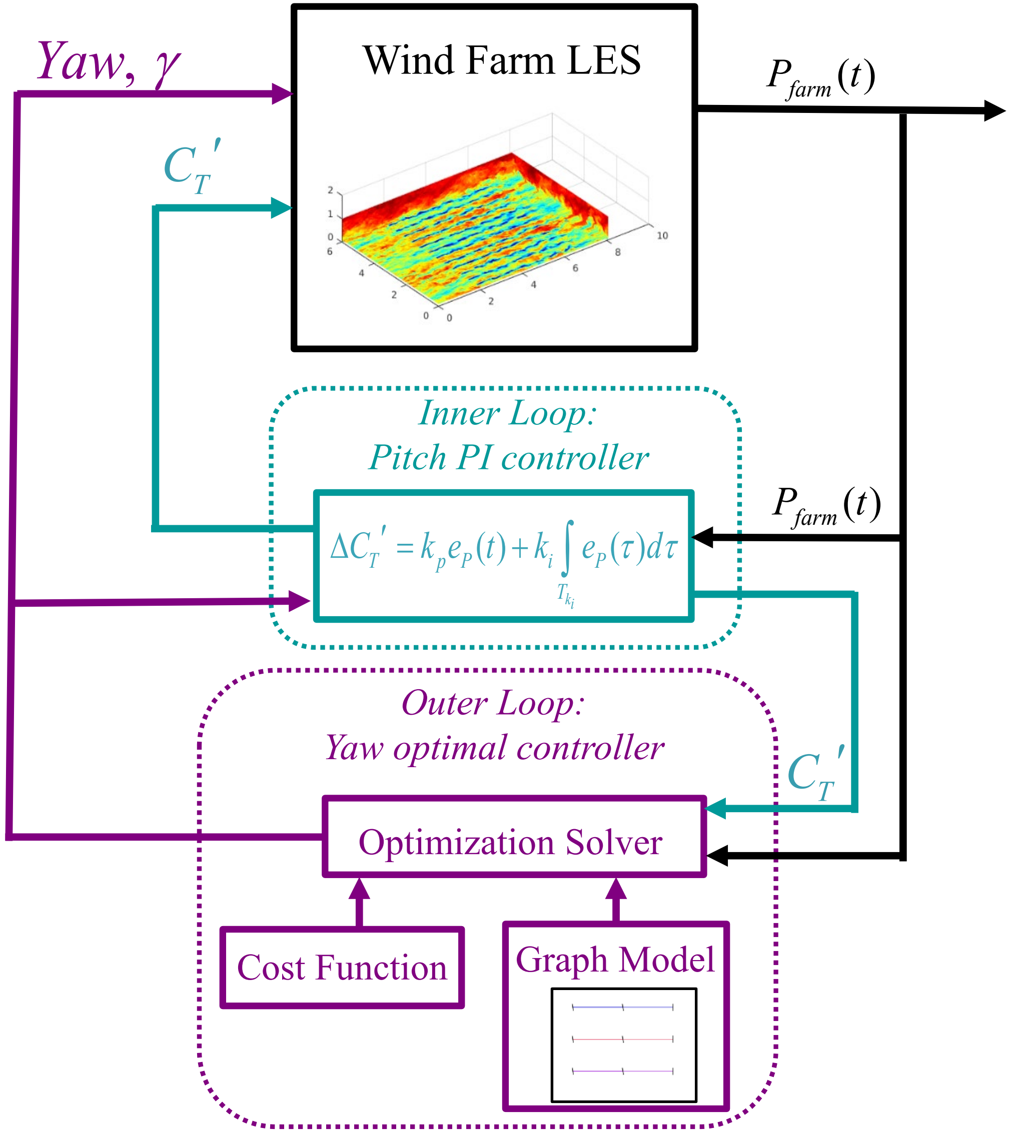


Figure adapted from Howland et al. 2019 demonstrating yaw optimization for power maximization

- Mostly in static setting and not taken in the timescales associated with dynamic yawing behavior (e.g. rate of yawing) the behavior of the farm as the effect of yaw actions propagate downstream
- Idea: use yaw to increase control authority in power tracking applications
  - Previously demonstrated in power maximization and tracking that did not aim to reduce derates e.g., Munters & Meyers 2018, Boersma et al 2019a, 2019b

Yaw augmented power tracking

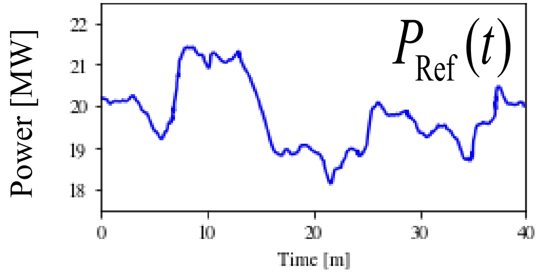
- Inner-outer loop control architecture
- Outer loop
  - model-constrained optimal control for the yaw
- Inner Loop
  - PI pitch controller



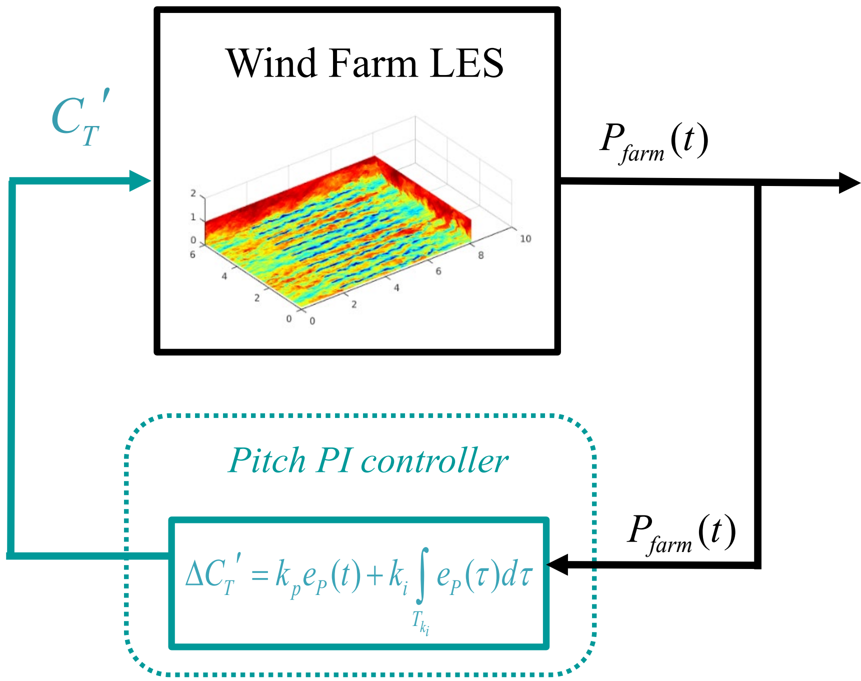
Inner loop: PI pitch control

- Control local thrust coefficient as a proxy for pitch

$$\Delta C_{T,i}' = k_p e_{P,i}(t) + k_i \int_{T_{k_i}} e_{P,i}(\tau)\, d\tau$$



$$e_{P,i} = P_{\mathrm{Ref,i}} - P_{\mathrm{LES,i}}$$



- Use measurements to distribute power reference across the turbines

$$P_{\mathrm{Ref},i} = \frac{1/T_{C_T'} \int_{T_{C_T'}} P_{\mathrm{LES,i}}(\tau)\, d\tau}{1/T_{C_T'} \int_{T_{C_T'}} P_{\mathrm{LES}}(\tau)\, d\tau} P_{\mathrm{Ref}}$$

k_p, k_i: Proportional and integral gain

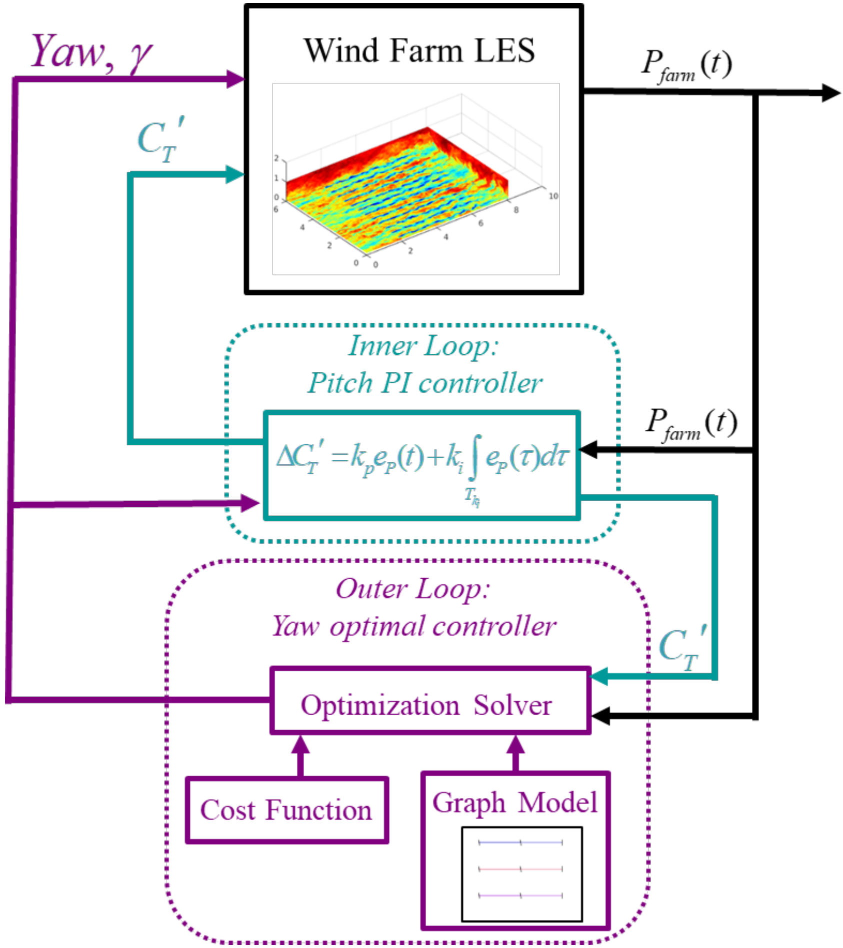
T_{k_i}: integral time

Incorporating power changes due to yaw actions

- Changes in power due to yaw are incorporated into the inner loop as a feedforward term
  - linear approximation for the change in the thrust around the cosine the angle change

$$\Delta C_{T,\gamma}' = \frac{\partial \Delta C_T'}{\partial \cos(\gamma)}\left[\cos(\gamma_2) - \cos(\gamma_1)\right]$$

$$\Delta C_T' = k_p e_P(t) + k_i \int_{T_{k_i}} e_P(\tau)\, d\tau + \Delta C_{T,\gamma}'$$



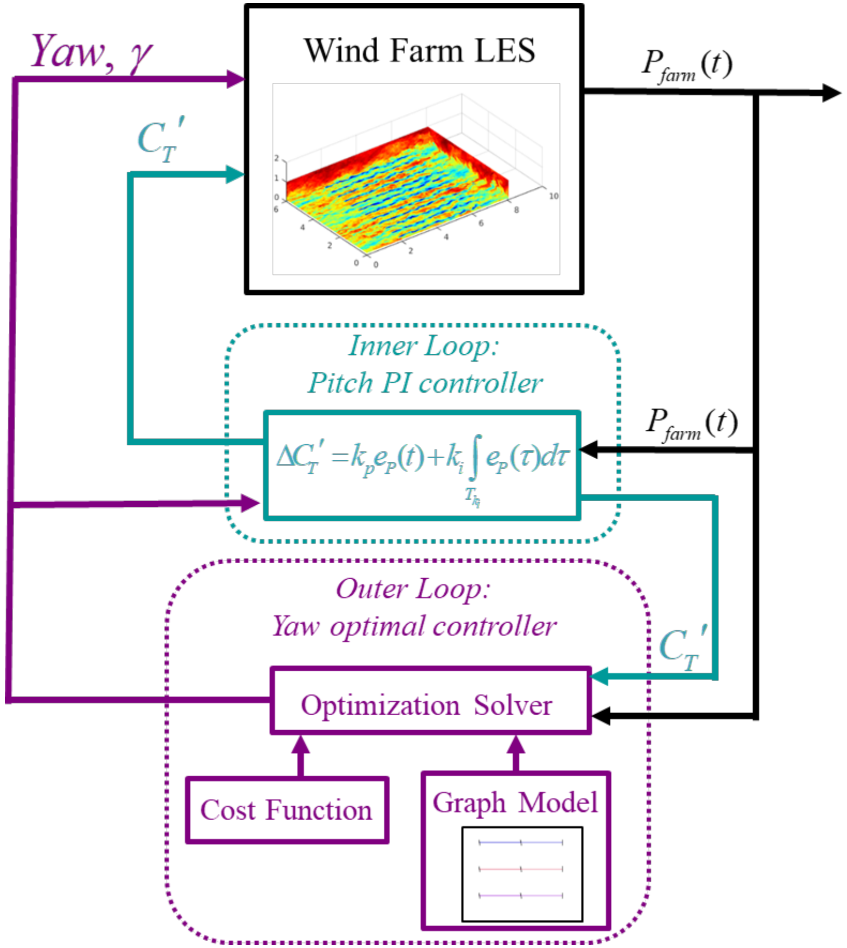
Outer loop yaw control (initial implementation)

- Optimize the cost function for a single yaw angle for each control period

$$J(\gamma)=\left(\int_{0}^{T_H}\left(P_{GM}-P_{ref}\right)^2 dt\right)$$

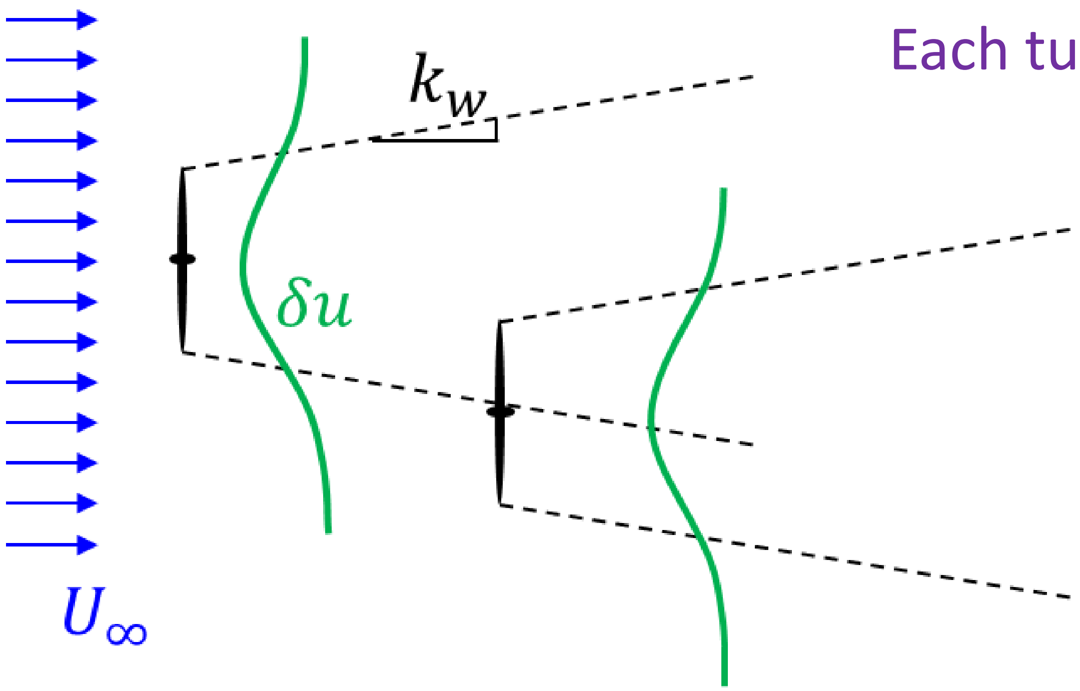
T_H: time horizon
γ: turbine yaw
T_γ: Yaw update interval

- **Trade off**: Easier to implement but less efficient and requires more updates for accuracy



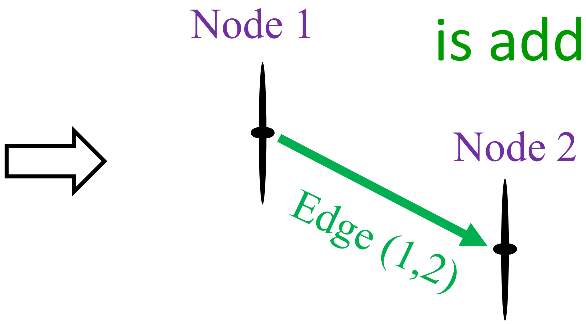
Computing time-dependent yaw angles

- Graph model of a wind farm (extends the approach in Annoni et al. 2019a, 2019b)



Each turbine is a node

If a turbine is in the wake of another turbine, a directed edge is added to the graph

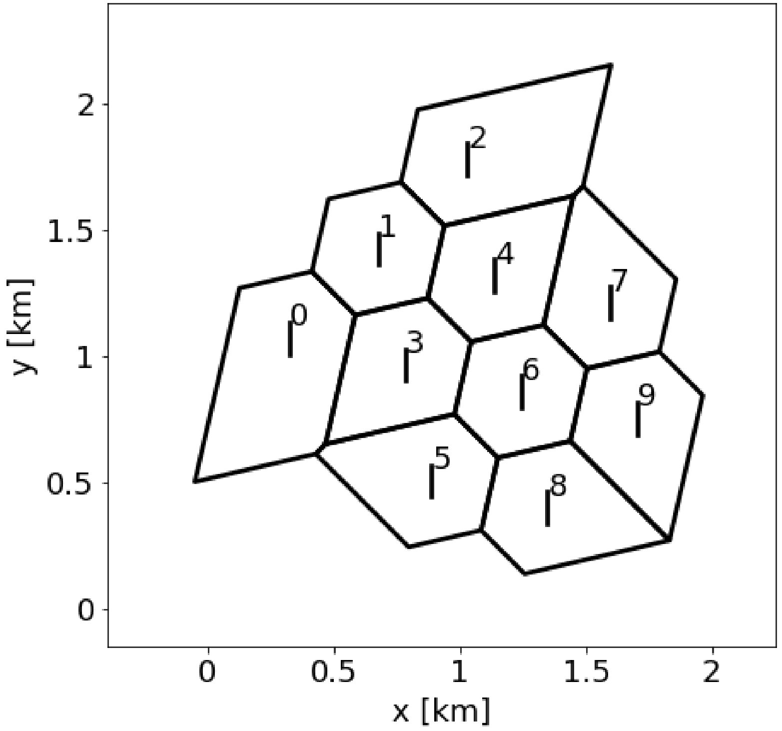


$\mathcal{G}(\mathcal{N},\mathcal{E})$ — $\mathcal{N}$: Nodes (turbines); $\mathcal{E}$: Edges (wake interactions)

- Divide the farm into weakly-connected subgraphs based on a leader (node) turbine $\mathcal{G}(\mathcal{N},\mathcal{E}) = \{g_1, g_2, \cdots, g_m\}$

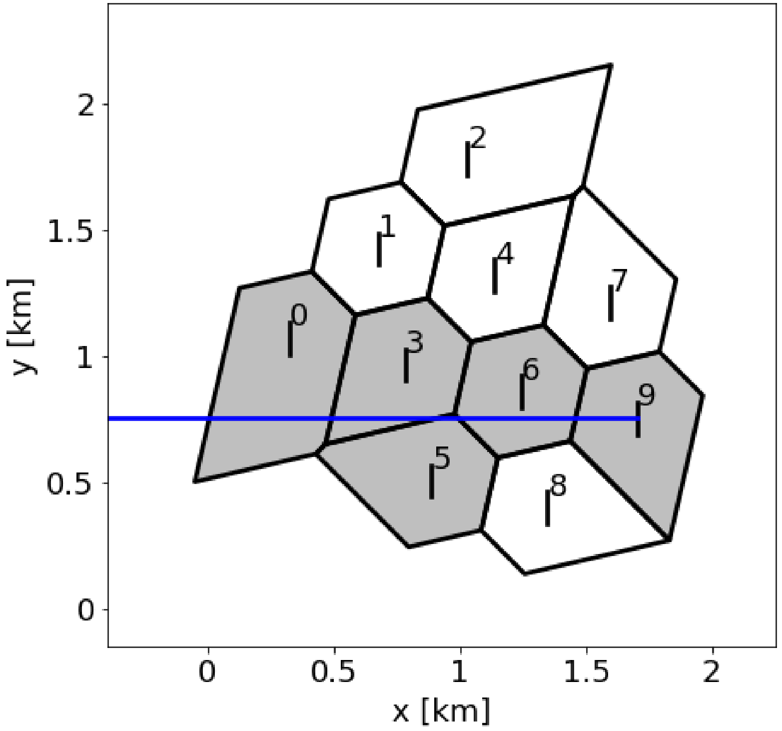
Generating a graph of an arbitrary wind farm geometry

- Define local turbine areas using Voronoi tessellation



Generating a graph of an arbitrary wind farm geometry

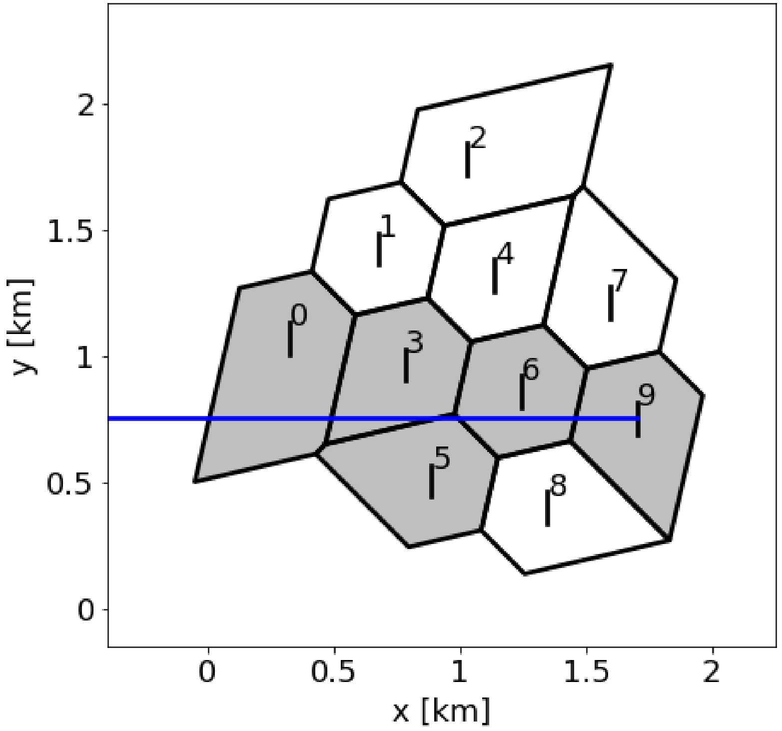
- Define local turbine areas using Voronoi tessellation

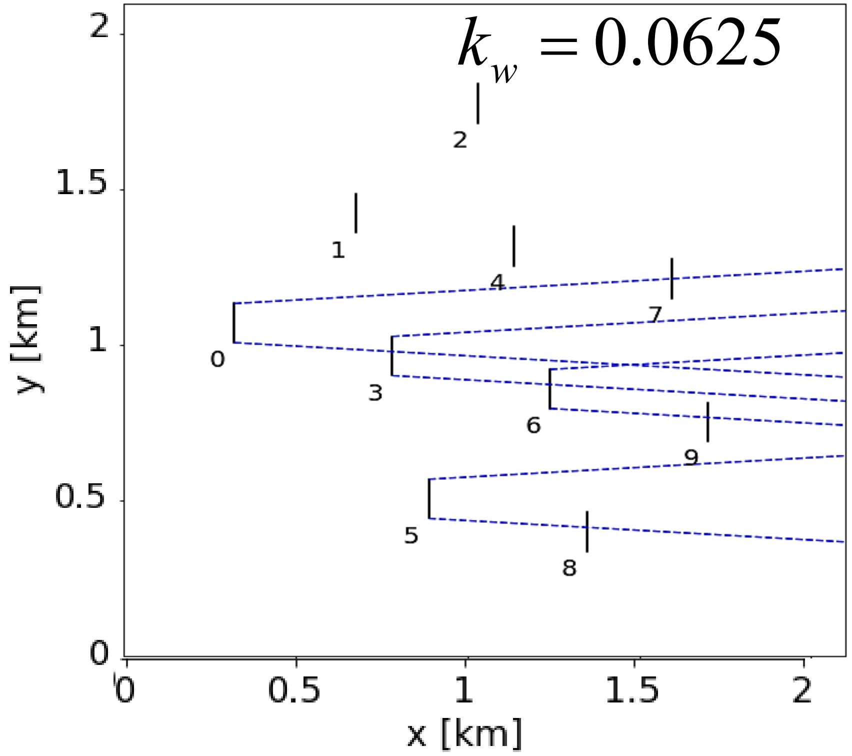


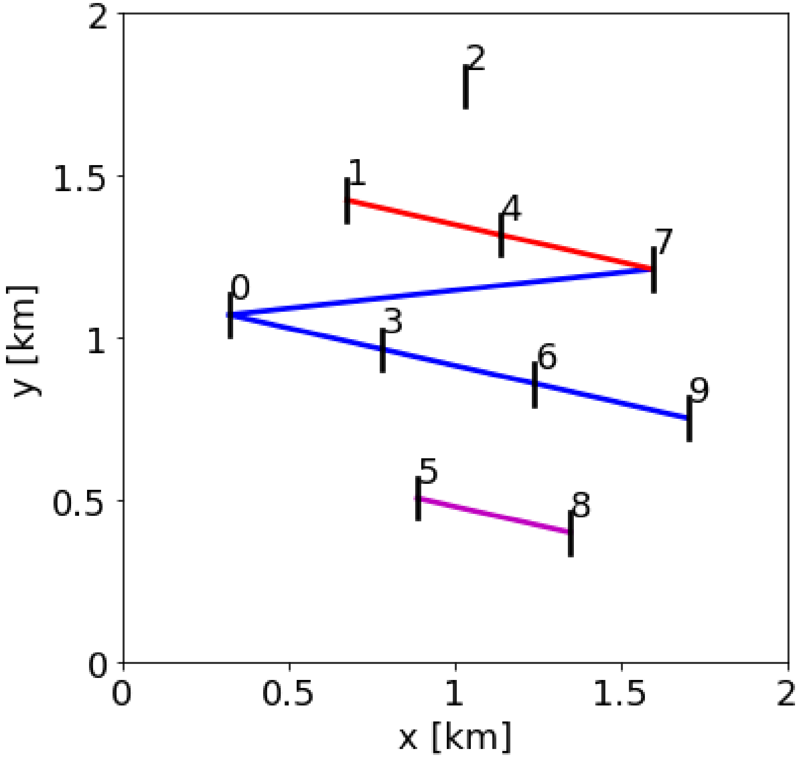
- Given an initial wind direction
  - Lead turbines and interconnections are defined based on the cells crossed as one traverses to the front of the farm
  - The wakes are defined using a linear wake growth (e.g. Jensen 1983 model)

Generating a graph of an arbitrary wind farm geometry

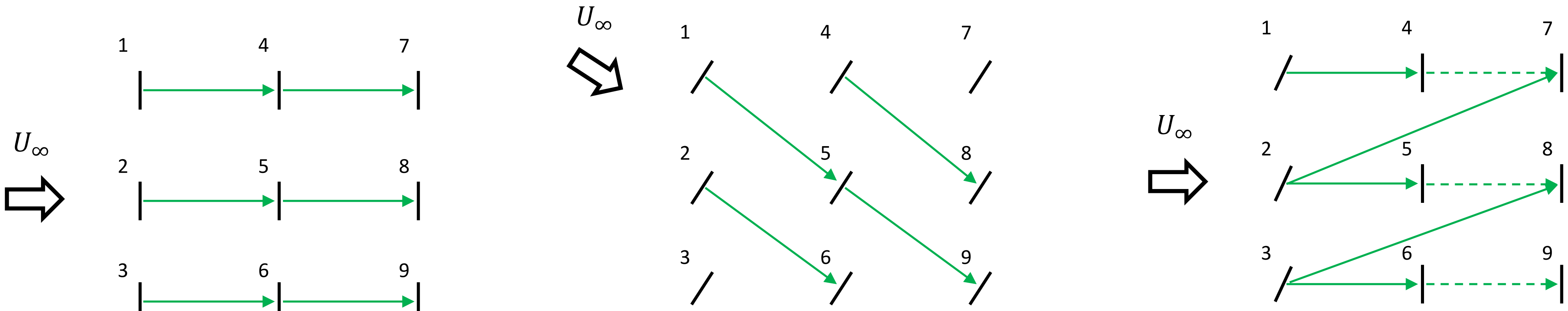
- The turbine wakes are described using linear wake growth







Change in wind farm condition = new graph topology



A wind direction change

A dynamic yaw change

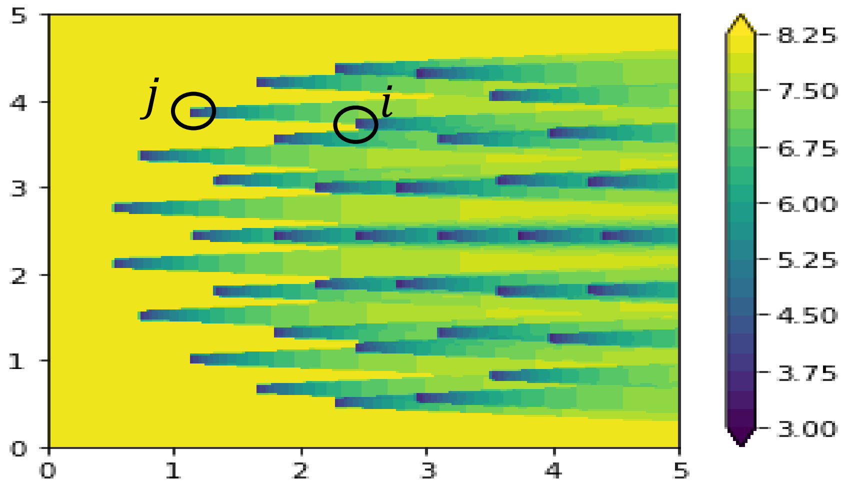
State dynamics

State Update Map $\Phi_{k+1} = \Phi_k + E_k$

- States: deficits between turbine pairs ϕ_i^j

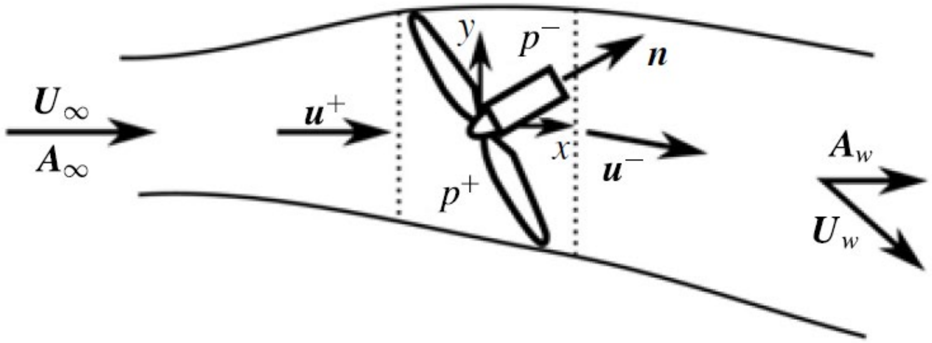
$$\Phi_k = \begin{bmatrix} \phi_1^1 & \phi_1^2 & \phi_1^3 & \cdots & \phi_1^N & \phi_2^1 & \cdots & \phi_N^{N-1} & \phi_N^N \end{bmatrix}^T$$

$U_\infty \Rightarrow$

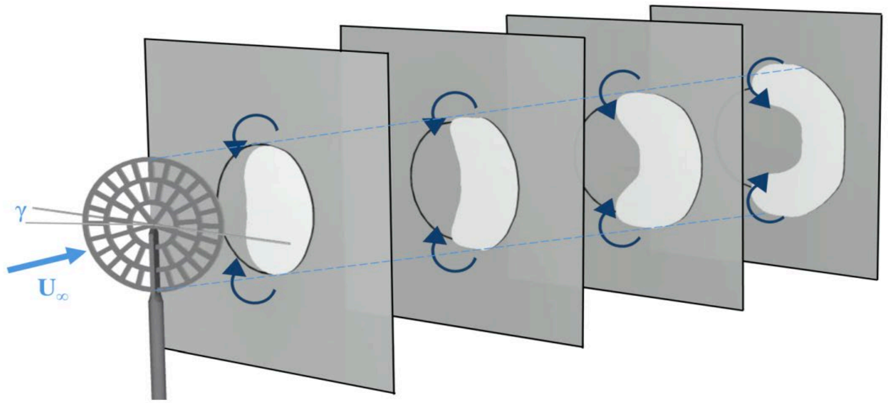


- Deficit model needs to account for deflection and curling of the wake

Wind turbine yaw



(c) Howland et al (2016)

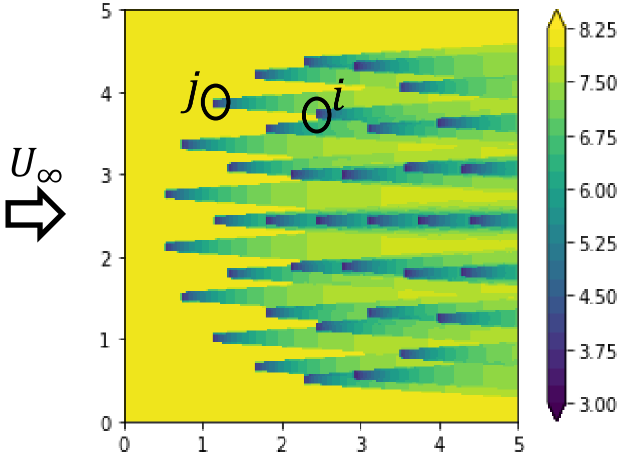


Dynamic graph for yawing turbine

Linear Map $\Phi_{k+1} = \Phi_k + E_k$

Normalized deficits at turbine i due to turbine j based on analytical curled model Bastankhah et al, 2021

$$\phi_i^j = \frac{1}{Area_{j^{th}\,disk}} \int_{Area_{j^{th}\,disk}} C(\Delta x_{i,j}) \exp\left[-\frac{(y-y_c)^2 + (z-z_h)^2}{2\sigma(\Delta x_{i,j},\theta)^2} \right] dy\,dz$$



Dynamic graph for yawing turbine

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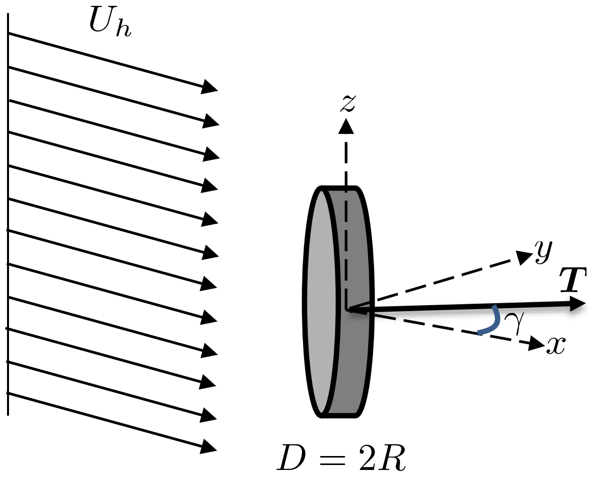
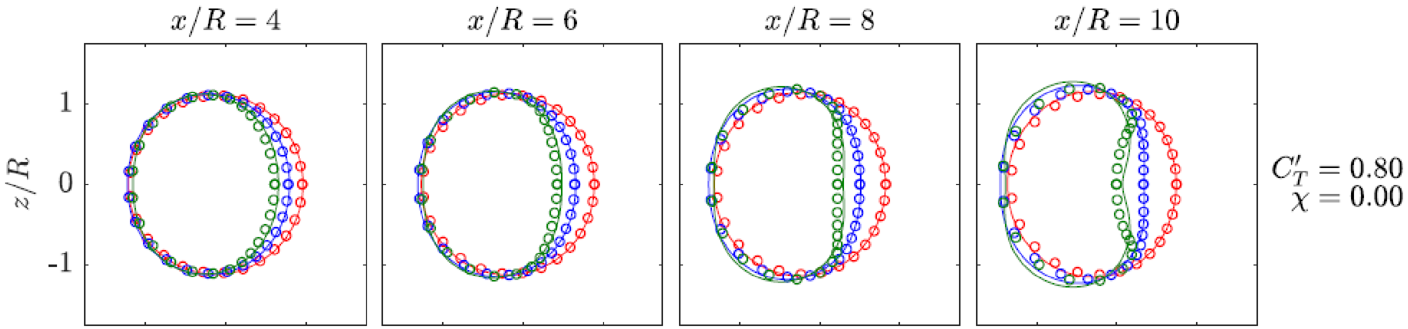
$\sigma(x,\theta) = k\,x + 0.4\xi(x,\theta)$ wake shape over distance, polar angle



$$C(x) = 1 - \sqrt{1 - \frac{C_T \cos^3\gamma}{2\tilde{\sigma}^2(x)/R^2}}$$

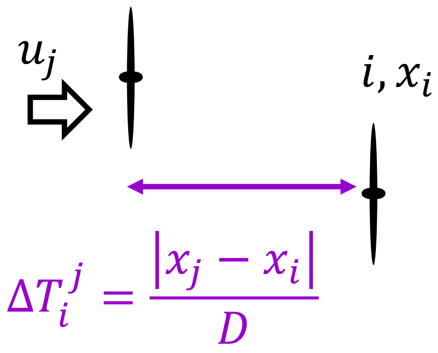


gure from Bastankhah et al, 2021

Solid lines: model results; symbols: LES results for different yaw angles

State update map $\Phi_{k+1} = \Phi_k + E_k$

Event Driven Input $E_k(\Phi_{e,k}, \tau_{e,k}, \Delta\mathcal{E}_{e,k})$

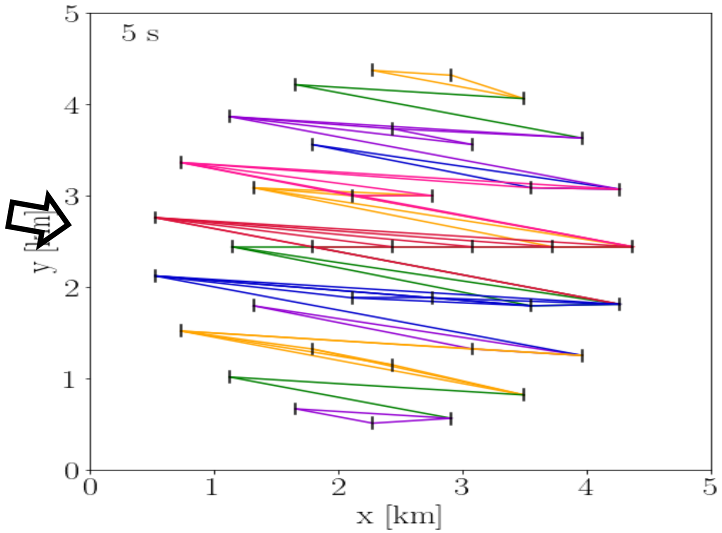


$\tau^j_{k,(i)} = \frac{D\,\Delta T_i^j}{u_j}$: Edge weights based on delays associated with information propagation over each edge

$\Delta\mathcal{E}_{e,k}$: a list of the edge changes

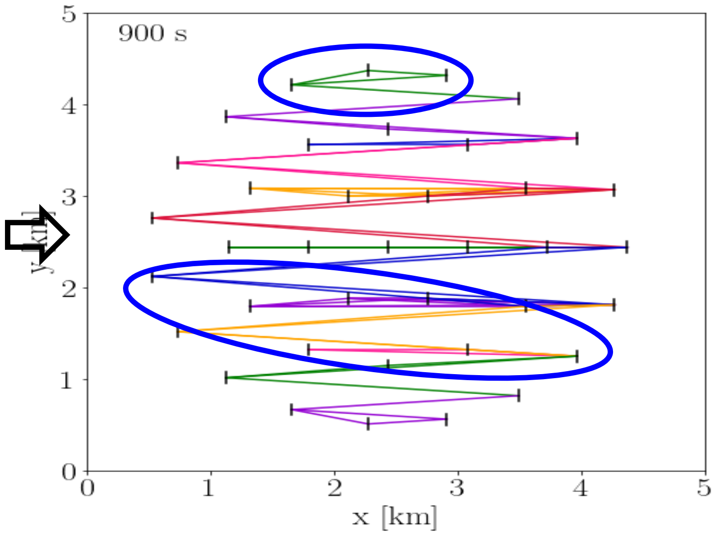
- System graph changes each timestep k (e.g. wind direction change over N timesteps)

Initial wind direction



Wind direction change over N update steps

$$\Phi_{k+1} = \Phi_k + E_k$$



System of equations

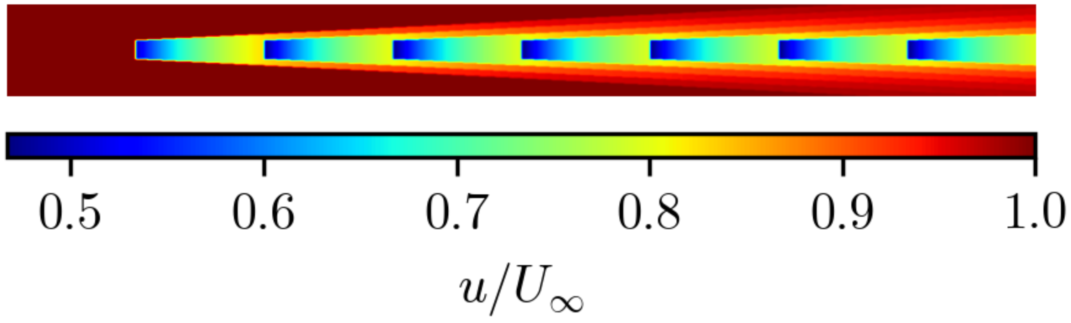
Update map $$\Phi_{k+1} = A\Phi_k + E_k$$

System output $$\alpha_{k+1} = \Lambda(\tau_k)\Phi_k(\tau_k)$$

Velocity at each turbine (disk velocity)

$$U_{d,k+1} = U_\infty(1-\alpha_{k+1})\left(1-\frac{C_T'}{4+C_T'}\right)$$

Linear wake superposition



Turbine power output

$$P_k = \frac{1}{2}\rho\left(\frac{1}{4}\pi D^2\right)U^3_{d,k+1}C_P'$$

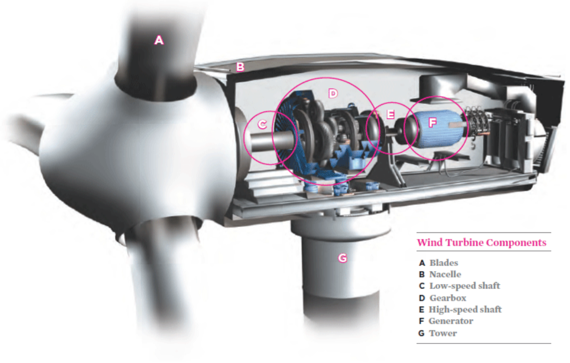


Illustration: © TurboSquid.com/Artist Rendering

Yaw model validation: static case

- Static study using JHU LESGO code (Open source code at: https://github.com/lesgo-jhu)

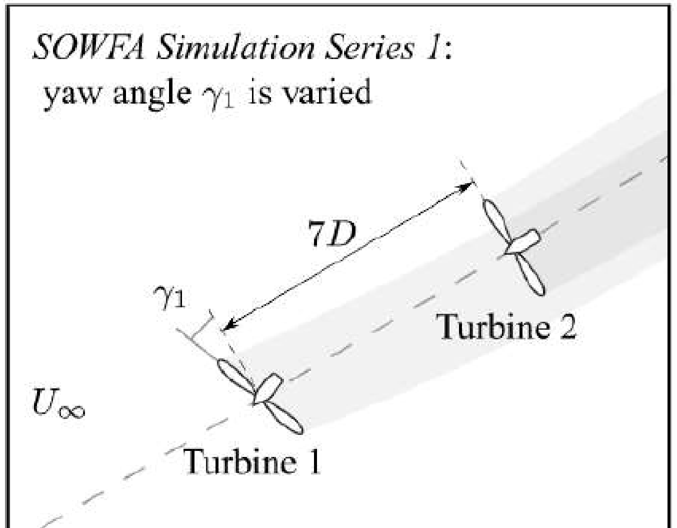
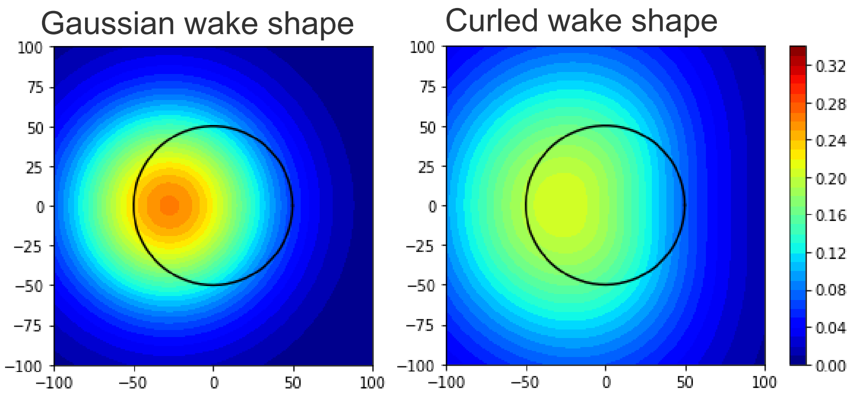
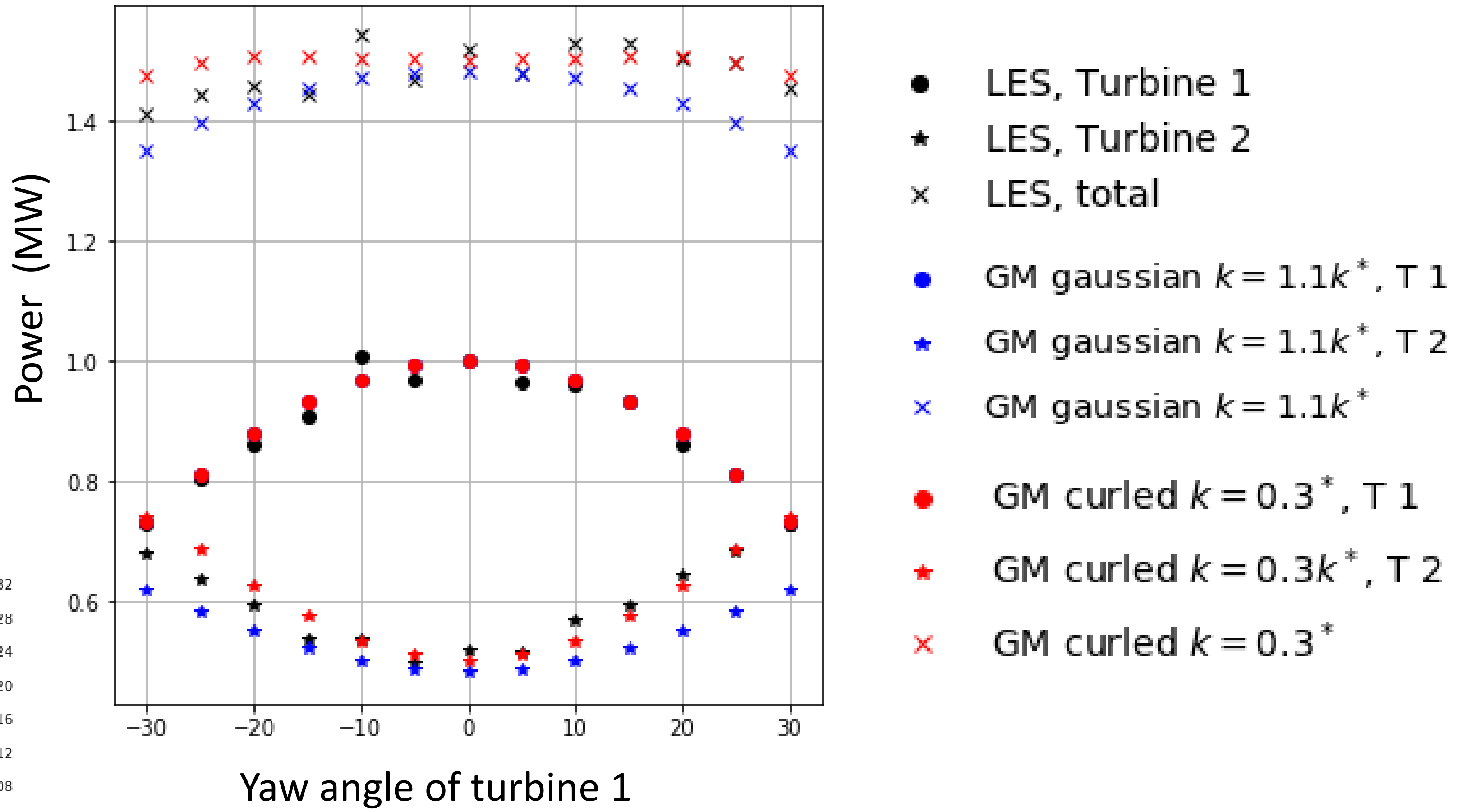


Figure from Gebraad et al. 2016

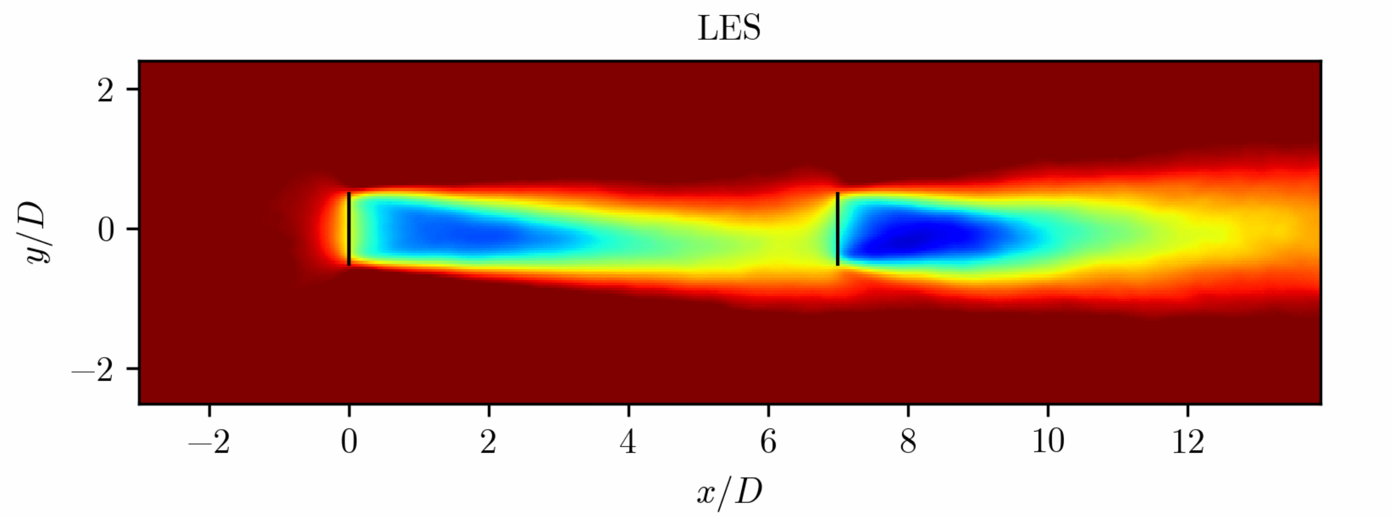




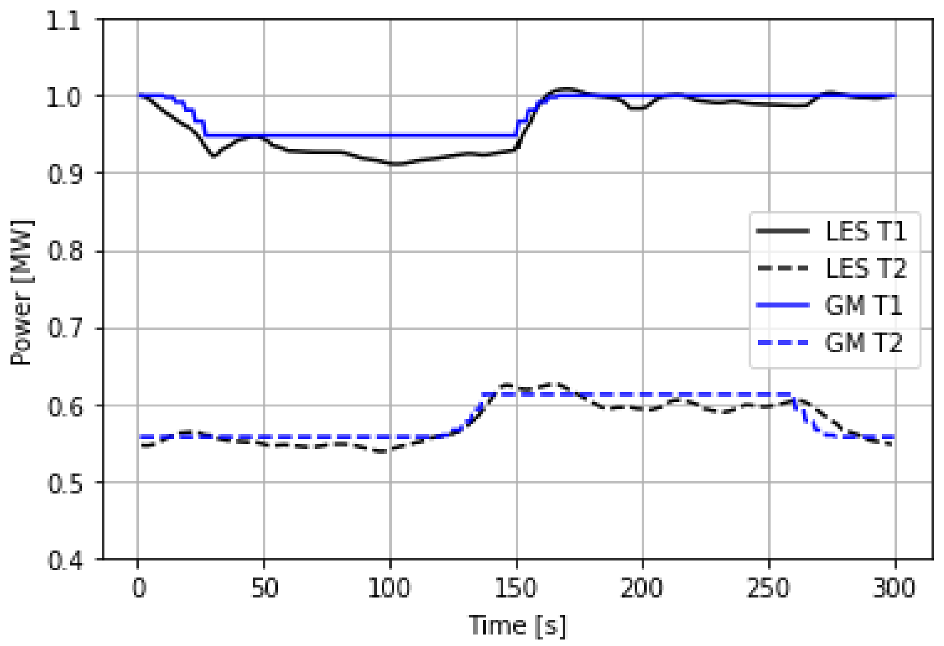
[Starke et al. 2023]

Dynamic yaw model validation

- Dynamically yaw the first turbine 15 degrees at 150 s



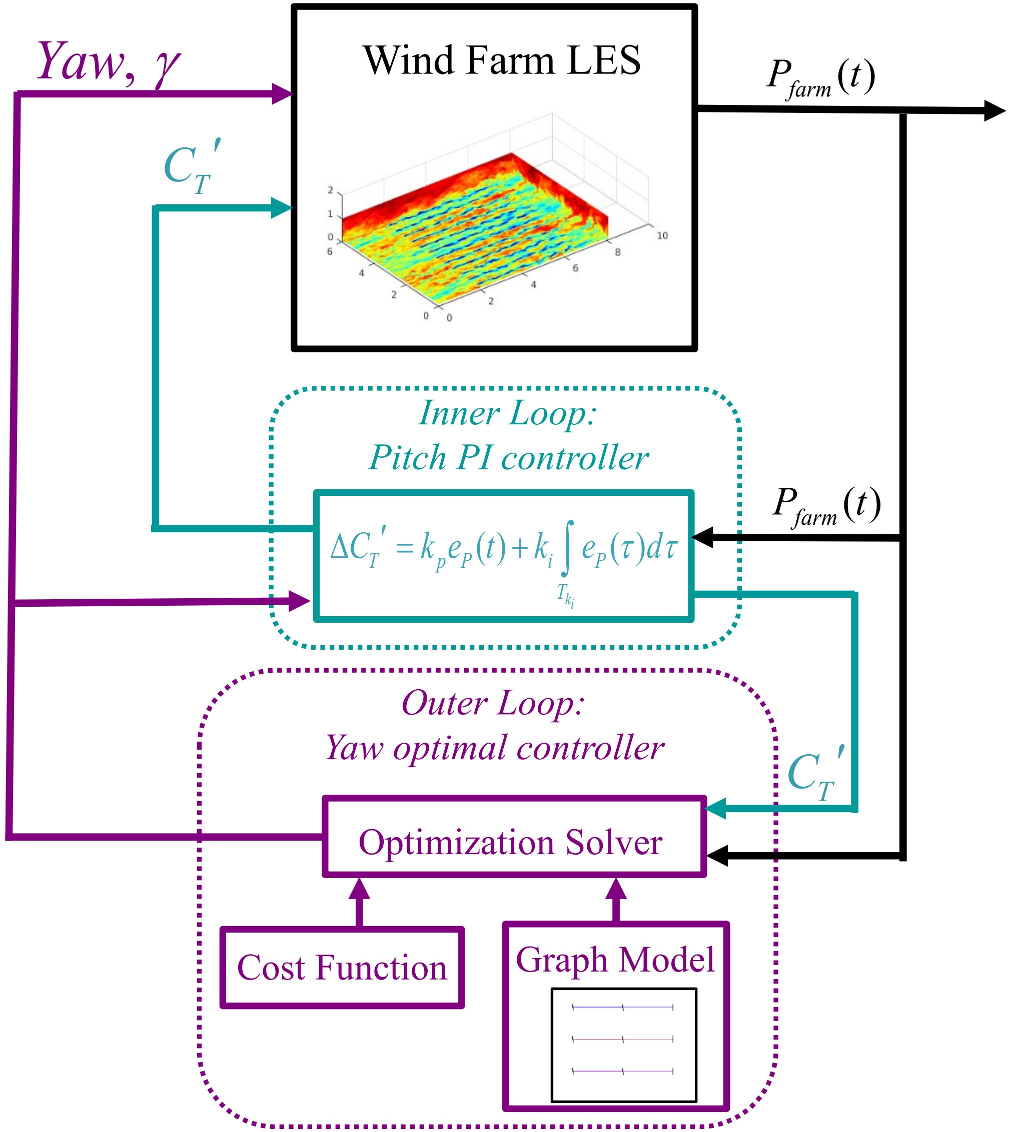
JHU LESGO code phase-averaged over 120 realizations



[Starke et al. Preprint]

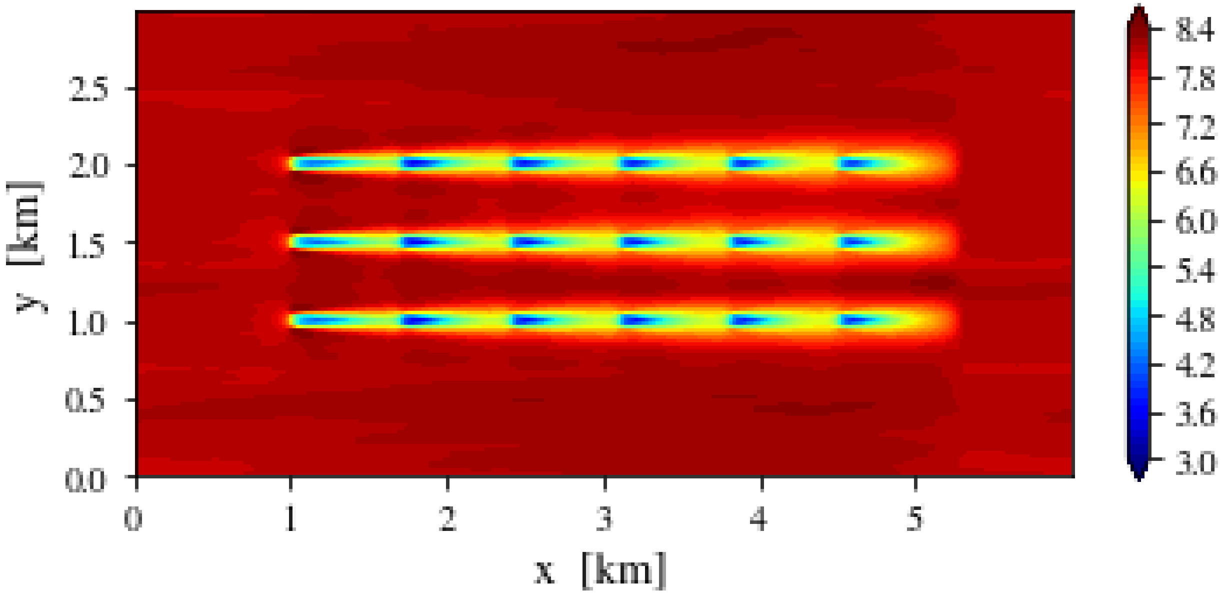
Yaw augmented power tracking

- Inner-outer loop control architecture
- Outer loop
  - model-constrained optimal control for the yaw
- Inner Loop
  - PI pitch controller

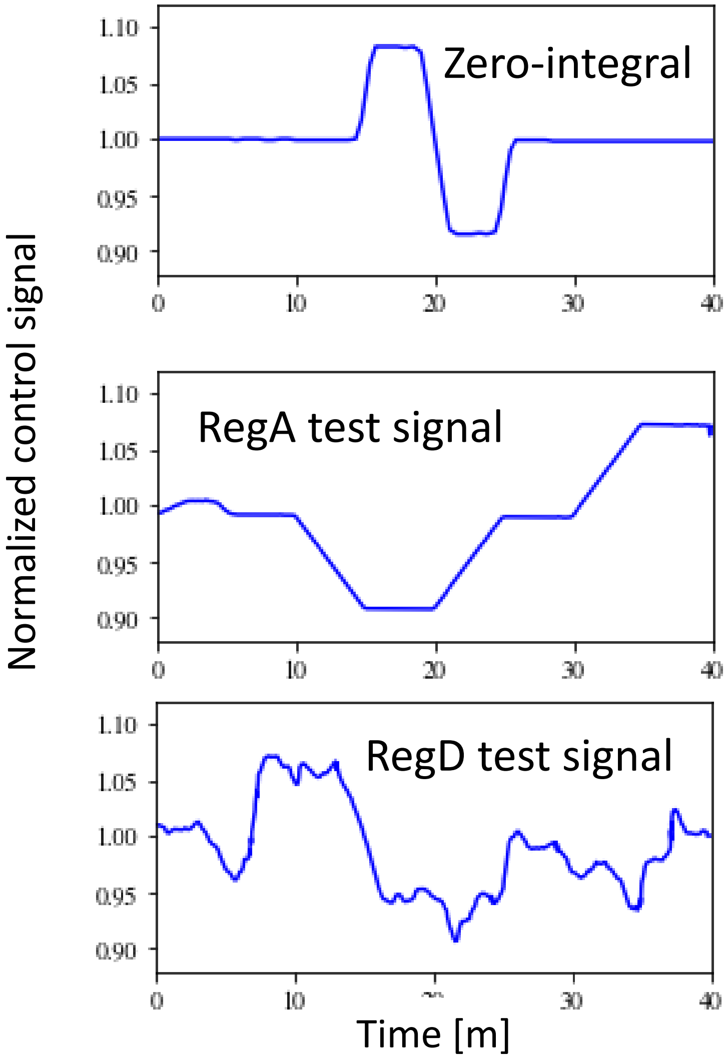


Preliminary control test case

18-turbine LES wind farm



3 test signals (8% regulation)

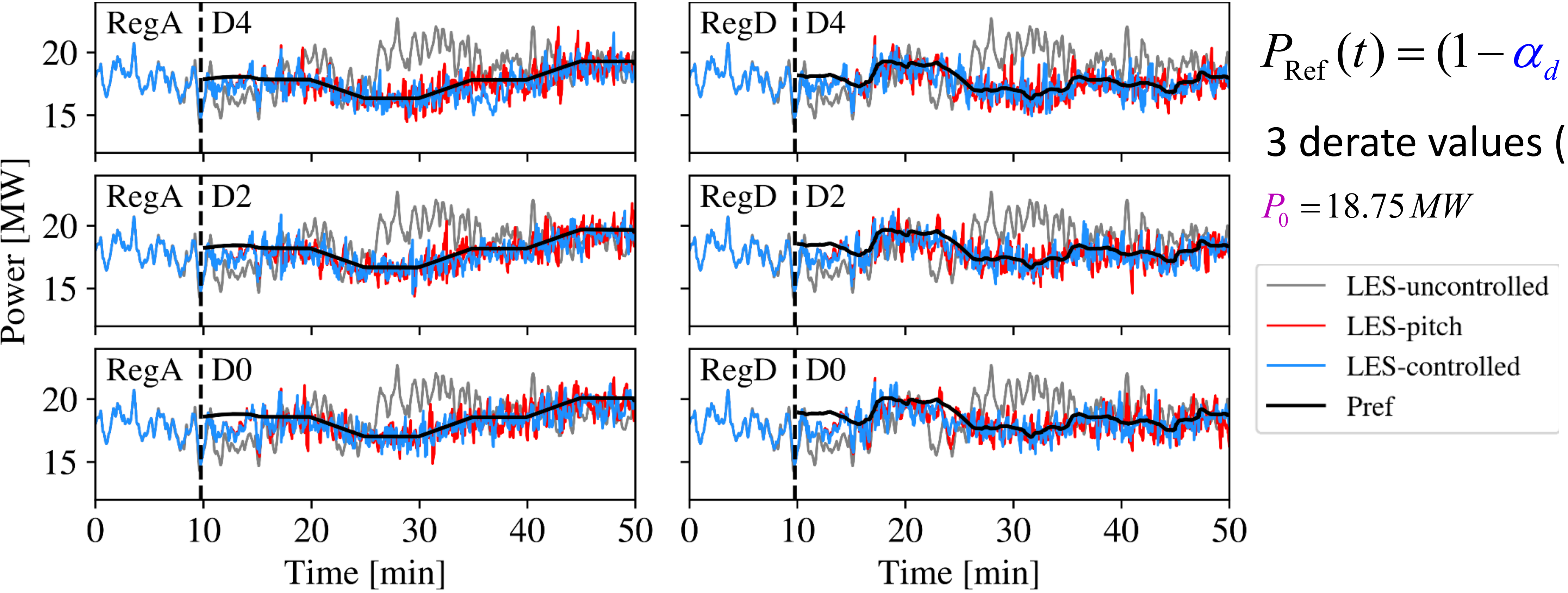


Tuning PI Gains

Performance metric

$$RMSE = \sqrt{\frac{1}{N_{ST}} \sum_{i=1}^{N_{ST}} \left(P_{\mathrm{LES,i}} - P_{\mathrm{Ref,i}} \right)^2}$$

Frequency regulation results (preliminary)



$$P_{\mathrm{Ref}}(t) = (1-\alpha_d)P_0 + r(t)P_0$$

3 derate values (0, 2, 4)

$P_0 = 18.75\,MW$

$T_H = 5\,\mathrm{min}$

$T_\gamma = 2\,\mathrm{min}$

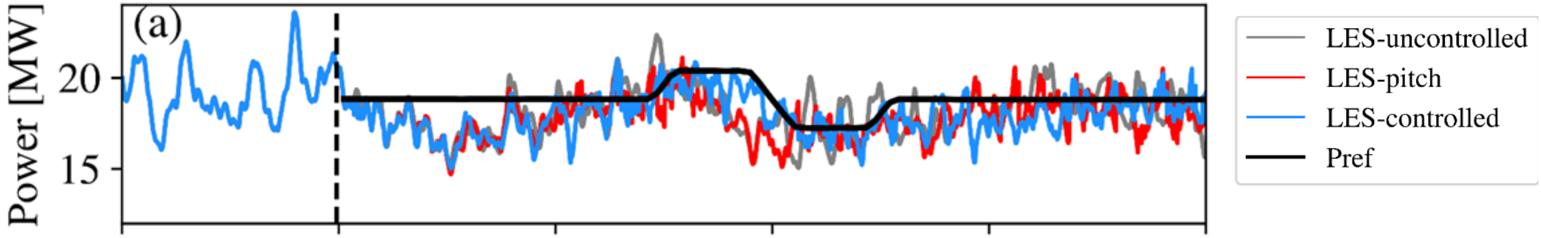
$T_{C_T'} = 10\,\mathrm{sec}$

Signal Type	4% derate		2% derate		0% derate	
	Yaw + Pitch	Pitch	Yaw + Pitch	Pitch	Yaw + Pitch	Pitch
RegA	0.90	0.82	0.84	0.85	0.90	0.93
RegD	0.82	0.84	0.85	0.92	0.97	1.01

[Starke et al. ACC 2023]

Yaw augmented pitch control (preliminary conclusions)

- Overall use of yaw for power tracking is complicated by the timescales (yaw is slow)
- Yaw seems to have added benefit when derates are lower
  - Noted benefit if the system is using greedy control (maximum thrust coefficient)



- Implementation of receding horizon approach in yaw loop may improve these results
  - New approaches needed
  - Computational trade-off needs to be examined

Acknowledgements

Collaborators: Charles Meneveau, Jennifer King and Johan Meyers



Students and Postdocs (current and former)
Carl Shapiro (AAAS Fellow), Genevieve Starke (NREL), Ghanesh Narasimhan, Manuel Ayala and Chengda Ji





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