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Optimization Under Uncertainty for Wake Steering Strategies

Julian Quick, Jennifer Annoni, Ryan King,
Katherine Dykes, Paul Fleming, and Andrew Ning

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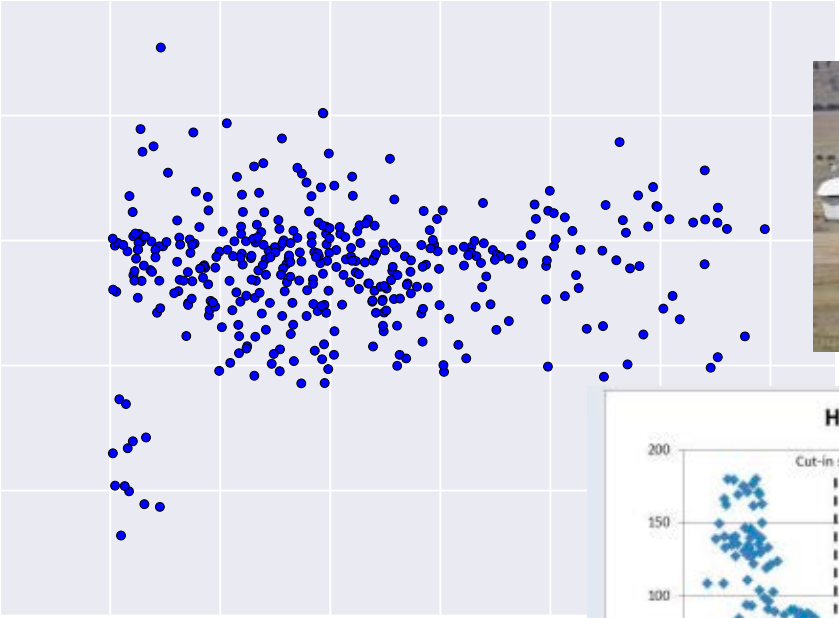
Outline

- Motivation
  - Epistemic uncertainties
  - Wake steering research at the National Renewable Energy Laboratory
- Optimization under uncertainty problem formulation
- Two-turbine case
- Princess Amalia Wind Farm case
- Conclusions & Next Steps

Introduction/Motivation–Yaw Position Uncertainty

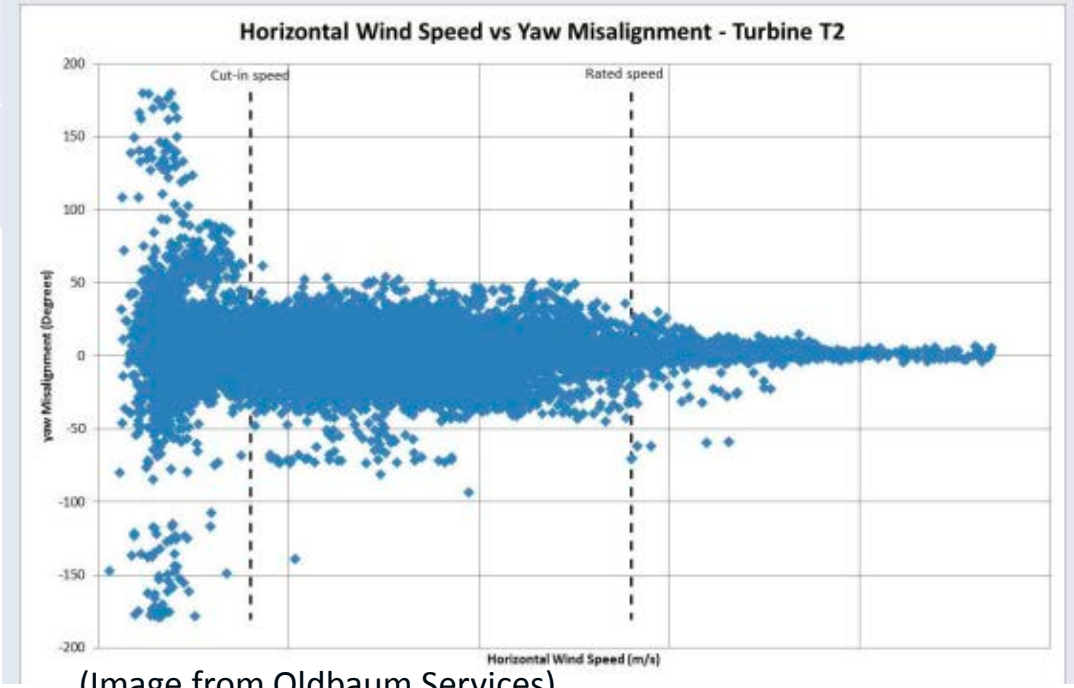
It is challenging to accurately characterize each turbine's yaw position

Yaw misalignment (°)



(Left data were recorded by NREL's DOE test turbine. Photo by Dennis Schroeder, NREL 19083)

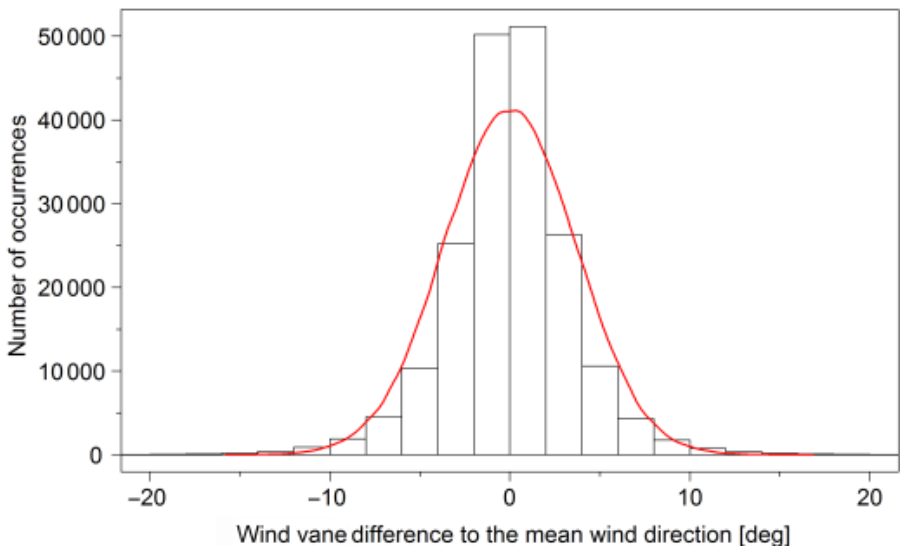
Wind Speed (meters per second [m/s])

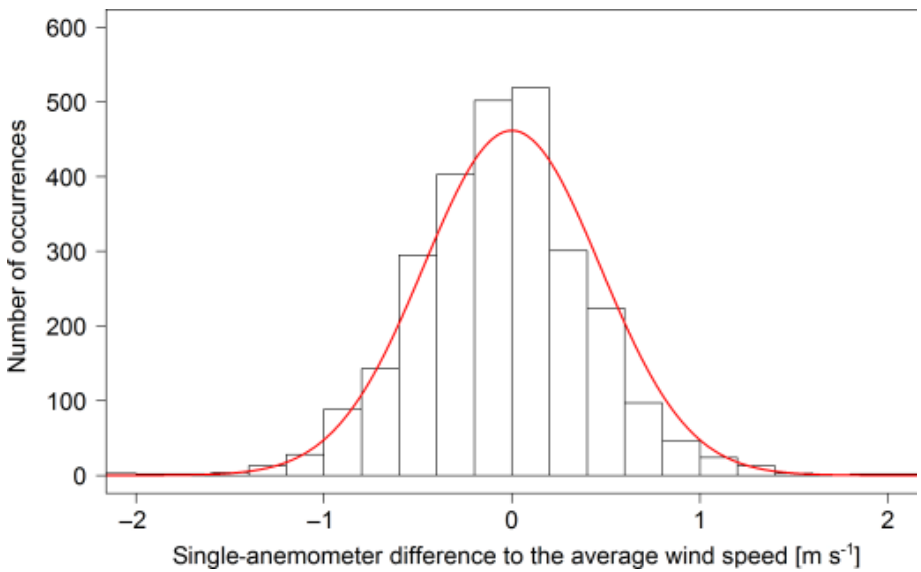


(Image from Oldbaum Services)

Introduction/Motivation–Inflow Uncertainty

We used literature values of uncertainty in the inflow speed and direction synthetic variables

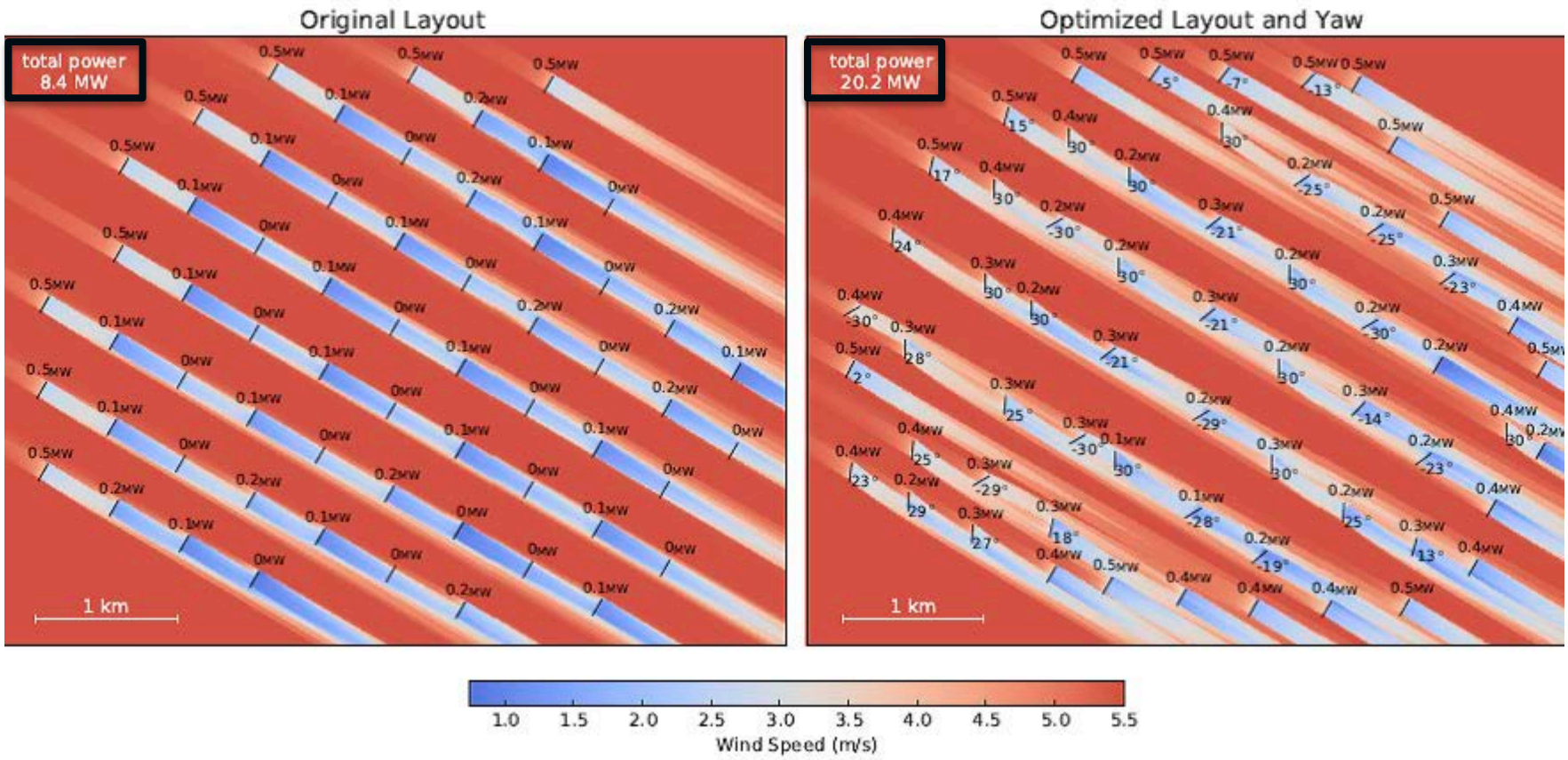




Mittelmeier, N., Blodau, T., and Kühn, M.: Monitoring offshore wind farm power performance with SCADA data and an advanced wake model, Wind Energy Science, 2, 175–187, doi:10.5194/wes-2-175-2017, http://www.wind-energ-sci.net/2/175/2017/, 2017.

Introduction/Motivation–Wake Steering

We can get more energy by controlling wind farms as a system of interconnected parts

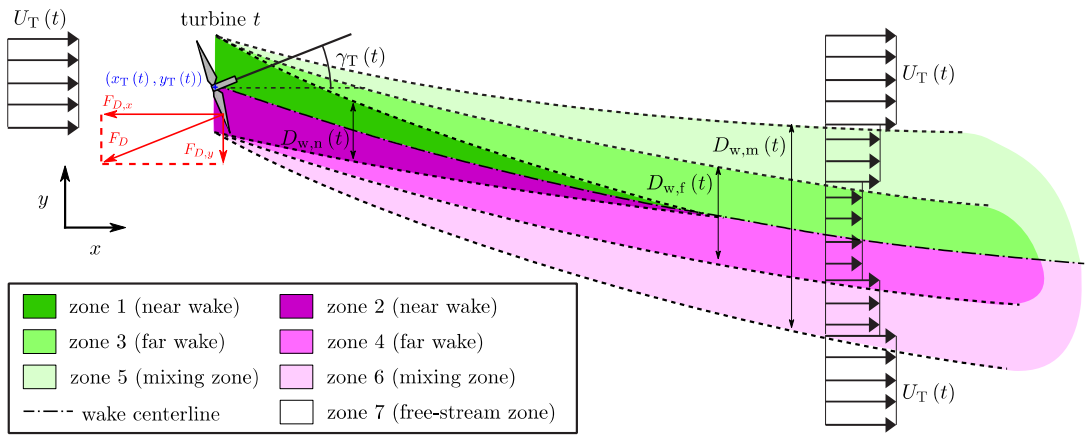


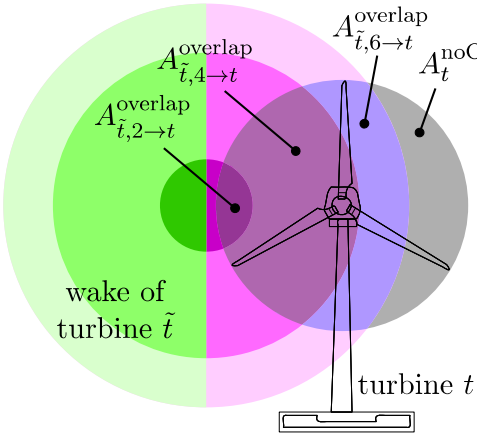
Gebraad, P., J. J. Thomas, A. Ning, P. Fleming, and K. Dykes. 2017. "Maximization of the annual energy production of wind power plants by optimization of layout and yaw-based wake control." *Wind Energy 20*, 97–107.

Methodology–Engineering Wake Model

The FLOw Redirection and Induction in Steady-State (FLORIS) wake model is a parametric model that approximates wake behavior as cones

FLOw Redirection and Induction in Steady-State (FLORIS) Wake Model





$$U_i = U_\infty \left(1 - 2\sqrt{\sum_j \left[a_j \sum_{q=1}^{3} c_{j,q}(X_i) \min\left(\frac{A^{overlap}_{j,i,q}}{A_i}, 1\right)\right]^2}\right)$$

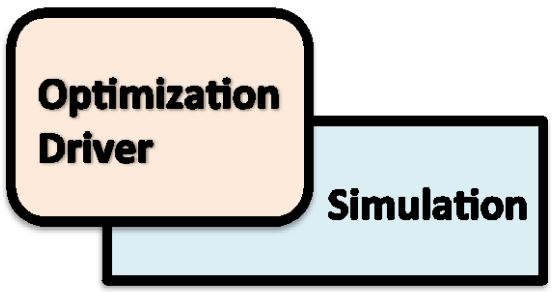
$$c_{i,q}(x) = \left(\frac{D_i}{D_i + 2k_e m_{U,q}[x - X_i]}\right)^2$$

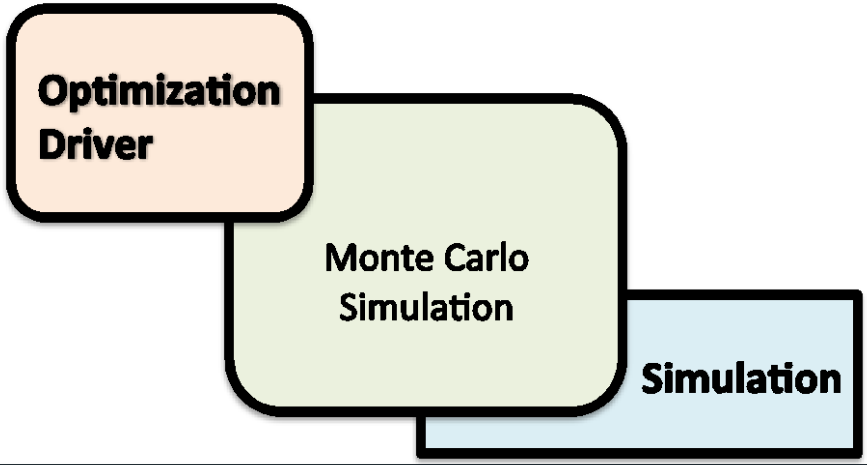
$$m_{U,q}(\gamma_i) = \frac{M_{U,q}}{\cos(a_U + b_U \gamma_i)}$$

Gebraad, P. M. O. and J. W. van Wingerden. 2014. "A control-oriented dynamic model for wakes in wind plants." *Journal of Physics: Conference Series* 524(1), 012186.

Methodology–Optimization Under Uncertainty (OUU)

We optimized a statistic describing the range of possible model outputs, given yaw position, direction, and speed uncertainty.





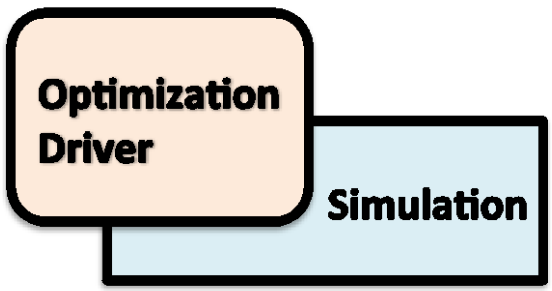
$$\widehat{\mathbb{E}}[\Pi(\boldsymbol{Y},\boldsymbol{\omega}_Y,\omega_\theta,\omega_u)] = \sum_{i=1}^{n}\sum_{j=1}^{m} P(u_{ij})P(\theta_i)\frac{1}{K}\sum_{K}\pi(\boldsymbol{Y}_{ij}+\boldsymbol{\omega}^k_{Yij},\theta_i+\omega^k_{\theta ij},u_{ij}+\omega^k_{uij})$$

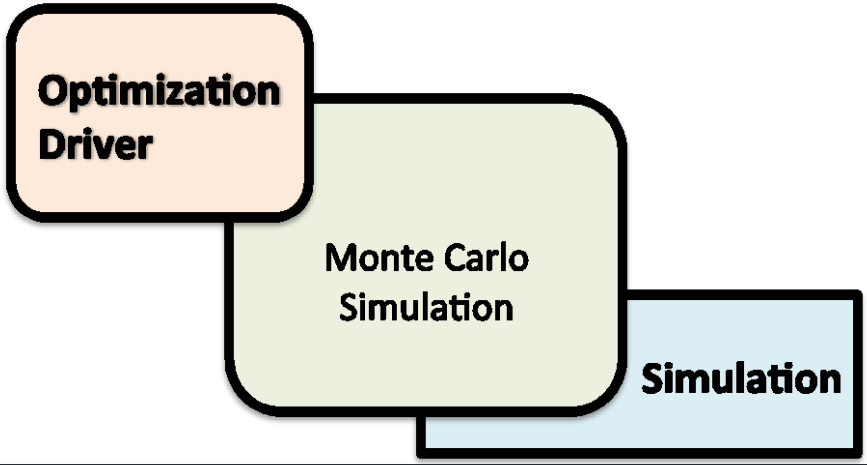
$$\boldsymbol{Y}^*_{OUU} = \arg\max_{\boldsymbol{Y}}\ \widehat{\mathbb{E}}[\Pi(\boldsymbol{Y},\boldsymbol{\omega}_Y,\omega_\theta,\omega_u)] = \arg\max_{\boldsymbol{Y}}\left(\sum_{i=1}^{n} P(\theta_i)\frac{1}{K}\sum_{K}\pi(\boldsymbol{Y}_i+\boldsymbol{\omega}^k_i,\theta_i+\omega^k_{\theta ij},u_{ij}+\omega^k_{uij})\right)$$

$$\boldsymbol{Y}^*_{det} = \arg\max_{\boldsymbol{Y}}\ \Pi(\boldsymbol{Y},\mathbb{E}[\boldsymbol{\omega}_Y],\mathbb{E}[\omega_\theta],\mathbb{E}[\omega_u]) = \arg\max_{\boldsymbol{Y}}\left(\sum_{i=1}^{n} P(\theta_i)\pi(\boldsymbol{Y}_{ij},\theta_i,u_{ij})\right)$$

Methodology–Optimization Under Uncertainty (OUU)

We define four metrics to describe the difference between the OUU, deterministic, and baseline (no steering) strategies.





$$VSS = \frac{\widehat{\mathbb{E}}[\Pi(\boldsymbol{Y}^*_{OUU}, \boldsymbol{\omega}_Y, \omega_\theta, \omega_u)]}{\widehat{\mathbb{E}}[\Pi(\boldsymbol{Y}^*_{det}, \boldsymbol{\omega}_Y, \omega_\theta, \omega_u)]}$$

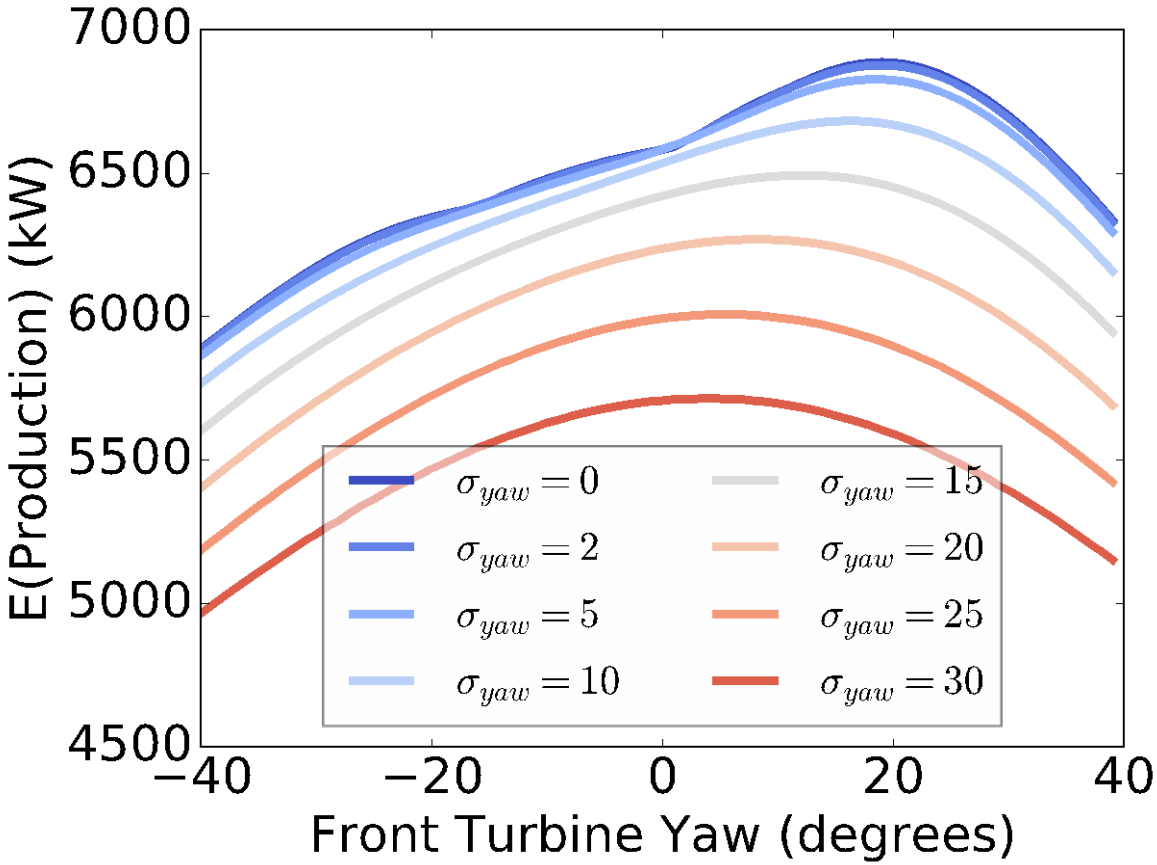
$$VSS_a = \frac{\widehat{\mathbb{E}}[\Pi(\boldsymbol{Y}^*_{det}, \boldsymbol{\omega}_Y, \omega_\theta, \omega_u)]}{\widehat{\mathbb{E}}[\Pi(\bar{\mathbf{0}}, \boldsymbol{\omega}_Y, \omega_\theta, \omega_u)]}$$

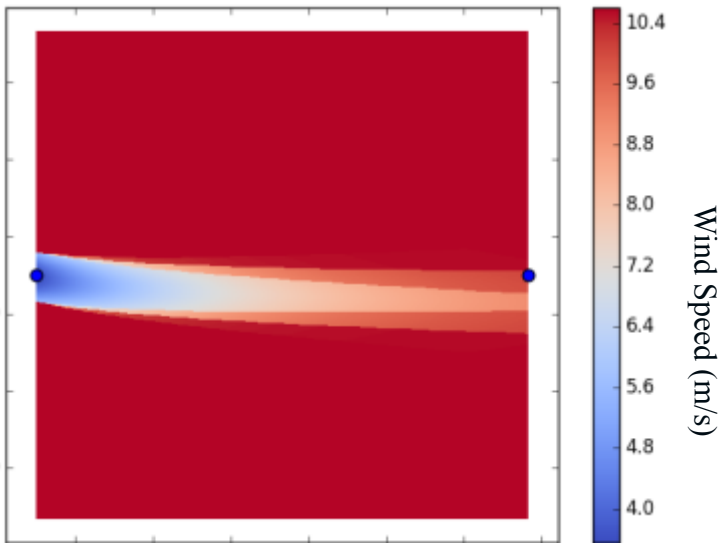
$$VSS_b = \frac{\widehat{\mathbb{E}}[\Pi(\boldsymbol{Y}^*_{OUU}, \boldsymbol{\omega}_Y, \omega_\theta, \omega_u)]}{\widehat{\mathbb{E}}[\Pi(\bar{\mathbf{0}}, \boldsymbol{\omega}_Y, \omega_\theta, \omega_u)]}$$

$$\eta = \frac{\pi(\boldsymbol{Y}^*_{det})}{\pi(\bar{\mathbf{0}})}$$

Case Studies–Two Turbines

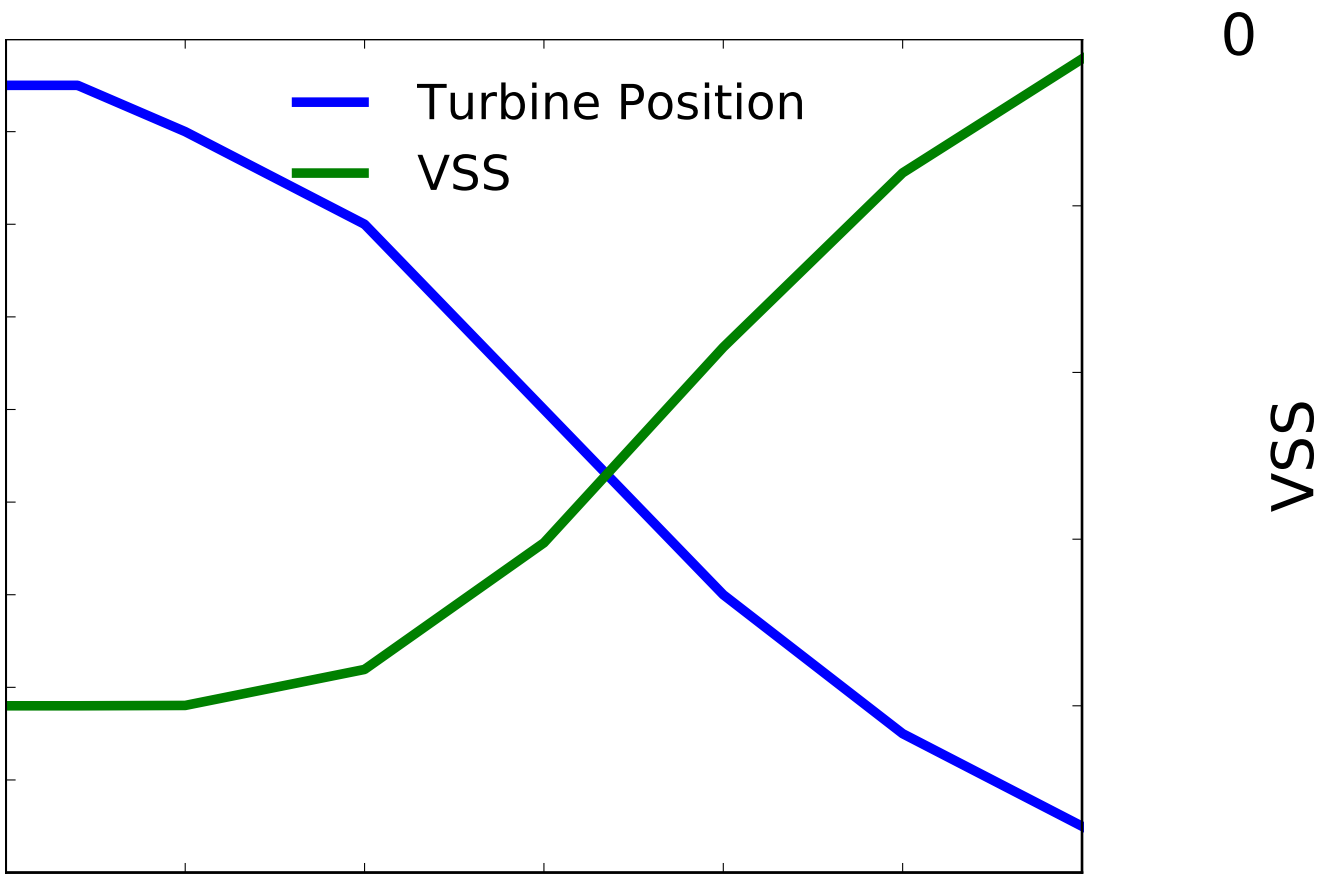
Two turbines, 10.6 m/s inflow, Gaussian yaw position uncertainty





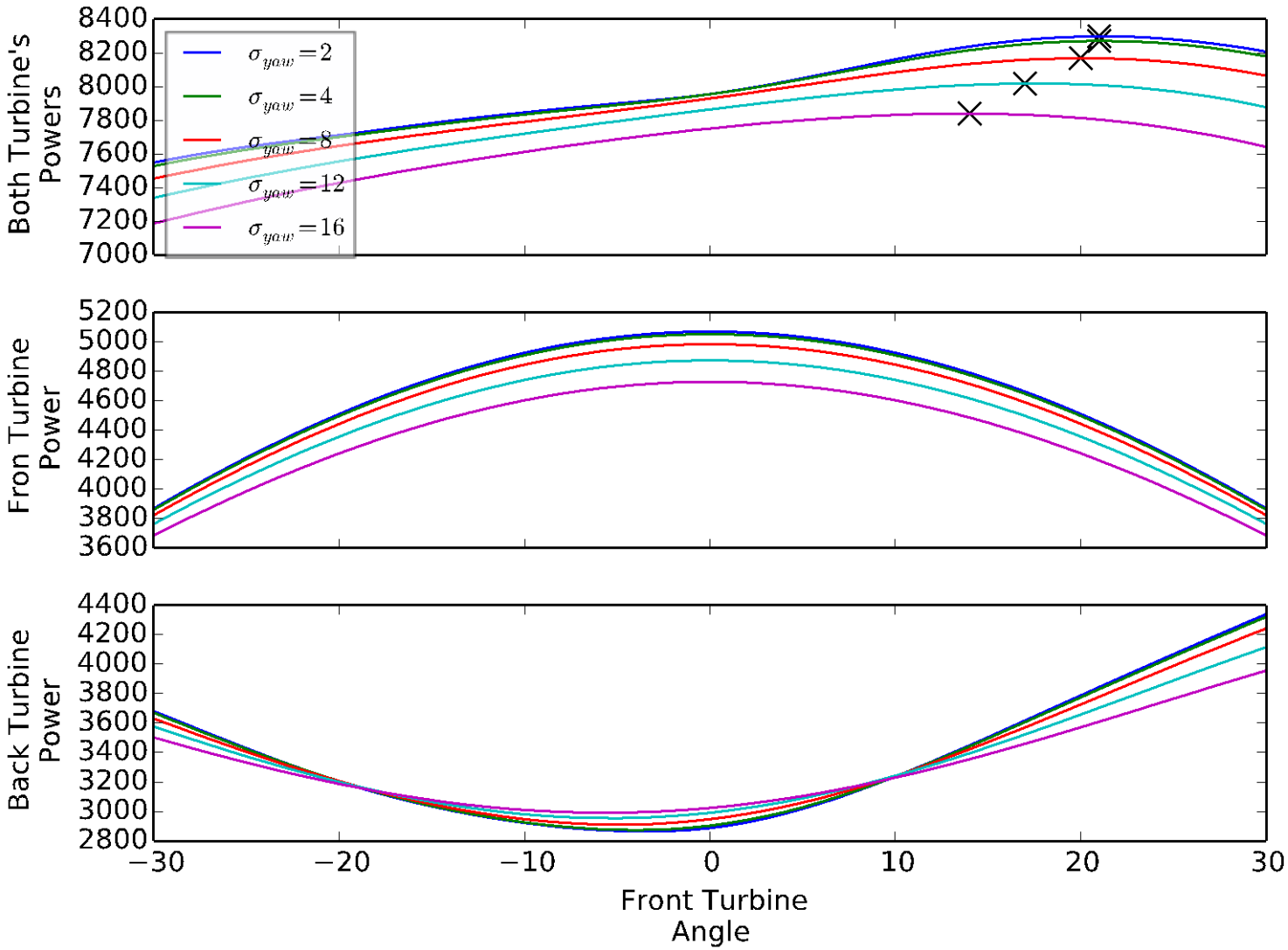
Case Studies–Two Turbines

As yaw position uncertainty increases, there is less benefit to wake steering and more value added by OUU



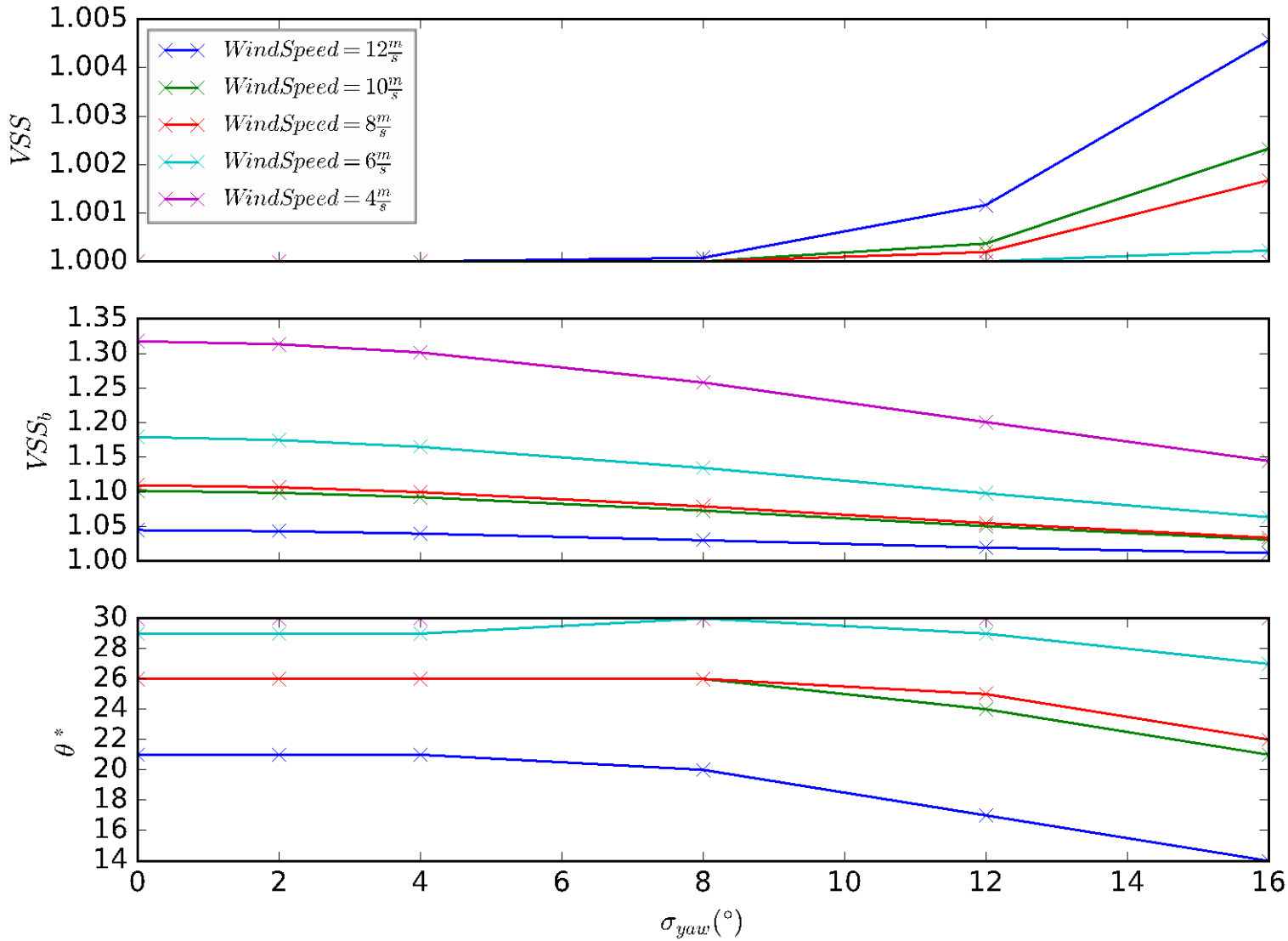
Case Studies–Two Turbines

Yaw position uncertainty contours with 12 m/s inflow. As yaw misalignment uncertainty increases, the back turbine sees less benefit from wake steering.



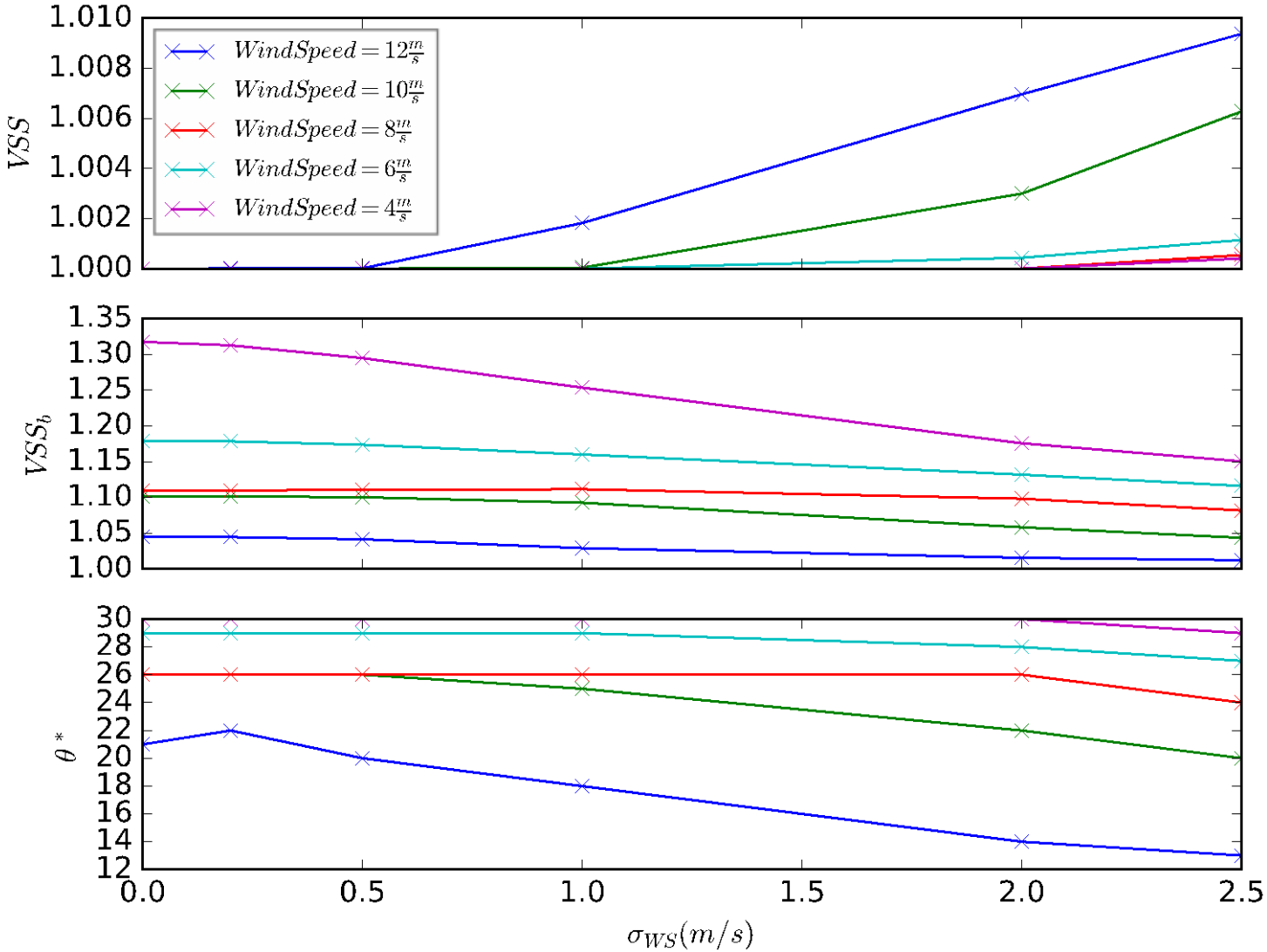
Case Studies–Two Turbines

Yaw position (°) uncertainty contours.



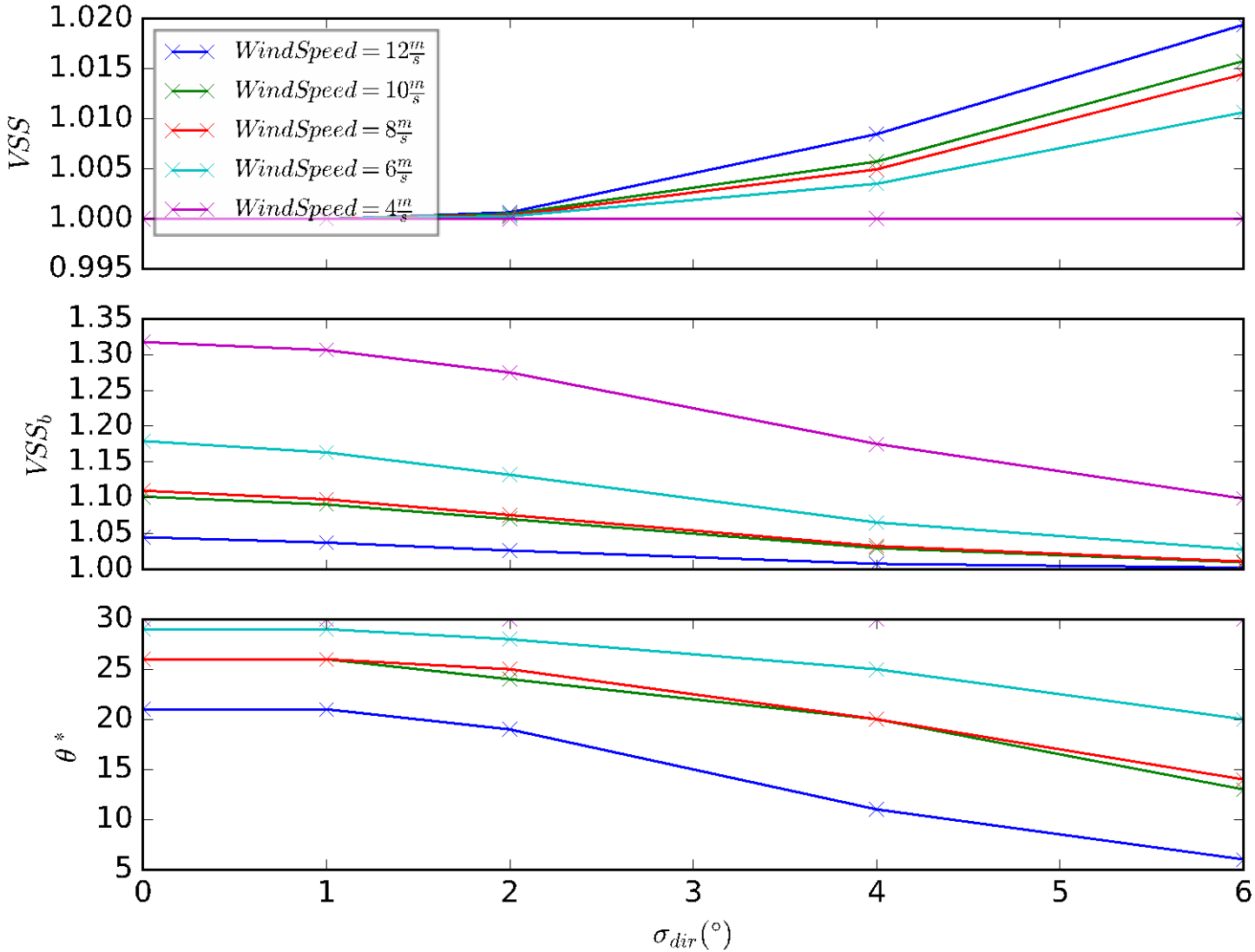
Case Studies–Two Turbines

Wind speed (m/s) uncertainty contours.



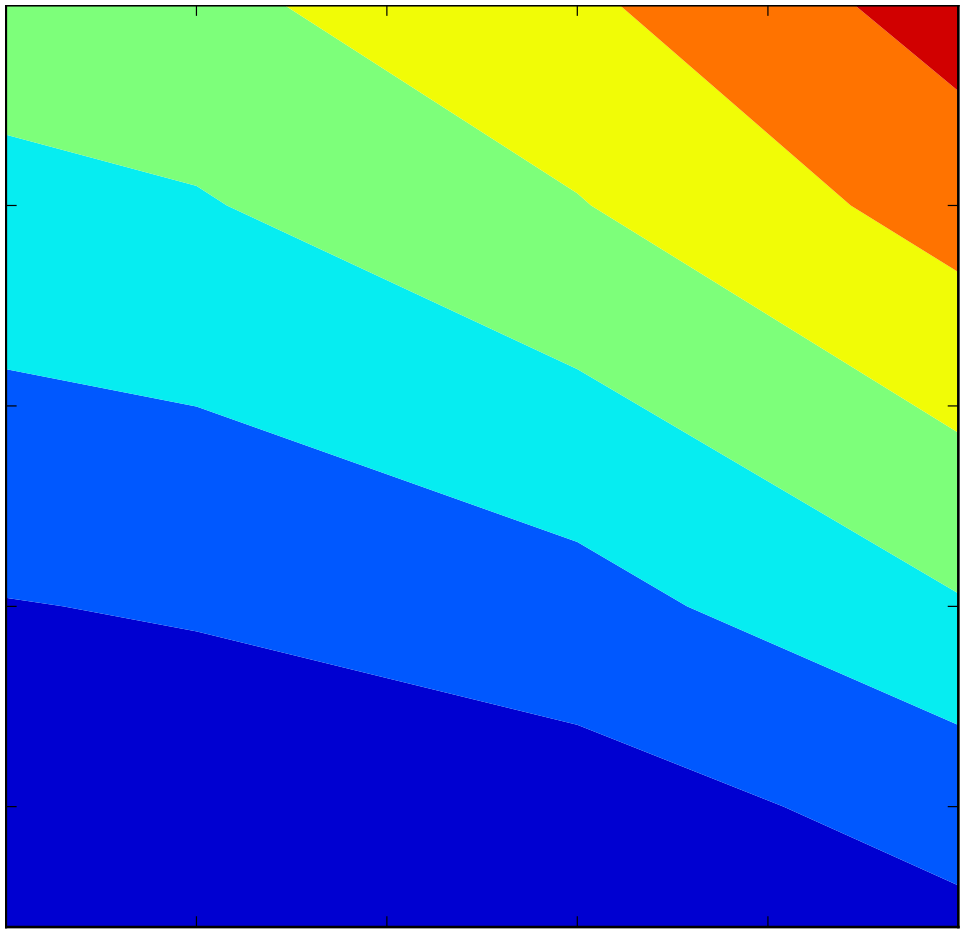
Case Studies–Two Turbines

Inflow direction (°) uncertainty contours.



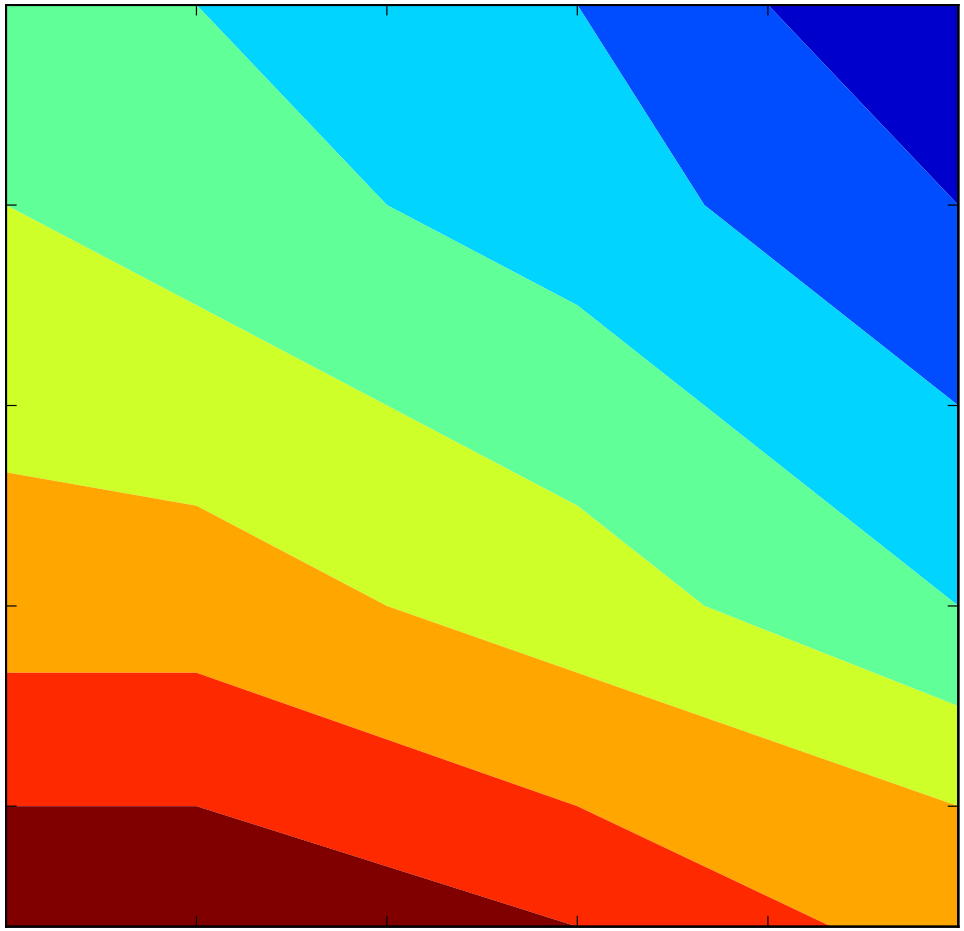
Case Studies–Two Turbines

Inflow speed and yaw position uncertainty VSS contours.



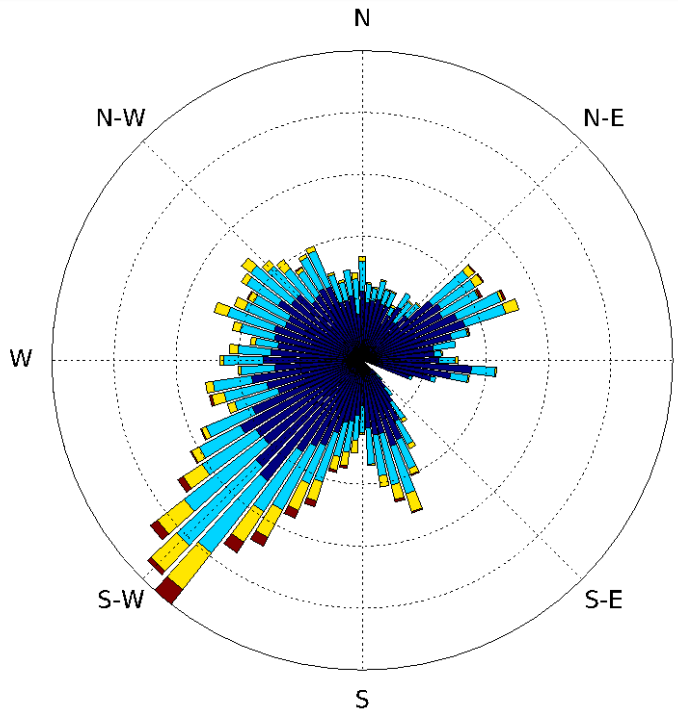
Case Studies–Two Turbines

Inflow speed and yaw position uncertainty optimal front turbine angle contours.



Case Studies–Princess Amalia Wind Farm

We optimized wake steering strategies for the Princess Amalia Wind Farm using deterministic and OUU formulations, examining the mean speed in each direction



Wind Speed (mps)

- [5.0 : 10.0)
- [10.0 : 15.0)
- [15.0 : 20.0)
- [20.0 : inf)

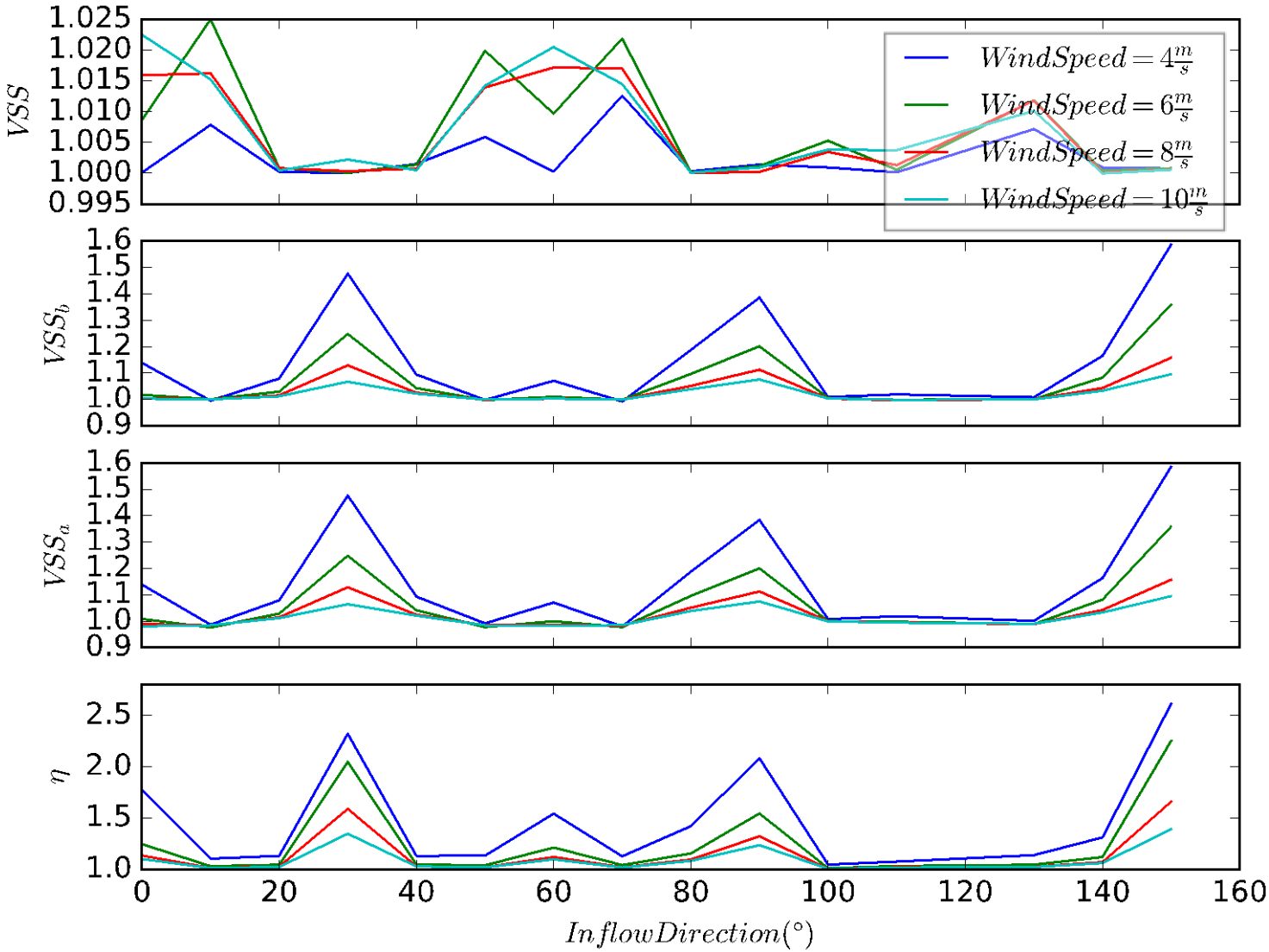
$\sigma(\omega_{yaw}) = 12°$

$\sigma(\omega_{\theta}) = 3.6°$

$\sigma(\omega_{WS}) = 0.56$ m/s

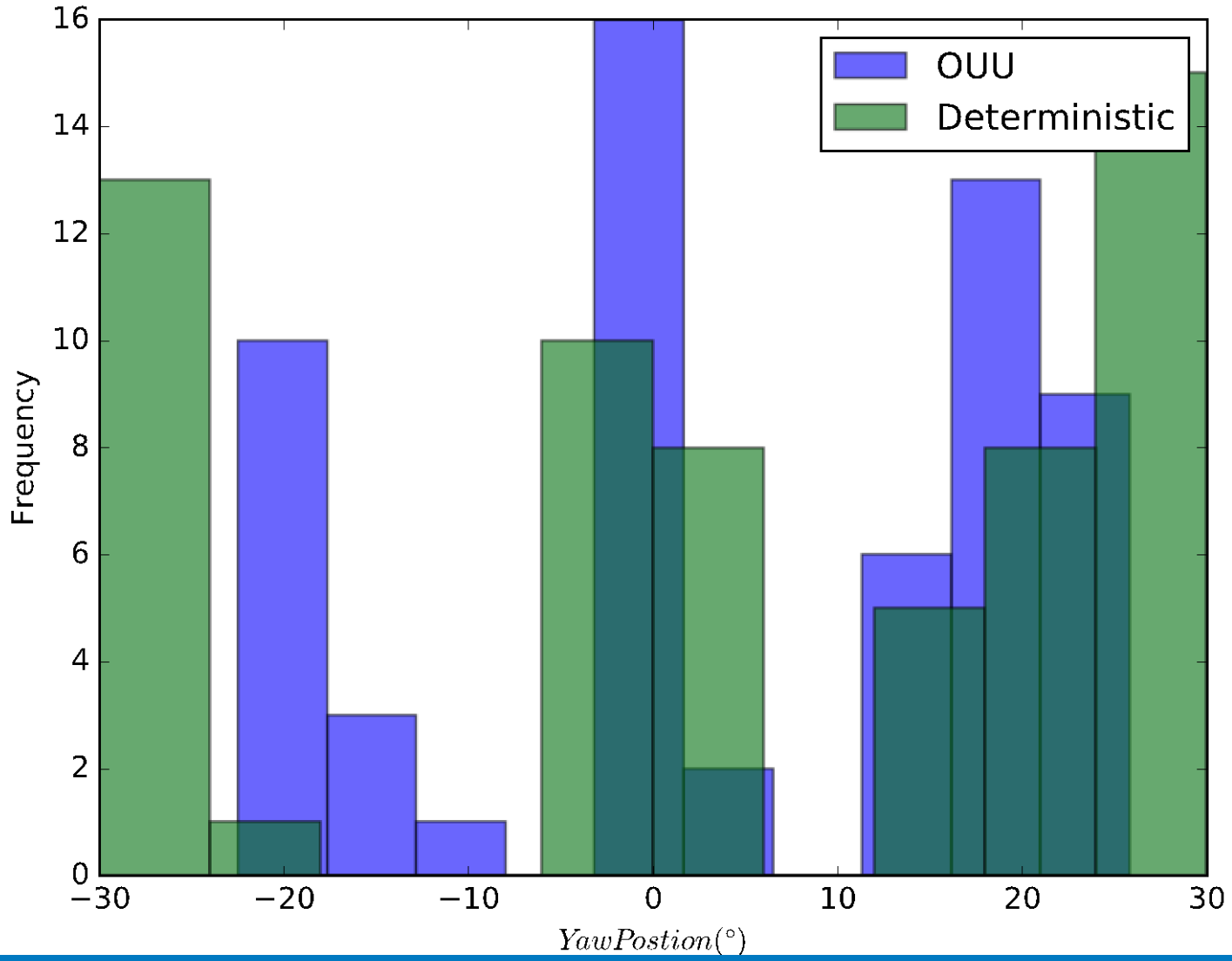
Case Studies–Princess Amalia Wind Farm

The VSS was highest in situations where the deterministic solution performed poorly



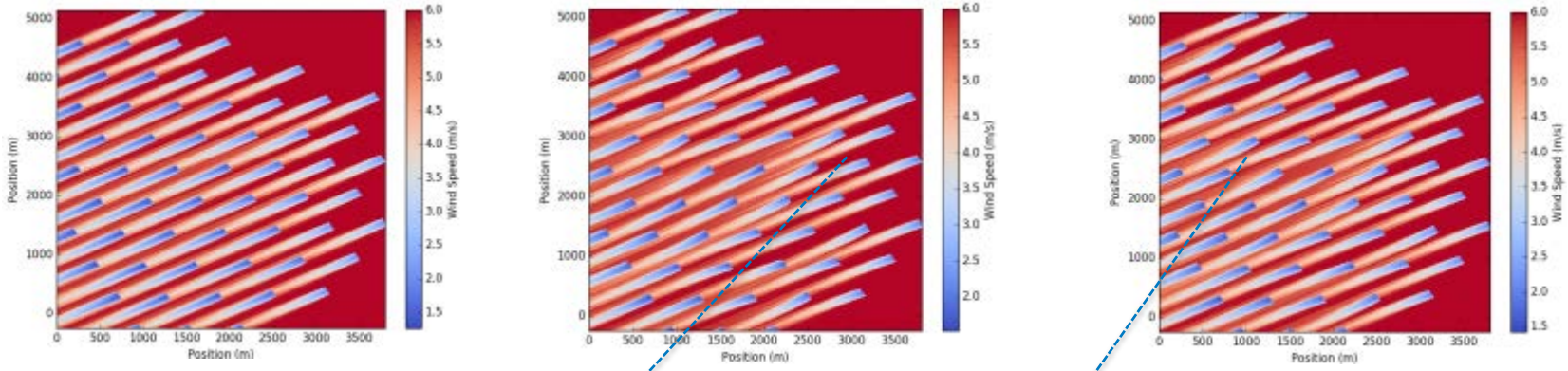
Case Studies–Princess Amalia Wind Farm

60° 6 m/s inflow: the OUU strategy has less extreme yaw offsets than the deterministic strategy



Case Studies–Princess Amalia Wind Farm (Northern Inflow)

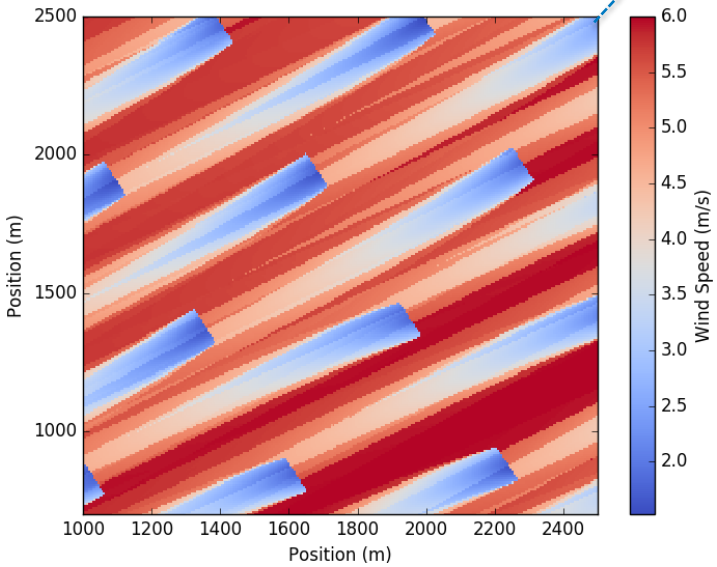
60° 6 m/s inflow: the deterministic strategy seems to steer wakes "next to" downstream turbines, whereas the OUU strategy does not steer the wakes as far.

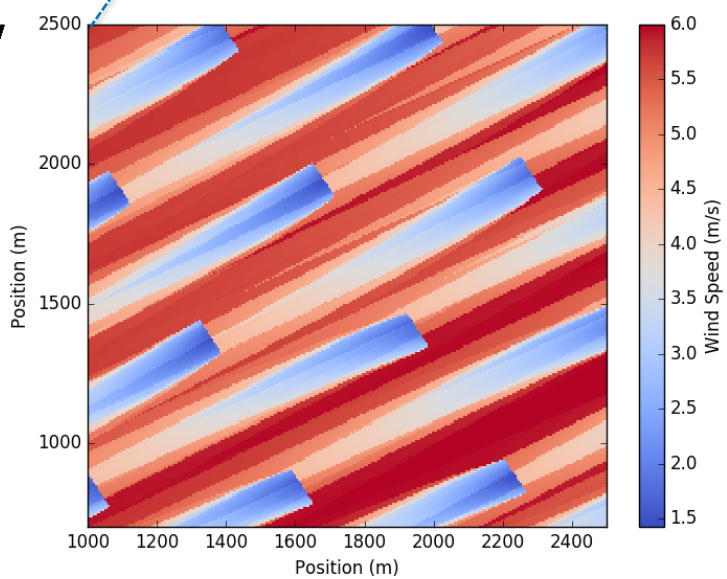


(a) No steering with northern inflow.

(b) Deterministic optimal steering with northern inflow

(c) OUU optimal steering with northern inflow.

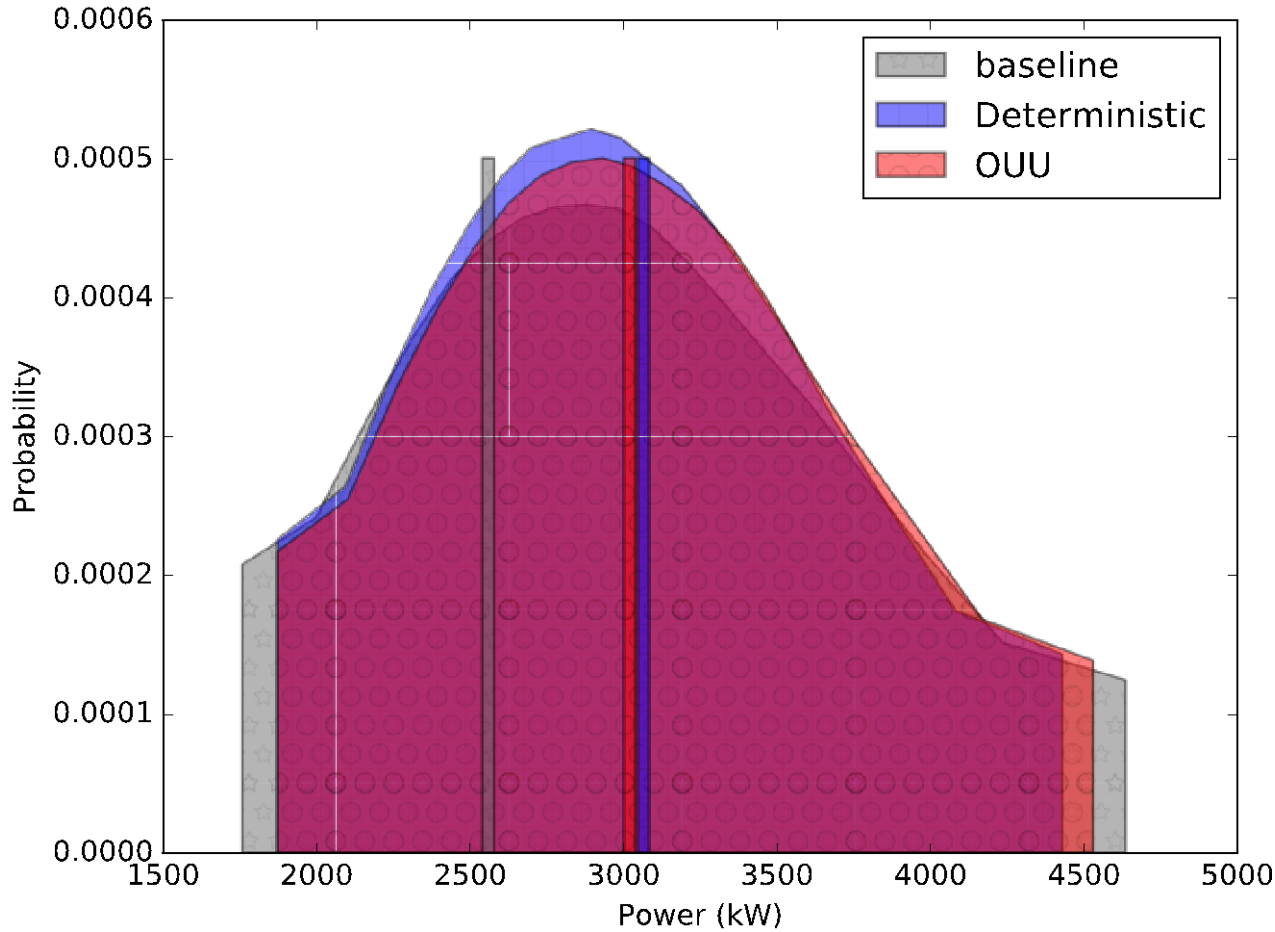




Case Studies–Princess Amalia Wind Farm

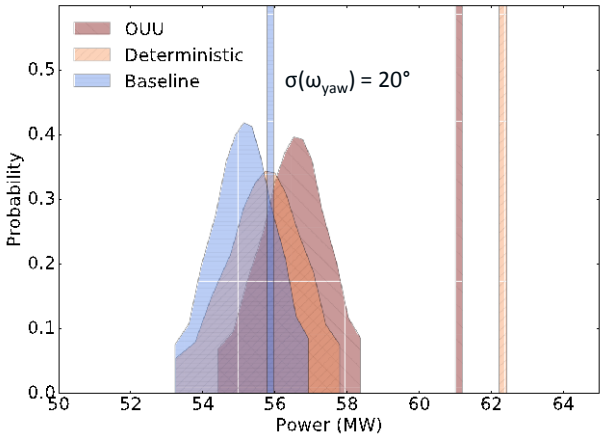
The straight bars are deterministic power forecasts and the filled curves show the range of possible outputs given yaw misalignment uncertainty. The OUU strategy has the least risk.

OUU Expectation: 3100 kW
Deterministic Expectation: 3050 kW
Baseline Expectation: 3070 kW



Conclusions & Next Steps

- Explicitly taking uncertainty into account produces more expected power with lesser yaw offsets than is produced when using the deterministic formulation
- Next steps:
  - Rigorously quantifying yaw position uncertainty
  - Taking loading into account
  - Quantifying model uncertainty
  - Identifying the most important uncertainty parameters.



Thank You!

Email: julian.quick@nrel.gov

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