ENVISION

Siting and Operation Decisions Under Uncertainties

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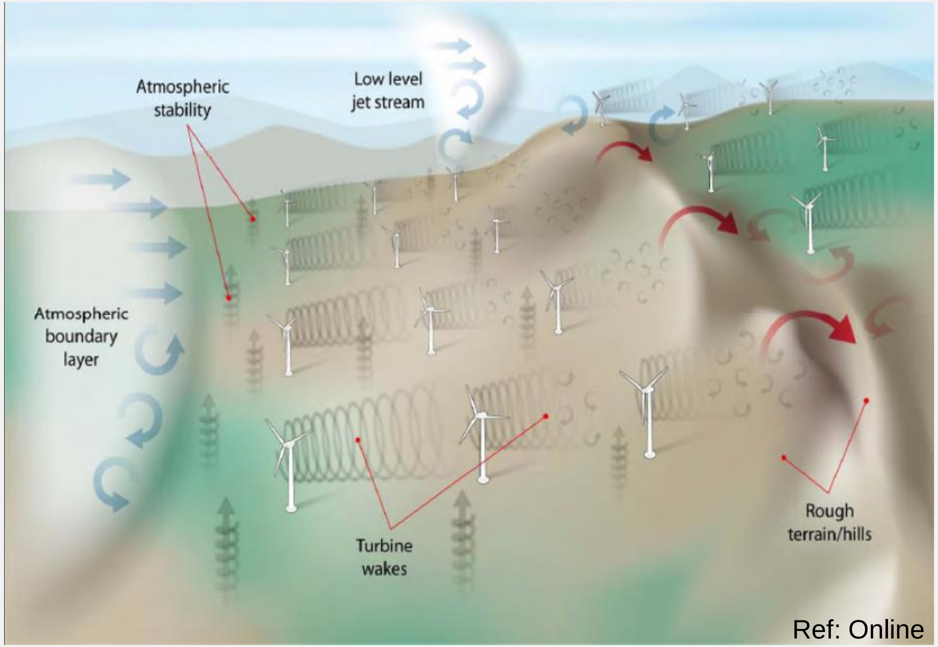
Complexity in Wind Farm Siting and Operation Decisions

- ❑ Variations in wind resource
- ❑ Uncertainties in site assessment
- ❑ Complexity in modeling aerodynamic interactions of turbines, wake motions
- ❑ Topological effects
- ❑ Effect of small time/space scales on the large scale quantities, such as loads.



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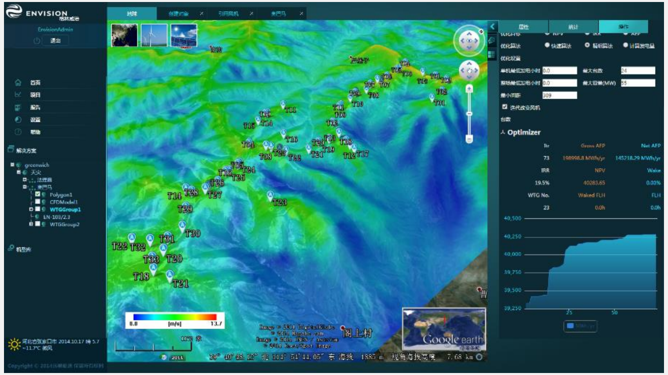
Greenwich Systems^{TM} Platform



Platform ensures the economic indicators of wind power assets and investments, provide customers with comprehensive technology solutions to wind farm planning, wind resource assessment, micro-siting, optimization, assessment of economic viability and post asset evaluation analysis.

Goal : To implement a quantitative, science-based and systematic risk assessment methodology for wind farm development and operation specifically at complex terrains.

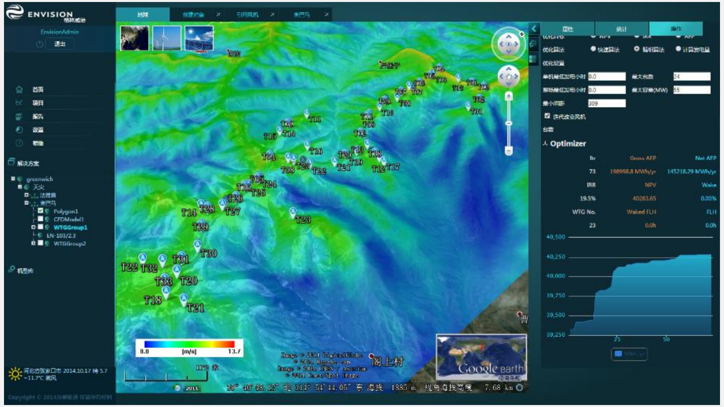
Risk is characterized as the effect of uncertainty on development and operational objectives.

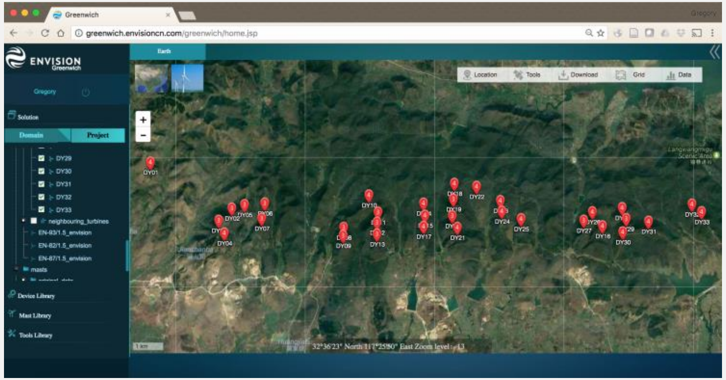
- power production: possible underperformance issues
- overloaded turbines: possible loads exceedances causing maintenance costs etc.

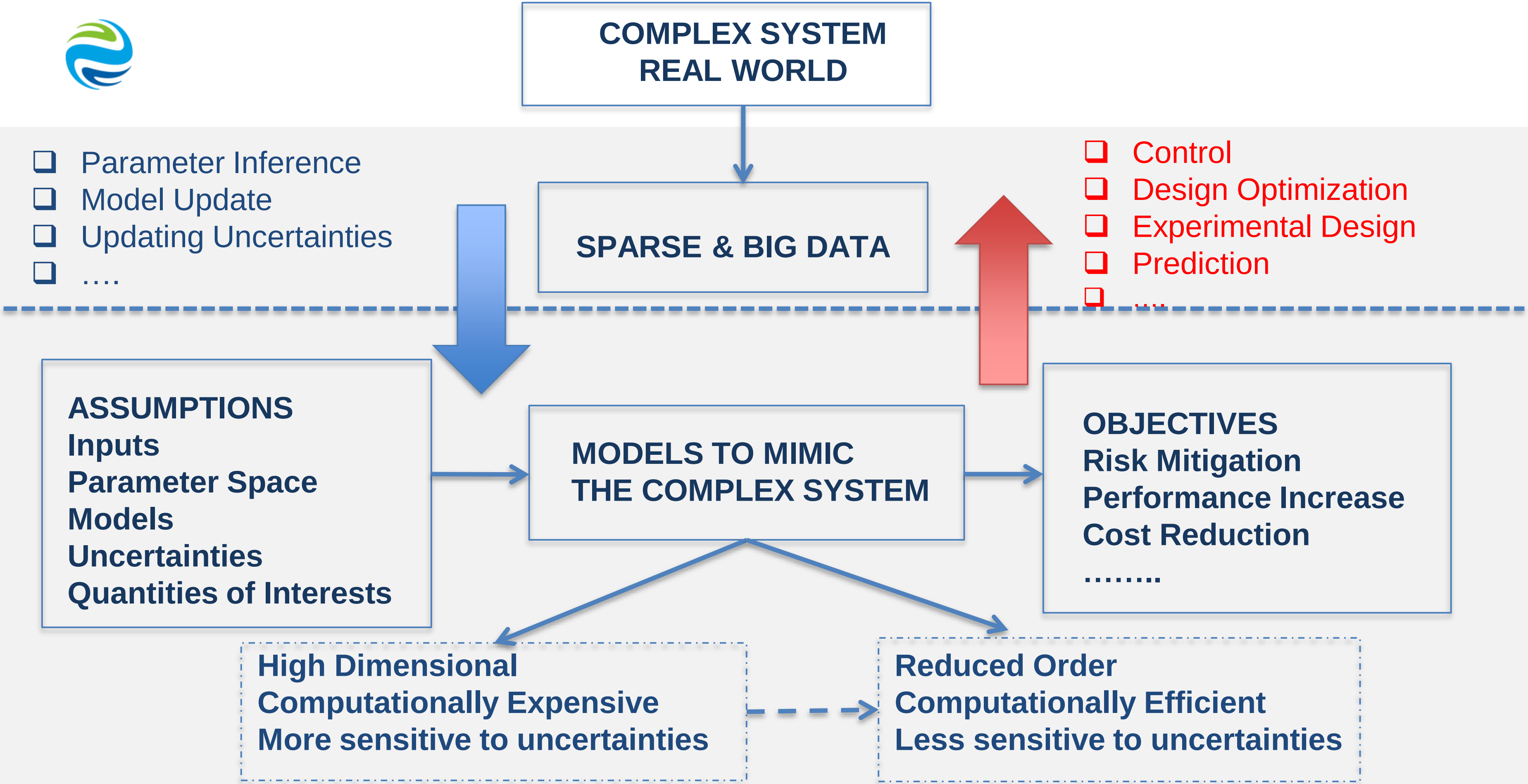
Offline feedback to Greenwich Systems™

Smart Wind Farm configuration and optimization

1. Closing the loop to feedback with original site configuration design and optimization is a powerful enabler;
2. Data mining across a wide sample of site operational performances guides the determination of best site design practices for:
   1. Measurement campaign planning;
   2. Long term reference and long term correlation of measurement data in specific climatic zones;
   3. CFD model selection and parameter tuning in various terrain complexities and local climate stratification tendencies;
   4. Wake model selection and parameter tuning







COMPLEX SYSTEM
REAL WORLD

SPARSE & BIG DATA

- ☐ Parameter Inference
- ☐ Model Update
- ☐ Updating Uncertainties
- ☐ ….

- ☐ Control
- ☐ Design Optimization
- ☐ Experimental Design
- ☐ Prediction
- ☐ ….

ASSUMPTIONS
Inputs
Parameter Space
Models
Uncertainties
Quantities of Interests

MODELS TO MIMIC
THE COMPLEX SYSTEM

OBJECTIVES
Risk Mitigation
Performance Increase
Cost Reduction
……..

High Dimensional
Computationally Expensive
More sensitive to uncertainties

Reduced Order
Computationally Efficient
Less sensitive to uncertainties

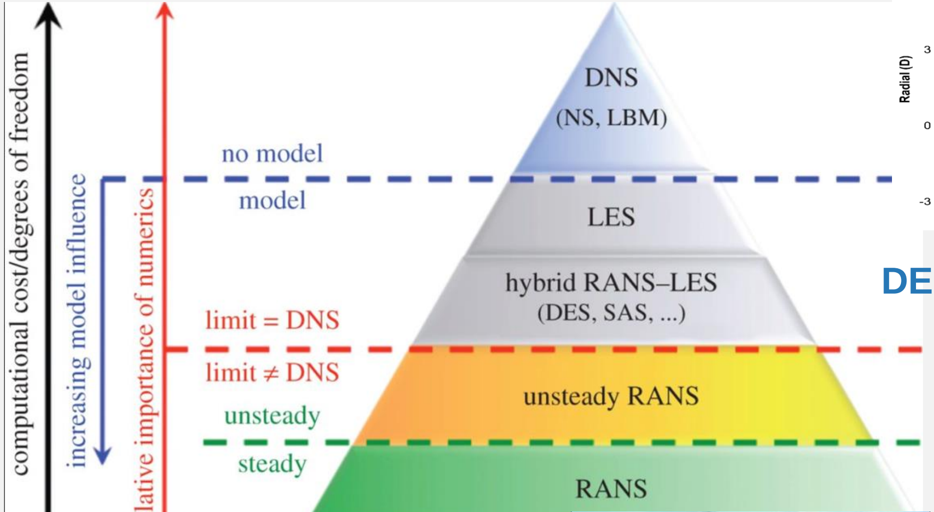
Propagating uncertainties with computational efficiency

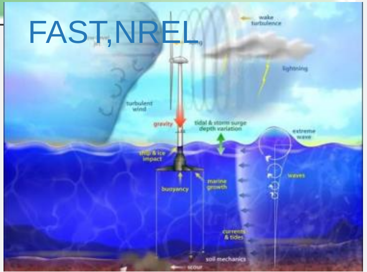
Obtaining reduced order models with accuracy

Models To Mimic The Complex System

Numerical Models

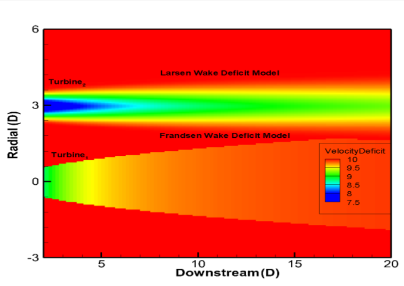
Farm solvers: RANS, URANS, DES, LES



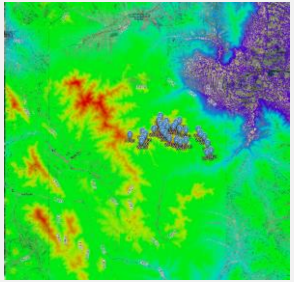

FAST,NREL

Aeroelastic solvers:
FAST/BLADED/HAWC2

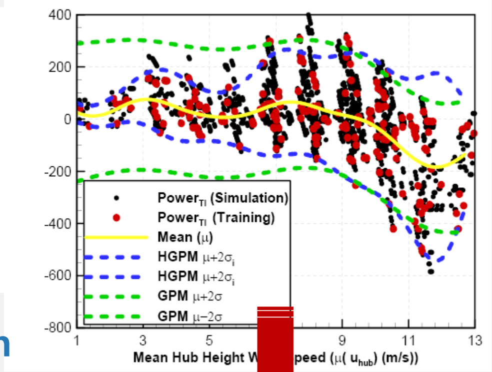
Semi-Analytical Models



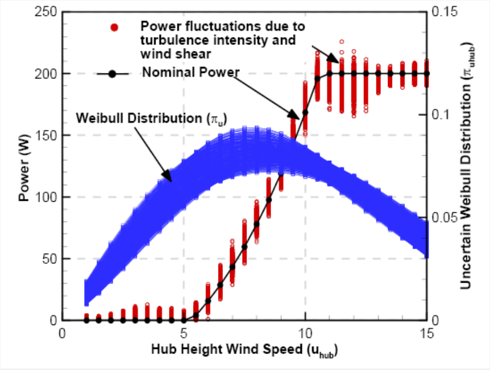
DES at Complex Terrain



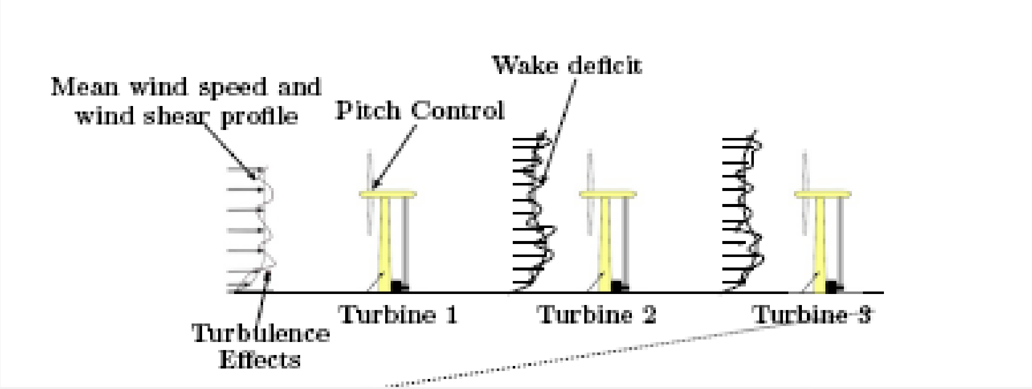
Stochastic Models



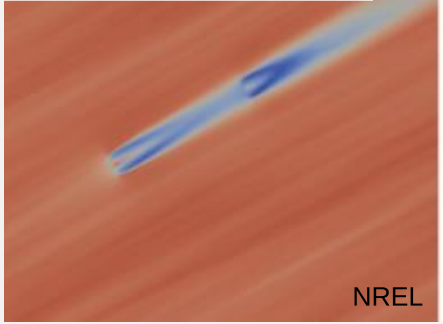
Uncertain Power Curve



Uncertainties in Wake Models – Case study

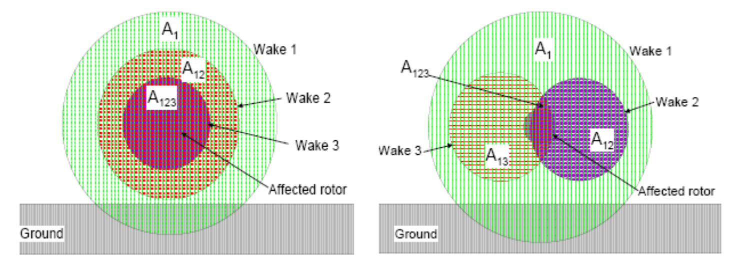


LES solution

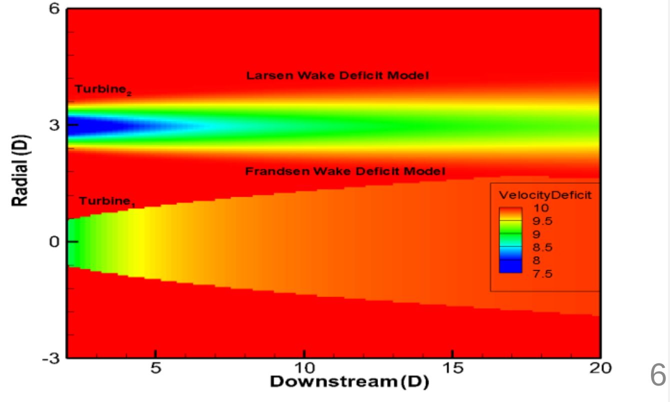


NREL

Wake Superposition



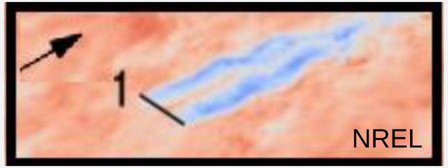
Semi-analytical Model

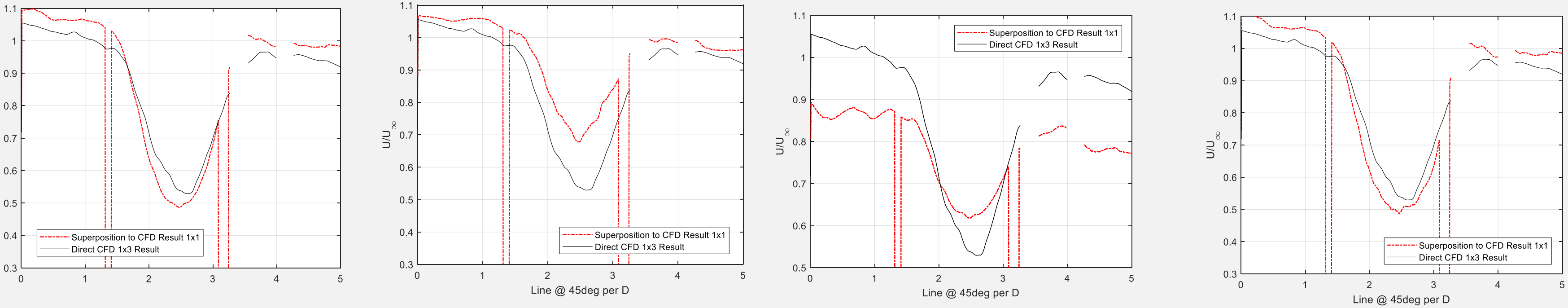


Wake Superposition

Superimpose 1 Turbine LES CFD simulation data using 4 different superposition rules for and compare with 2 Turbine Case LES CFD simulation data. (Neutral atmospheric stability, flat terrain)

@ 8D Diameter downstream of T1
(T1 and T2 are 5D separated)





Linear Superposition

Geometric Sum

Sum of Squares

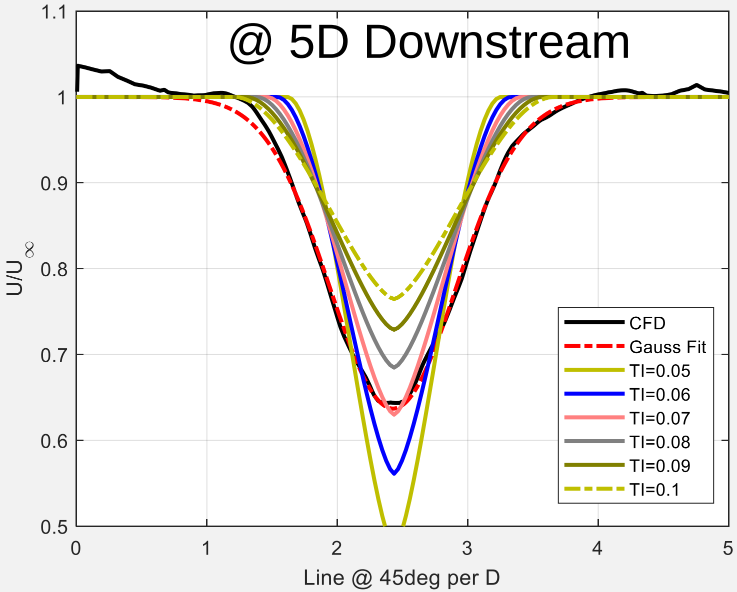
Energy Balance

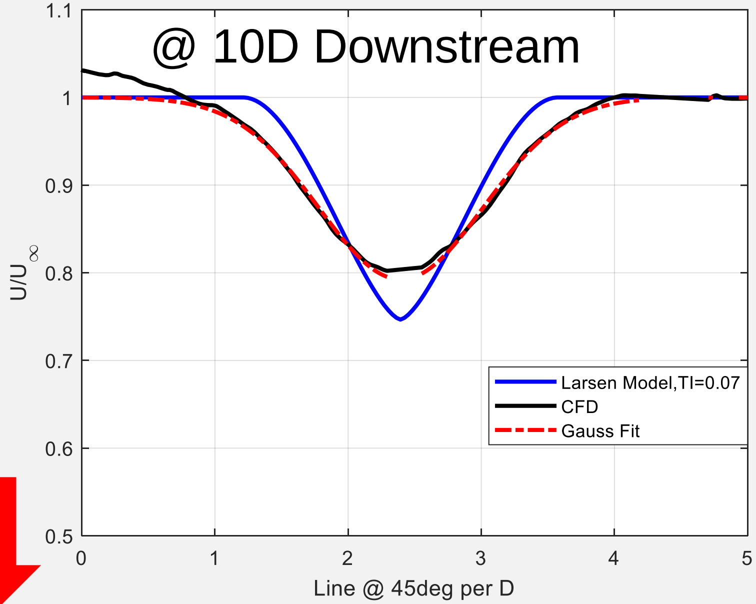
red lines: superimposed 1Turbine LES solution

black lines : direct 2 Turbine LES solution

Wake Deficiency Modeling: Larsen Model

1 Turbine Case : changes in the wake deficiency based on TI, TI = 0.07 is selected



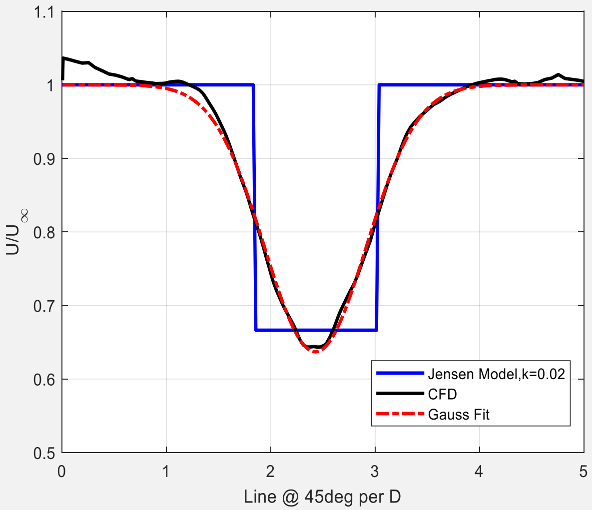


there is still a discrepancy in the
wake diameter & wake deficiency

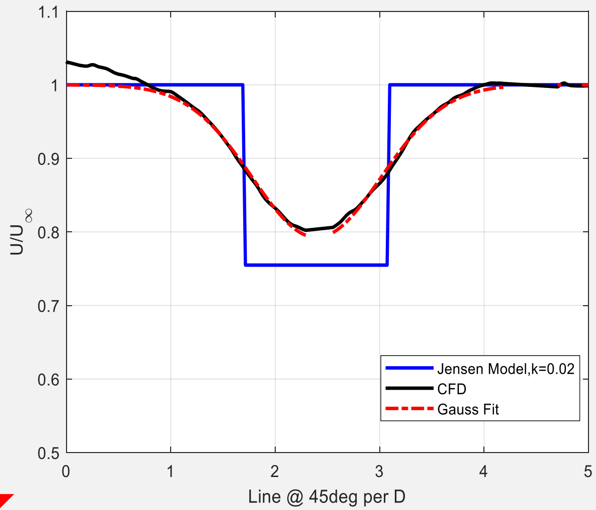
Wake Deficiency Modeling : Jensen Model

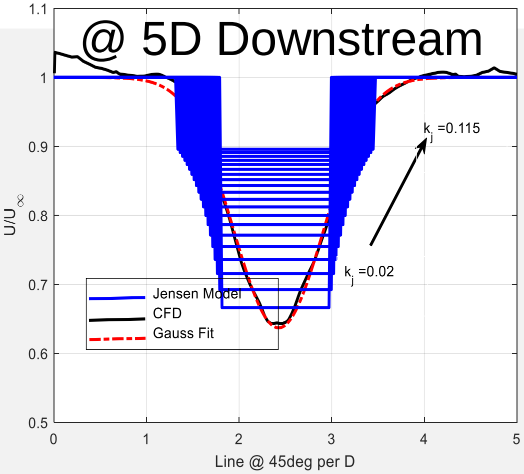
Jensen Model with k = 0.02

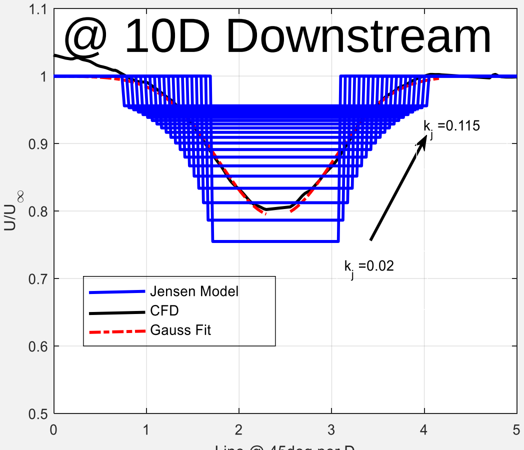
@ 5D Downstream



@ 10D Downstream





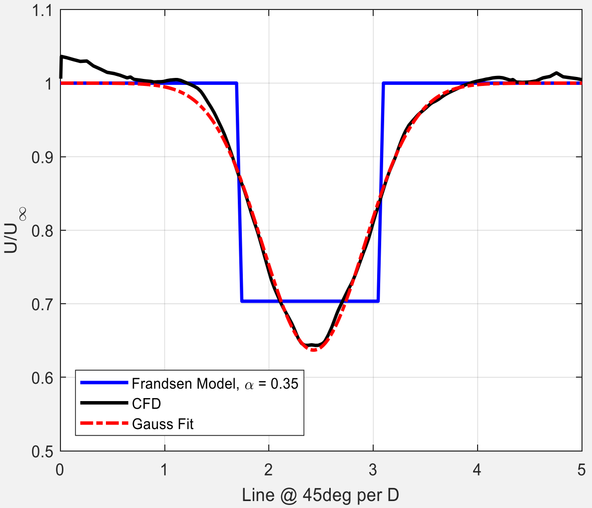


One k value can not be used to simulate
the complete downstream behavior,
even only with 1 Turbine case

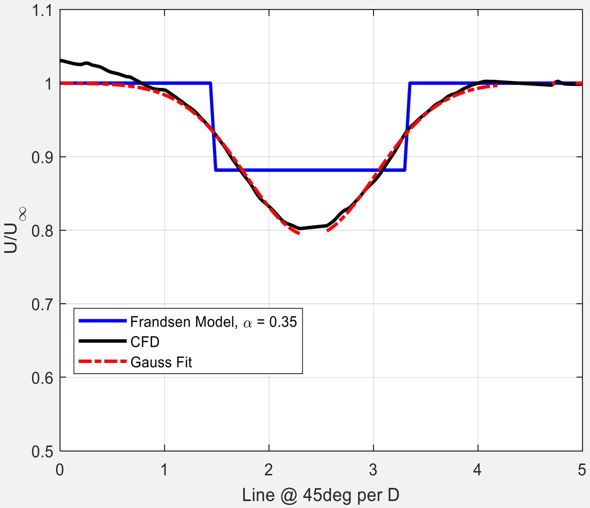
Wake Deficiency Modeling: Frandsen Model

Frandsen Model with α = 0.35

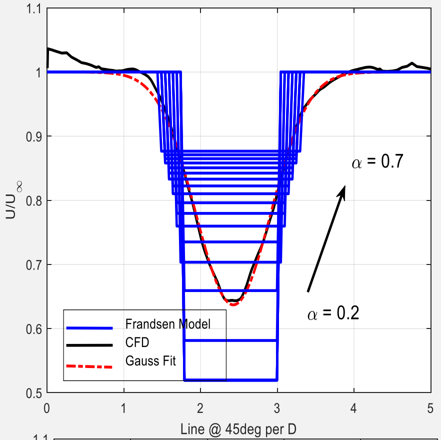
@ 5D Downstream

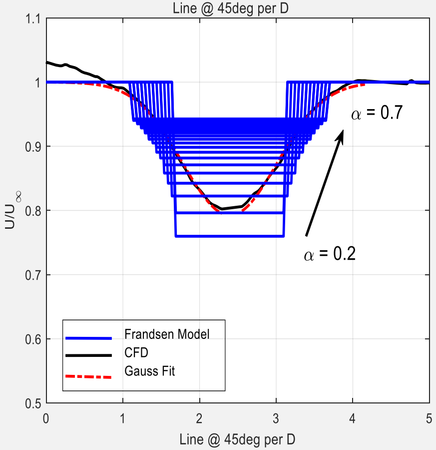


@ 10D Downstream

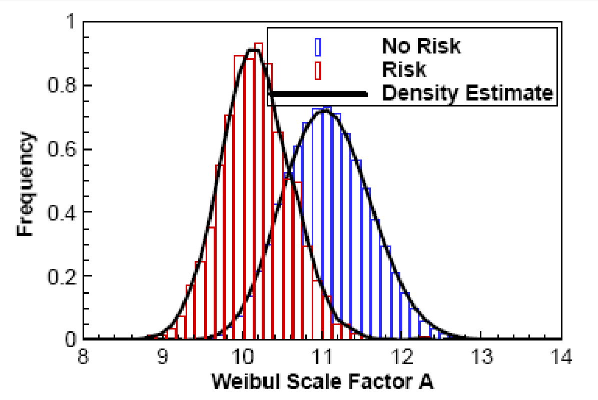


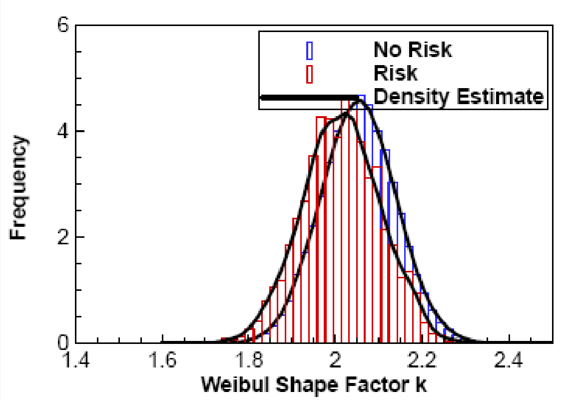
One α value can not be used to simulate the complete downstream behavior, even only with 1 Turbine case

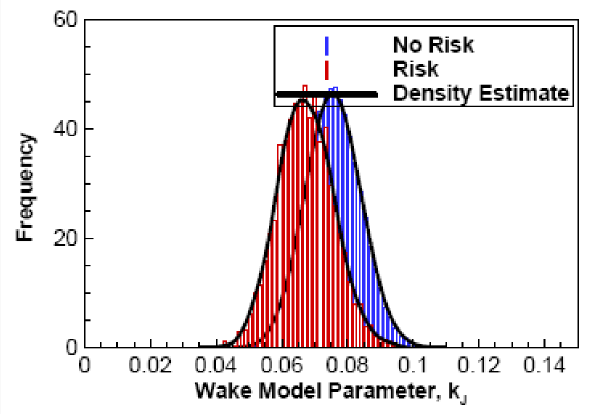




Siting Perspective – Regional Sensitivity Analysis







$$S_{R_j} = D_{KL}(P_{x_j} || Q_{x_j})$$

	Layout	
	Aligned	Staggered
A	1.6534	7.194
k	0.1052	0.5629
k_j	0.4934	0.0012
β_1	0.1937	0.0299
β_2	0.0246	0.0013

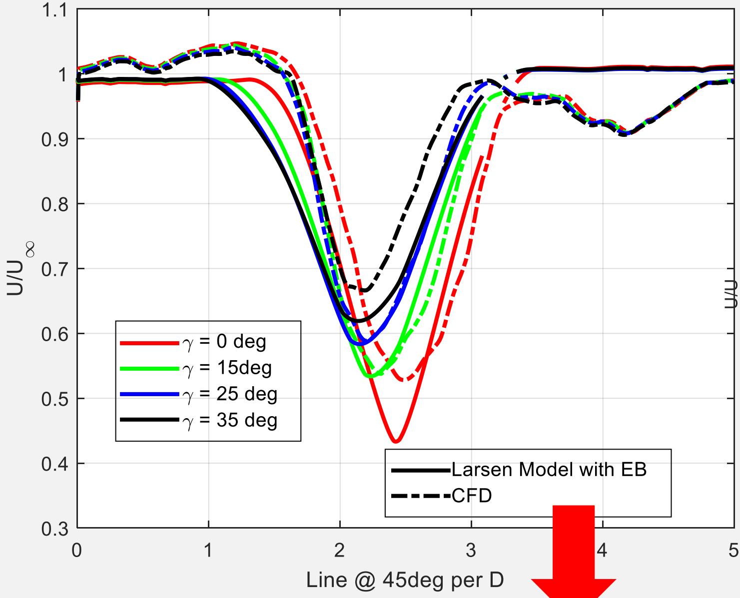
Wake modeling uncertainty is very critical for siting

Wind Resource Assessment

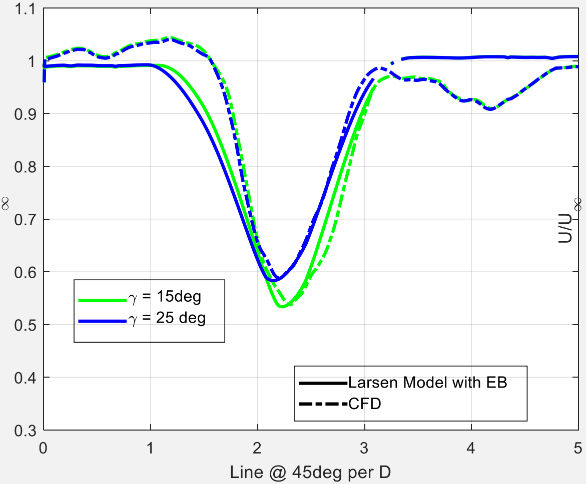
Turbine Operation

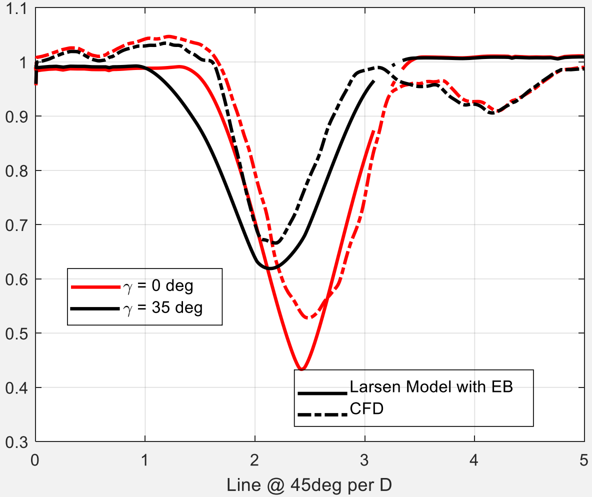
Modeling for Yaw Control

2 Turbine Case @8D Downstream Location, Larsen Model with EB Superposition



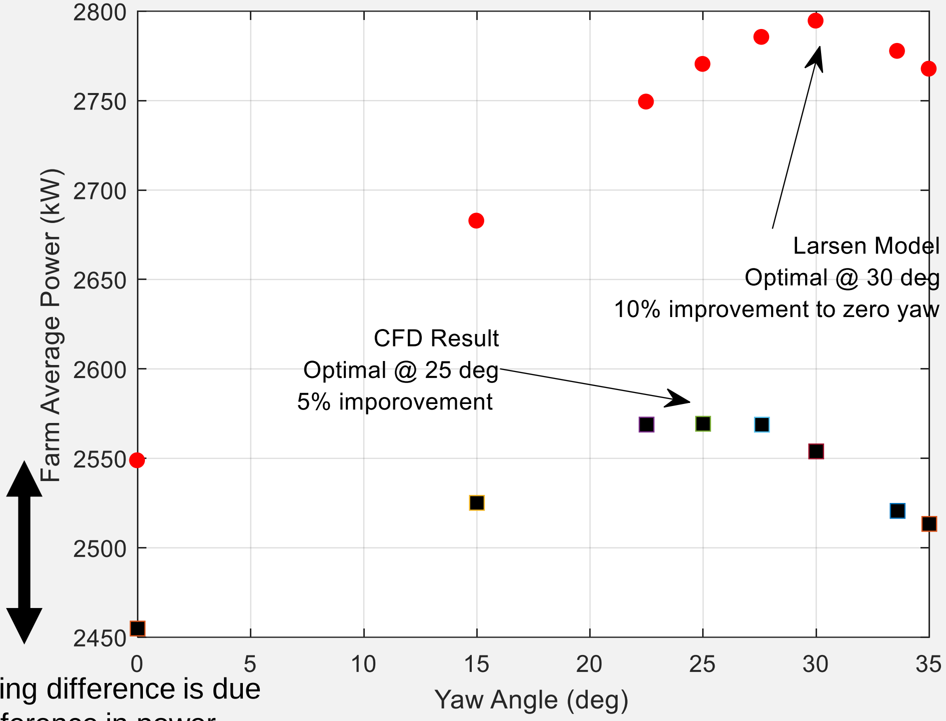
Matches with CFD quite well for some yaw angles





Both wake Center offset and wake deficiency can not be captured when there is an array of Turbines for all yaw angles

Control Perspective



The scaling difference is due to the difference in power available and power produced.

Larsen Model Predicts 10% improvement with yaw control of 30 deg, when turbines are separated 5D.

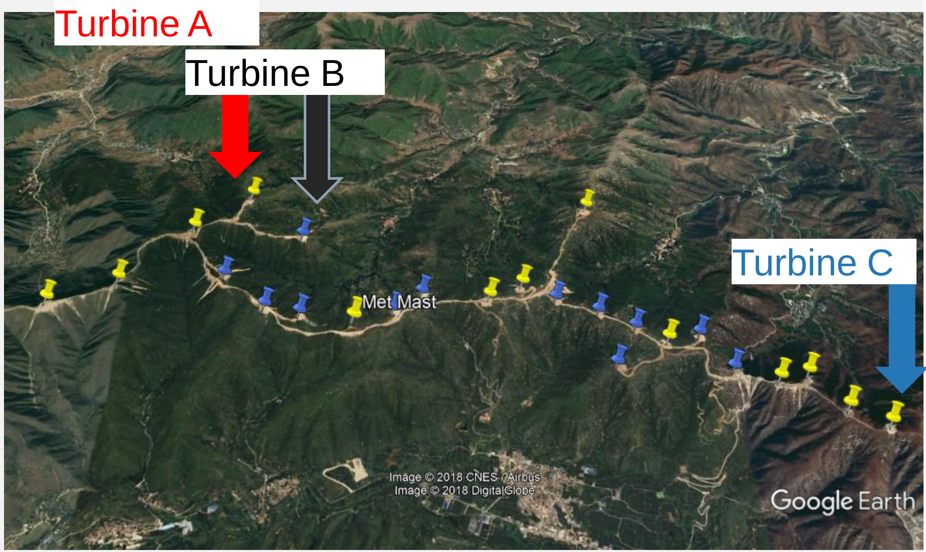
CFD computes 5% improvement with 25deg yaw control

Risk Assessment and Mitigation in Complex Terrain

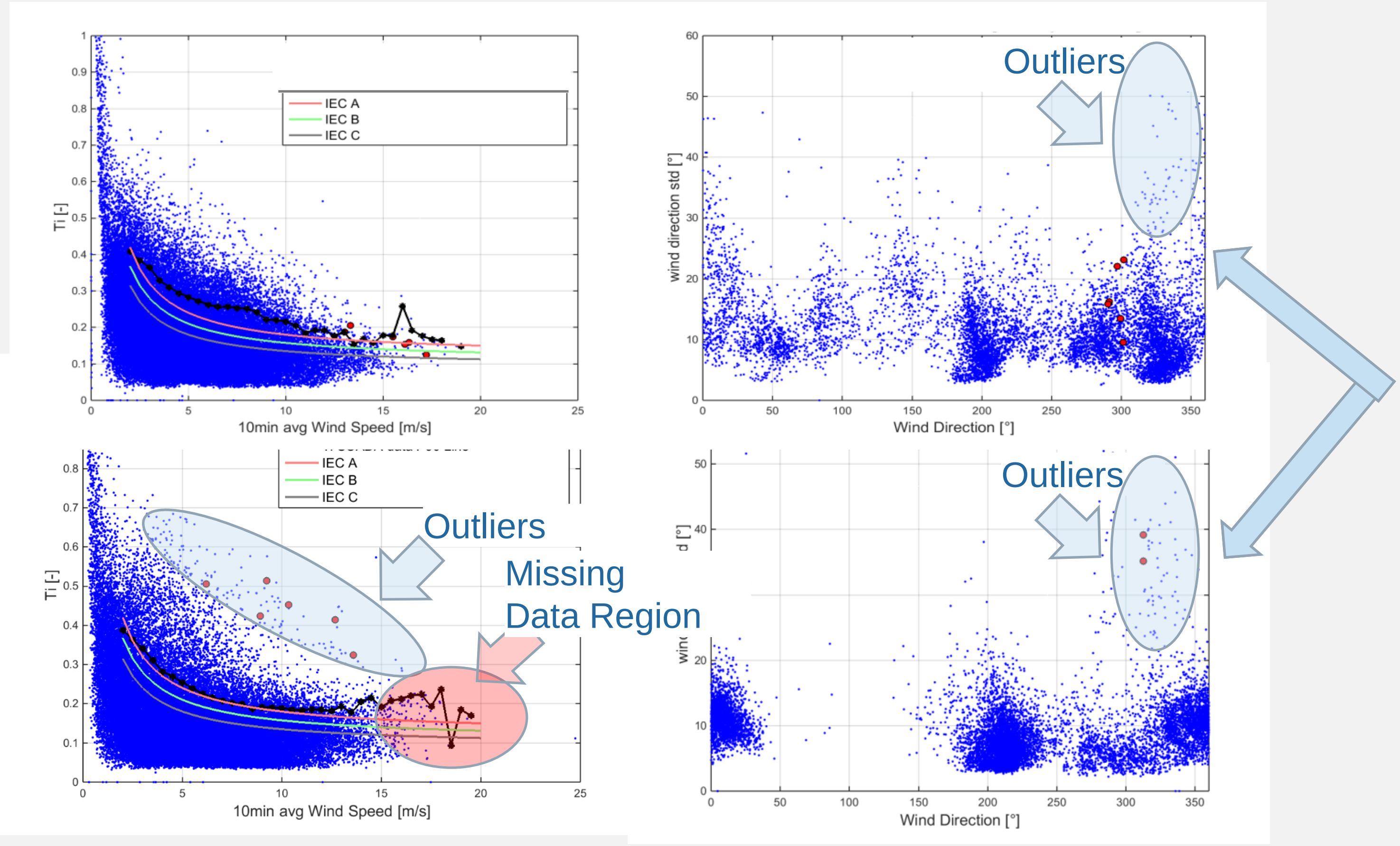
Data Model Coupling

Complex terrain siting and operation is challenging due to

- **Uncertainties in wind resource assessment**
  - Spatial variations that can not be well captured by limited number of met masts.
  - Directional dependency of wind parameters, such as turbulence intensity, vertical and horizontal sheer, veer
- **Frequently experience conditions beyond IEC standards**
- **Load-aware siting in order to avoid underperformance issues.**



Directional Dependent-Spatial Variations and Extreme conditions



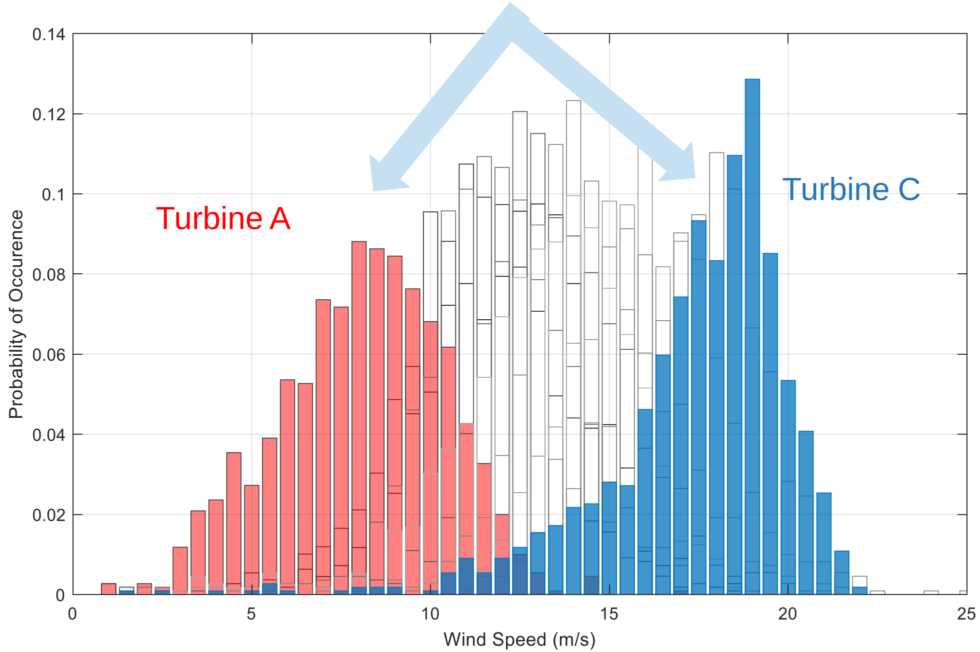
Both upstream turbine and downstream turbine experience outliers (above IEC standards)

Some wind directions show higher variations.

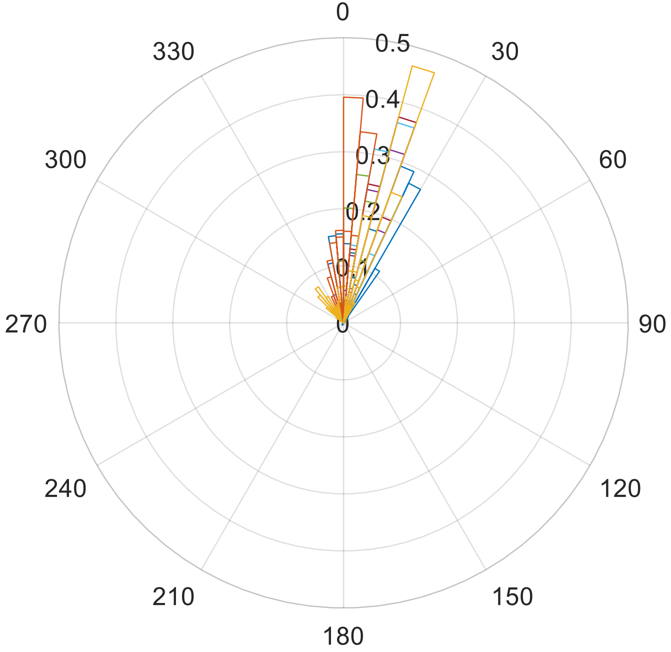
Censored data statistics, i.e. field does not experience very often hence data is missing.

Directional Dependent-Spatial Variations

They are all upstream turbines



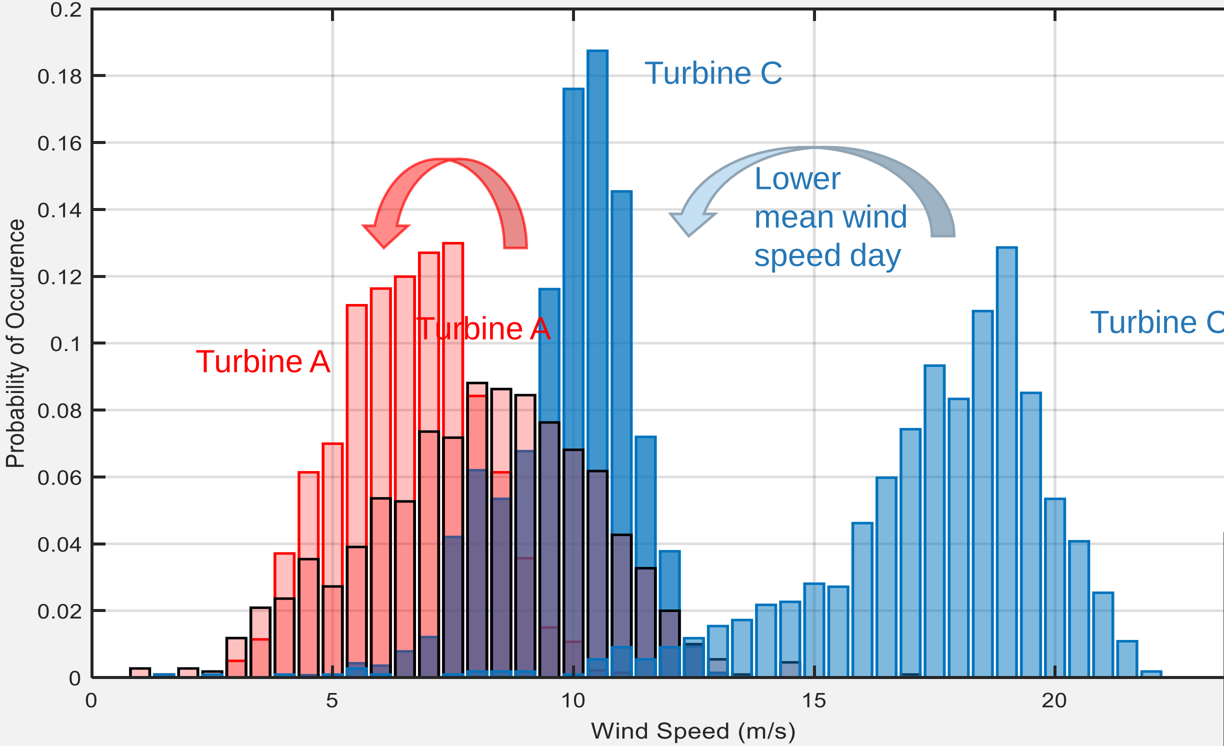
Calibrated wind directions at each turbine location



Data mining to determine directional dependent wind speed distributions across the terrain for a complete period of operation.

Build a statistical model for AEP improvement site specific control strategy.

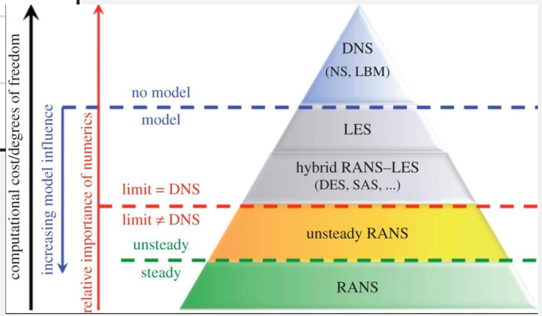
Topology Induced Spatial Variations



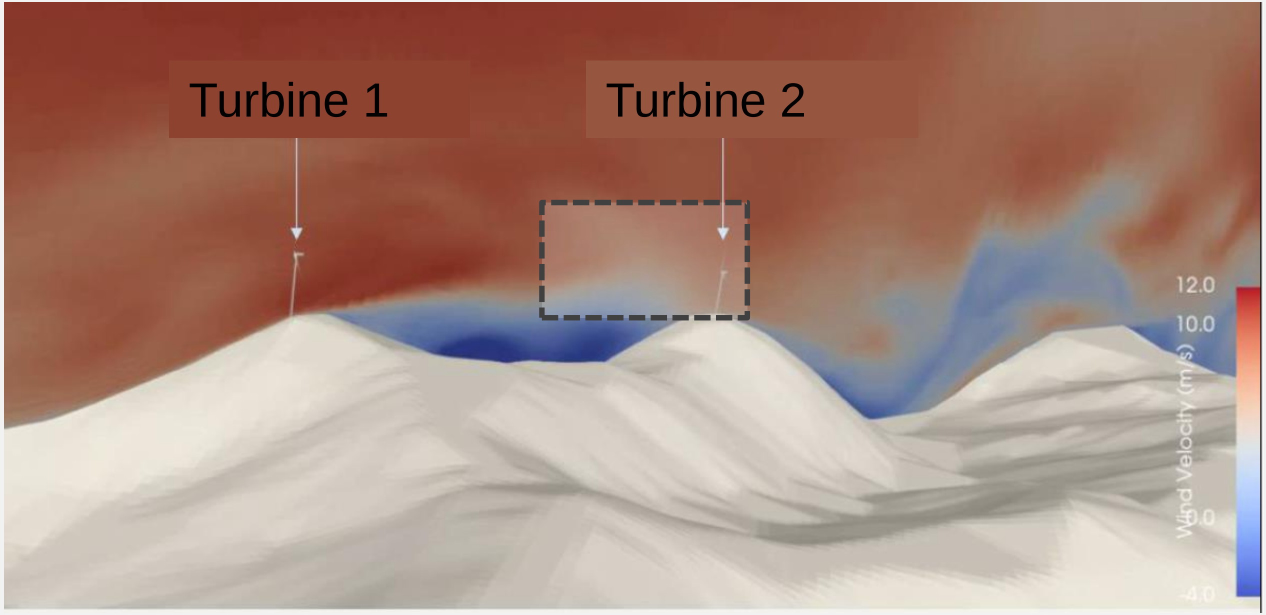
Move from point-wise hub height measurement to flow field analysis with CFD for load comparison

Linear relationship does not work.

Seek for indicators (such as temperature variations) and climb the model pyramid to higher fidelity solvers for flow analysis.



Topology induced complex flow in front of a rotor disc



CFD Experts : Greg Oxley, Kyle Hutchings and Pankaj Jha

Extract the wind in front of the rotor disc: windbox approach

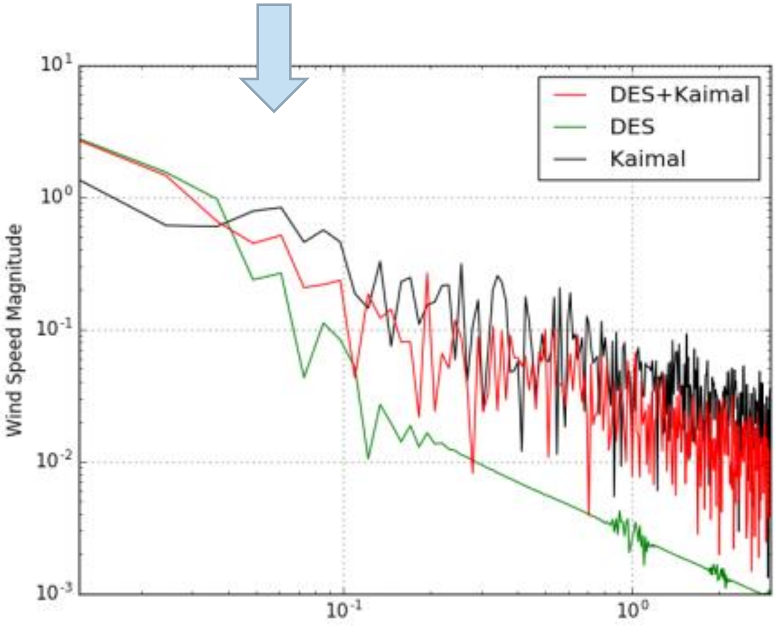
Compare the variations in wind speed and direction with the field.

Compare the loads with the field.

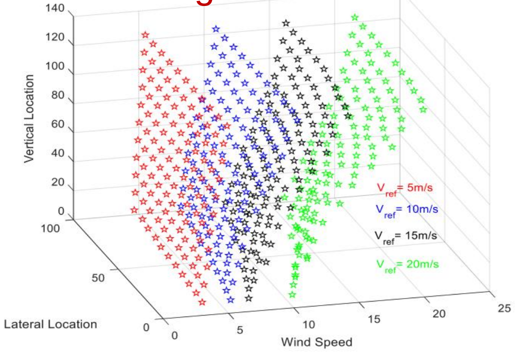
Advise a further measurement campaign, such as LIDAR (experimental design).

Comparison with IEC Standards and common practices

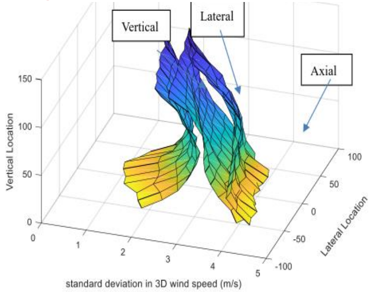
At low frequency region, Kaimal-IEC underestimates wind power density.



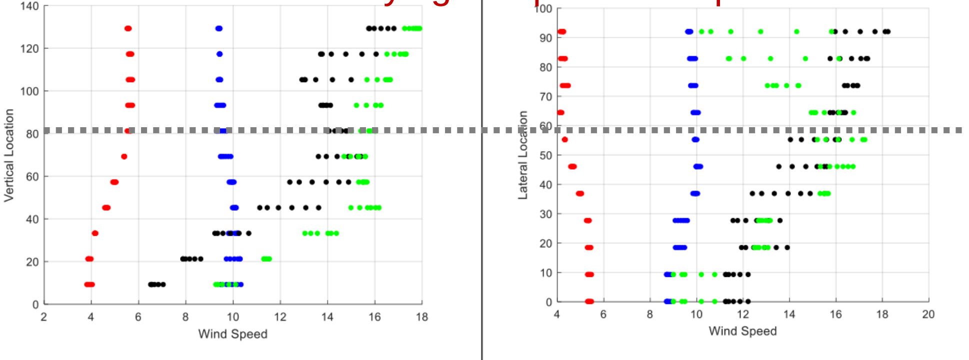
Linear scaling does not work



Standard deviations in 3D vary across the rotor disc



Time Varying complex shear profiles



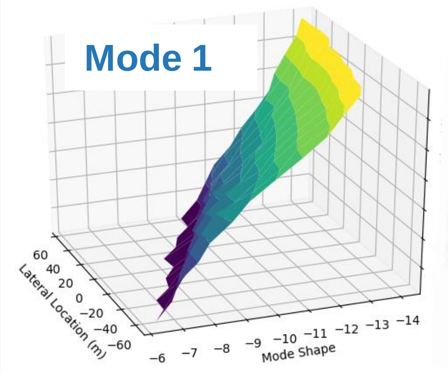
(a) Vertical Shear

(b) Horizontal Shear

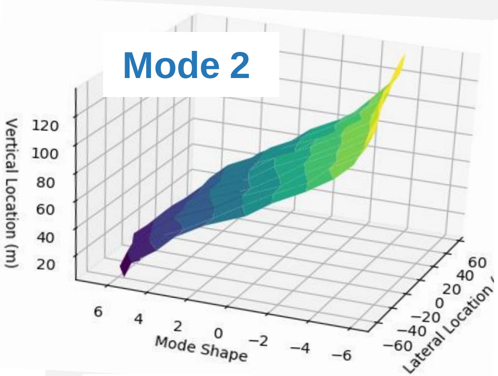
POD based ROMS and Correlating with Topology

Very expensive to solve DES for all terrains/farms and conditions: flow directions, wind speeds etc. Reduced order modeling and correlating with topology is under investigation.

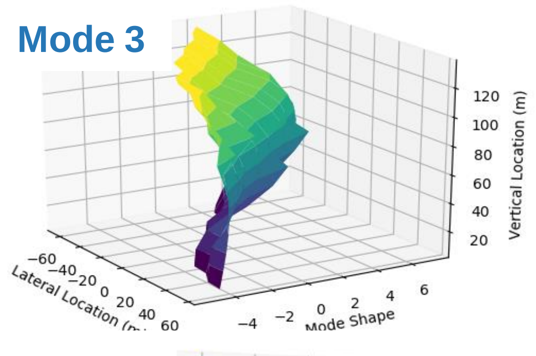
Mode 1



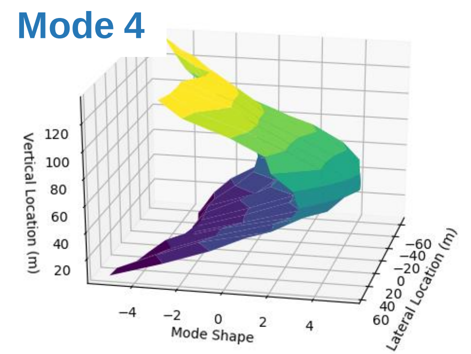
Mode 2



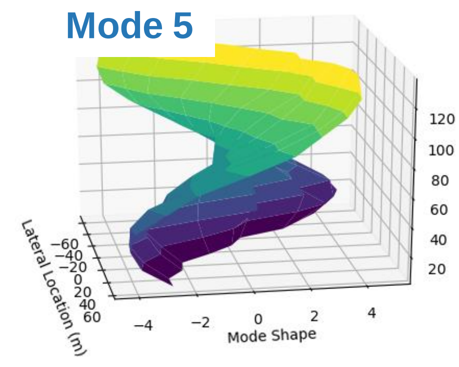
Mode 3



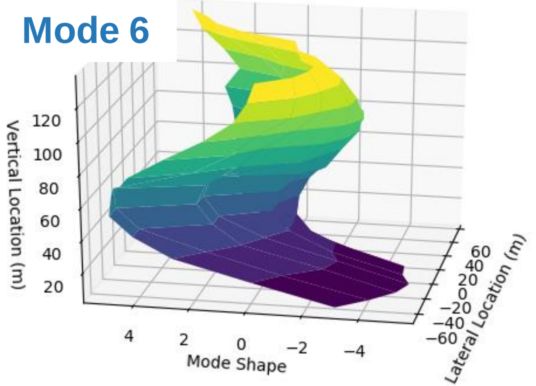
Mode 4



Mode 5



Mode 6



Key Takeaways

1. Many sources of uncertainties exist both in siting and operational decisions, which can cause risk of not meeting power production promises, early component failures or even catastrophic failures.
2. Data is sparse, we can not put towers everywhere, nor we can perform years of measurements. Data-Model coupling for drawing the complete flow field information is must. Yet, high fidelity models are expensive to run, we need statistical and reduced order models.
3. IEC standards may not be sufficient for complex terrains, in order to avoid performance degradation, load-aware siting becomes crucial. For loads information required in terms of time-scale and space-scale is different than AEP.
4. Both siting and operations decisions should be performed with assessing the risk, and as more data become available, we need to update our uncertainty models, and allocate our resources based on the current state of knowledge.

Solving the Challenges for a Sustainable Future

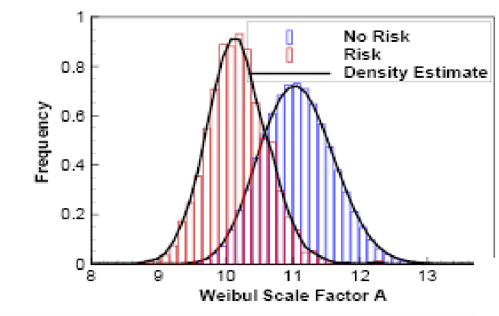
Sensitivity Analysis and Risk Assessment

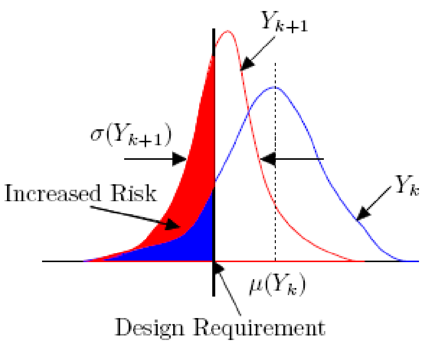
Regional Sensitivity Analysis

Ranks the risk contributing factors

KL-Distance between "fail" and "pass"

$$S_{R_j} = D_{KL}(P_{x_j} || Q_{x_j})$$

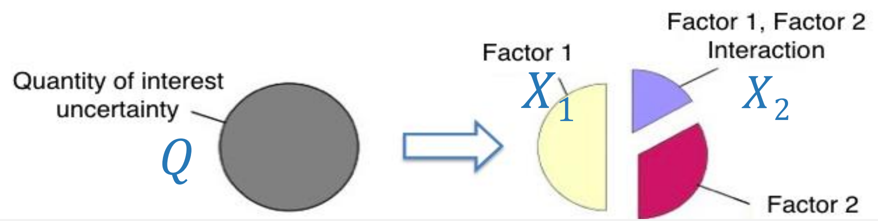




Global Sensitivity Analysis

Ranks the variance contributing factors

Sobol main effect indices, S_i



$$S_i = \frac{\mathrm{var}(\mathrm{E}[Q \mid X_i])}{\mathrm{var}(Q)} = \frac{\mathrm{var}(Q) - \mathrm{E}[\mathrm{var}(Q \mid X_i)]}{\mathrm{var}(Q)}$$

Risk Measure

Probability of Failure (relates to V@R)

$$\rho_{FP} = P(Y < y_D) = \int_0^{\infty} g(x_d, X_u, y_D) x_{ui} d_{ui}$$