Design and Optimization of Wind Systems Through a Systems Engineering Approach

Katherine Dykes, Rick Damiani, Paul Fleming, Peter Graf, Andrew Ning, George Scott, Ryan King, Yi Guo, Jen Annoni, Julian Quick, Latha Sethuraman, Jason Jonkman, Jason Fields, and Paul Veers

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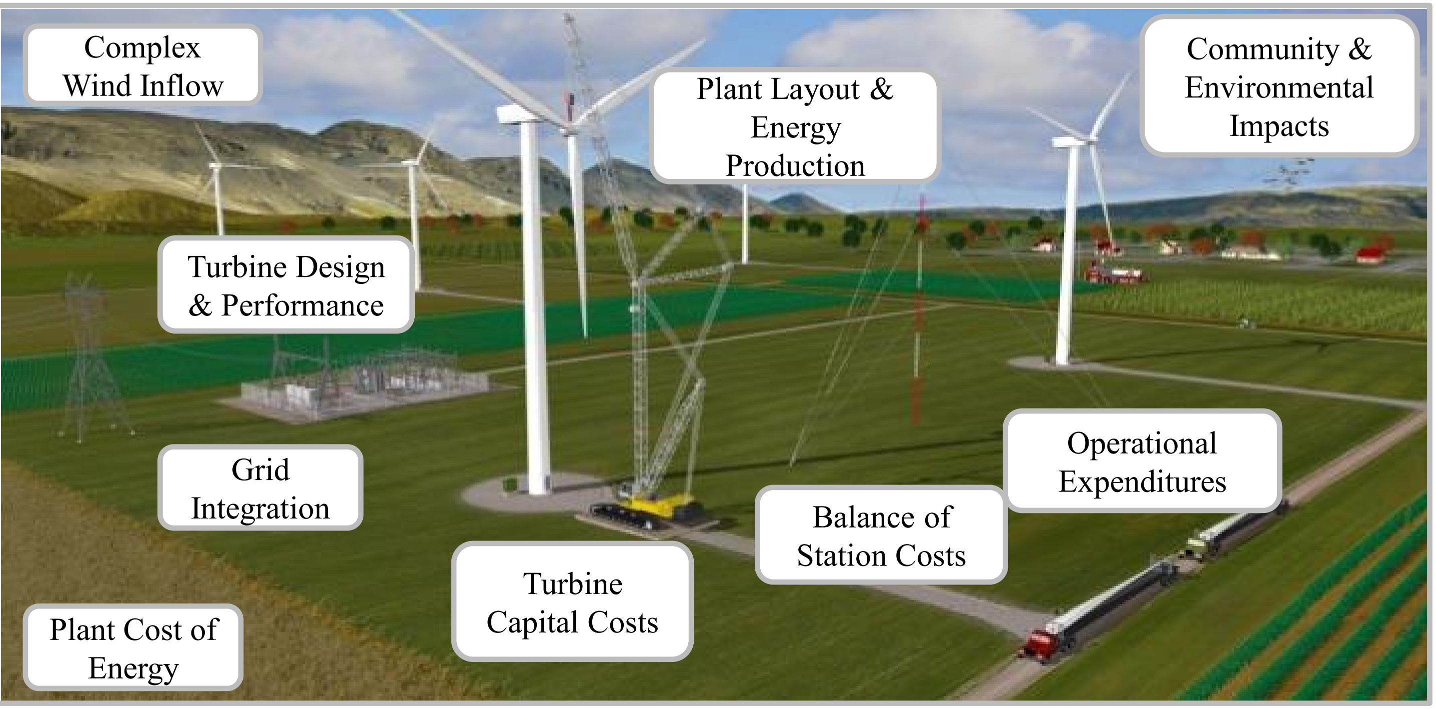
Motivation and Needs

- Wind plants are technically complex and highly coupled systems
- Plant design, development and operations are partitioned across a large industry between sub-sectors
- This results in sub-optimal system-level performance and cost and risk aversion to the adoption of new innovations



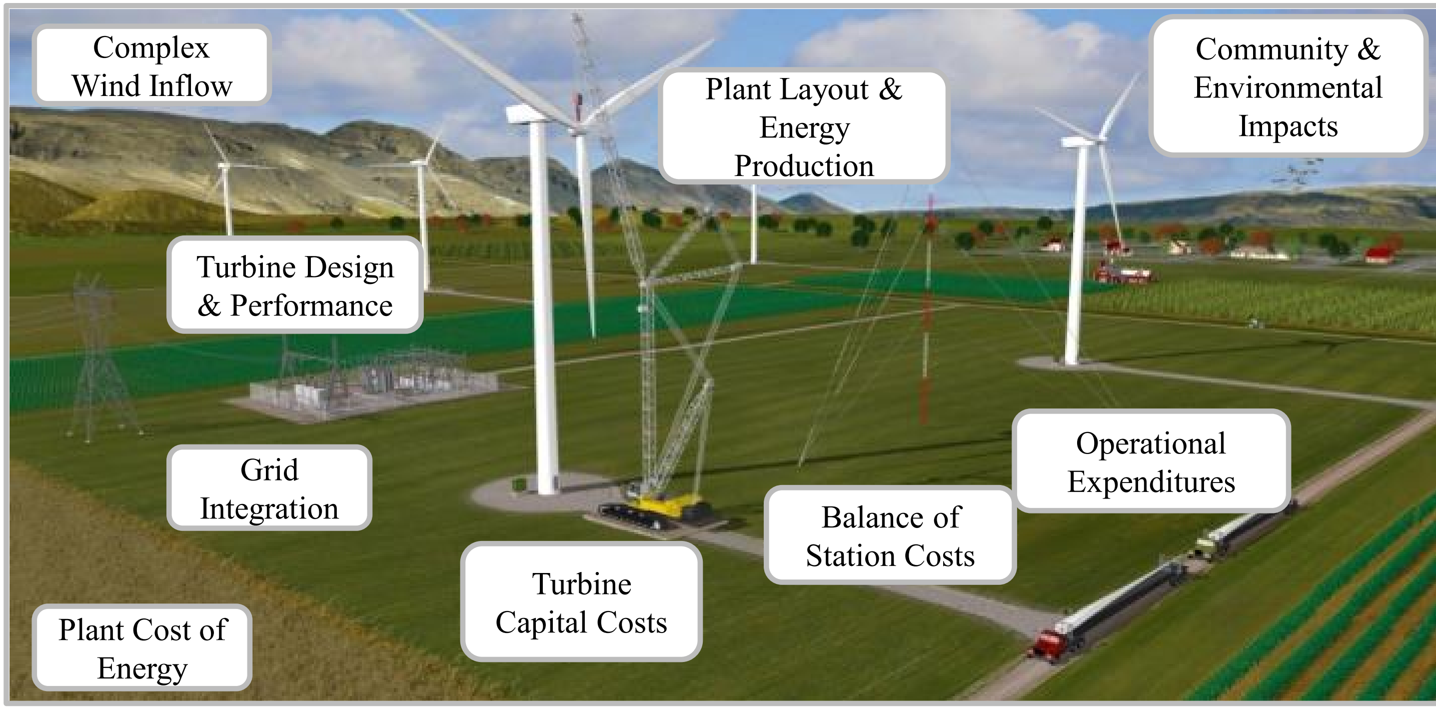
A full wind plant involves stakeholders and large technical complexity
Graphic: Al Hicks, NREL

Assessing Wind Plant Cost of Energy

- Often use simplified Cost of Energy representation as global system objective:

$$\boldsymbol{LCOE = \frac{FCR * (CAPEX) + OPEX}{AEP}}$$

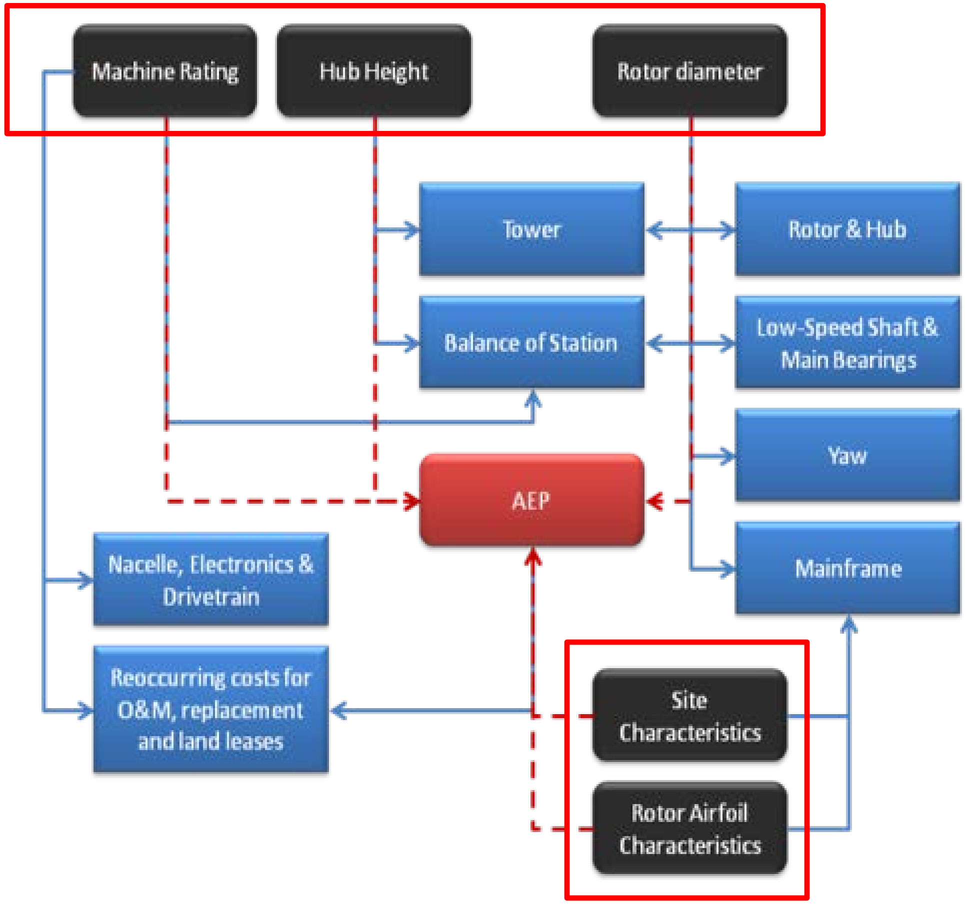
- LCOE is the levelized cost of energy
- CAPEX is the sum of Balance of Station and Turbine Capital Cost (for full project)
- OPEX are the annual operating expenses
- AEP is the net annual energy production
- FCR is the fixed charge rate to annualize CAPEX



Assessing Cost of Wind Energy

- Old "NREL Cost and Scaling Model" uses parameterized functional relationships calibrated to historical trends
  - Originated with detailed design studies in early 2000s (WindPACT)
  - Abstraction to simple parametric relationships
  - Useful for two primary types of analyses on system costs:
    - Changing input factor prices over time
    - Scaling of conventional technology within a limited range
  - Publically available model

2006 Cost and Scaling Model Structure



Wind Energy Systems Engineering

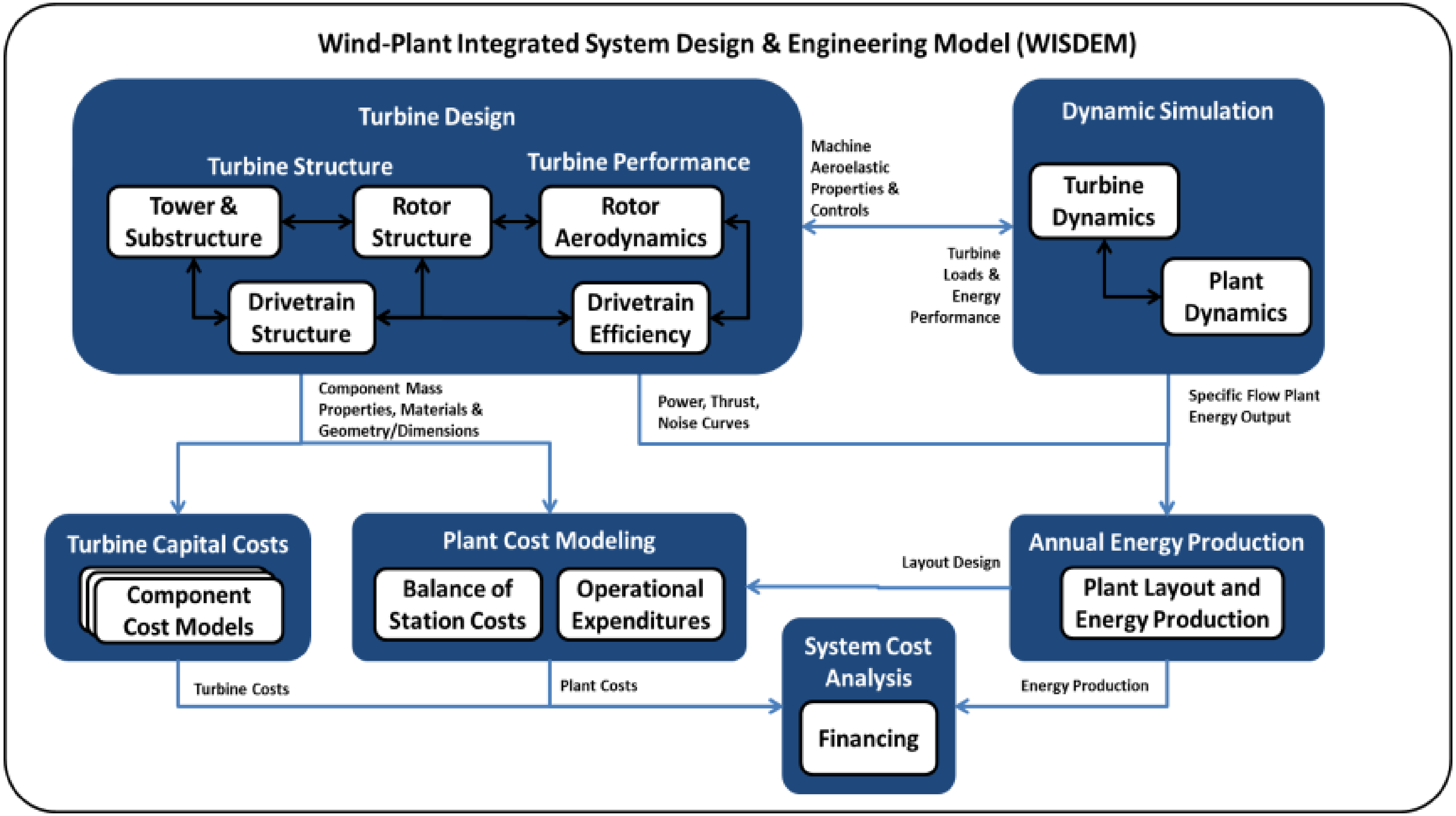
To address these challenges, the NREL wind energy systems engineering initiative has developed an analysis platform and research capability to capture important system interactions to achieve a better understanding of how to improve *system-level* performance and achieve *system-level* cost reductions.

Objectives include:

- Integrating wind plant engineering performance and cost software modeling to enable full system analysis
- Applying a variety of advanced analysis methods in multidisciplinary design analysis and optimization (MDAO) and related fields to the study of wind plant system performance and cost
- Developing a common platform and toolset to promote collaborative research and analysis among national laboratories, industry, and academia.

Wind-Plant Integrated System Design & Engineering Model

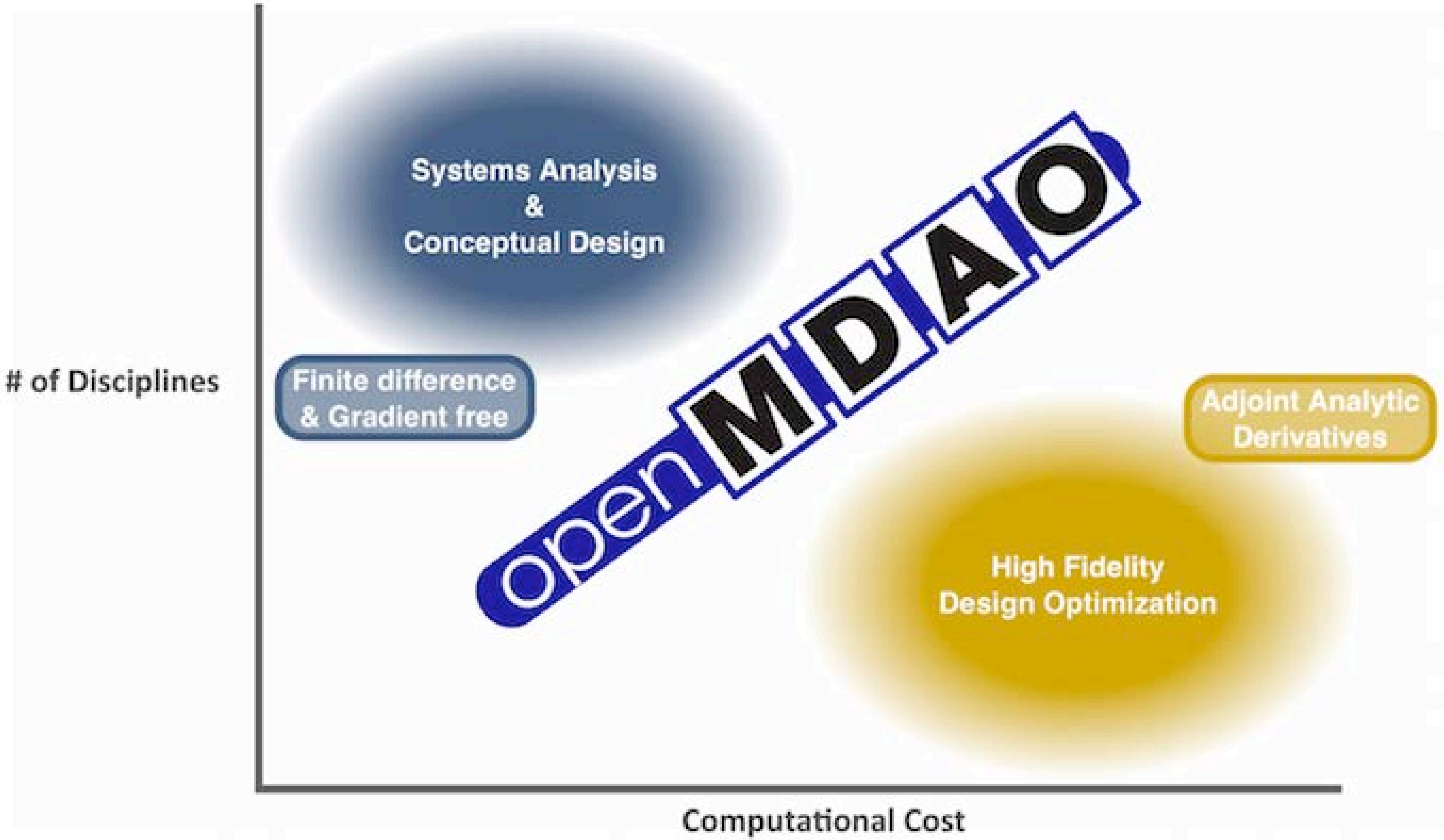
WISDEM™ creates a virtual, vertically integrated wind plant from components to operations.



http://nwtc.nrel.gov/WISDEM

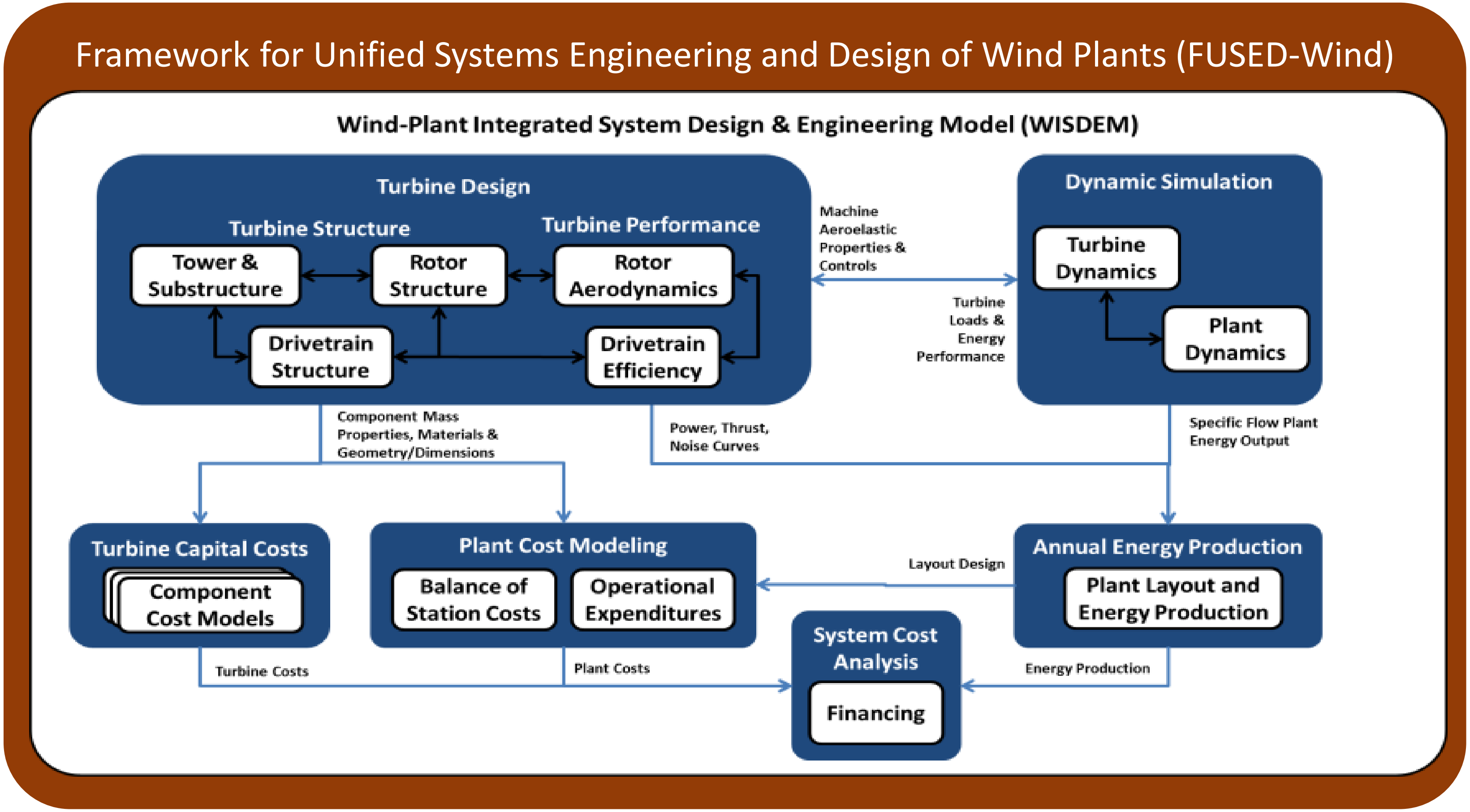
Software Platform

- Capability built on OpenMDAO (http://openmdao.org)



FUSED-Wind (DTU Wind Energy / NREL Collaboration)

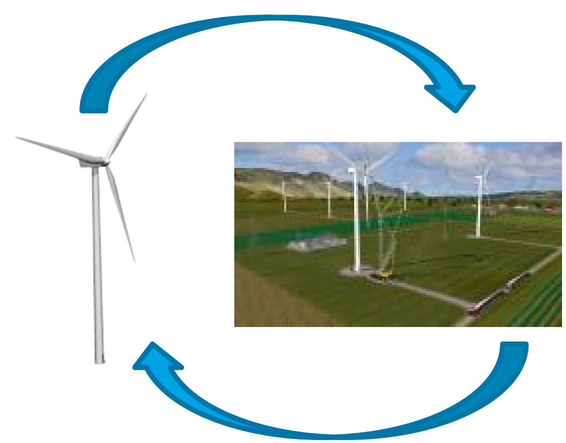
The Framework for Unified Systems Engineering of Wind Plants (FUSED-Wind) provides a standard and software implementation for integrating wind system models.



http://fusedwind.org

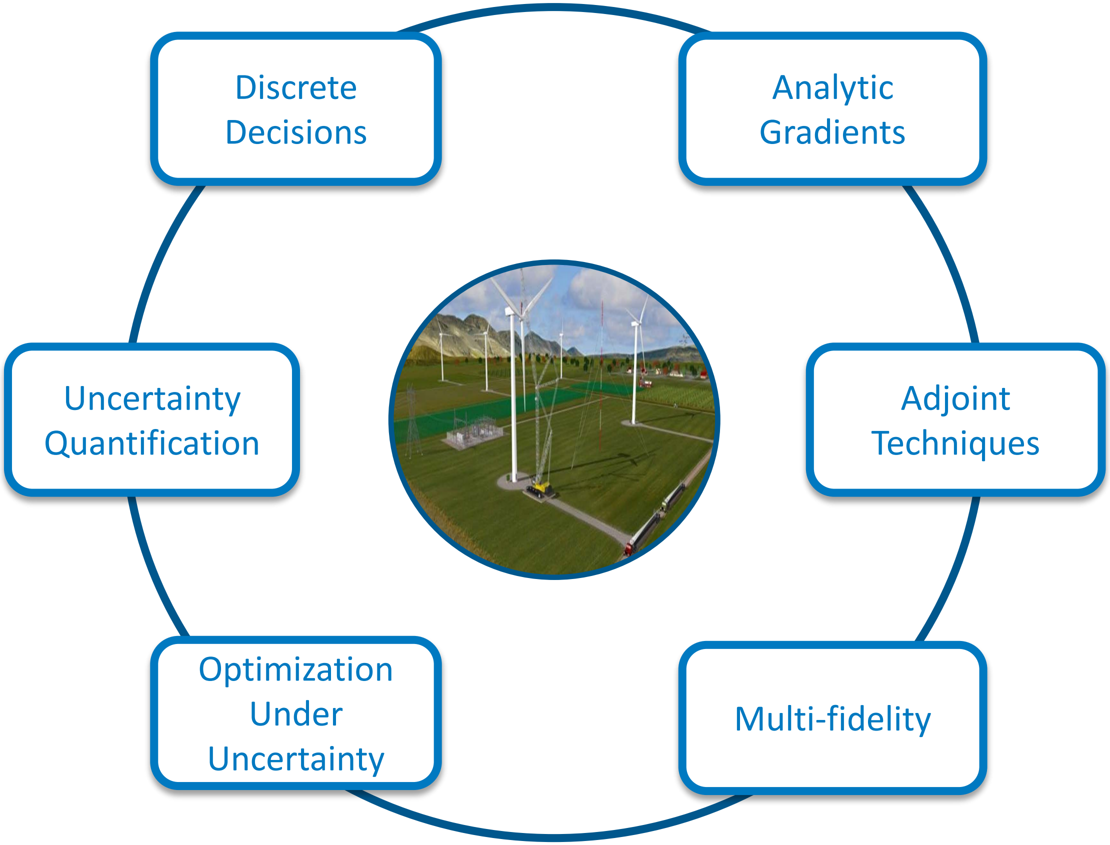
MDAO Research for wind energy

- Using FUSED-Wind / WISDEM, we demonstrate value of integrated system modeling and multi-disciplinary design, analysis and optimization (MDAO)
  - Integrated turbine design (rotor aero-structure, full turbine optimization)
  - Integrated plant design and operations (wind plant controls and layout, layout and hub height, layout and support structure)
  - Integrated turbine and plant optimization (multi-turbine layout designs, site-specific turbine / support structure design)



MDAO Research for Wind Energy

- Using FUSED-Wind / WISDEM, we investigate novel approaches to wind system analysis and MDAO



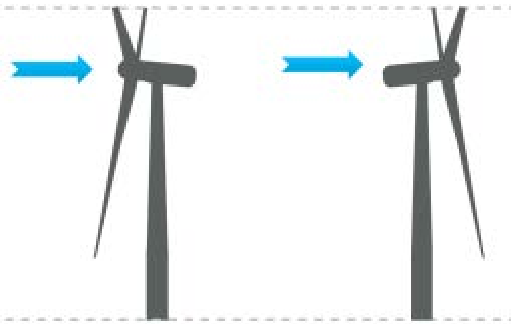
Analytic Gradients

Integrated Turbine Design

WISDEM^{TM} : Examples and Applications

Turbine Design

WISDEM™ : TurbineSE – Downwind vs. Upwind

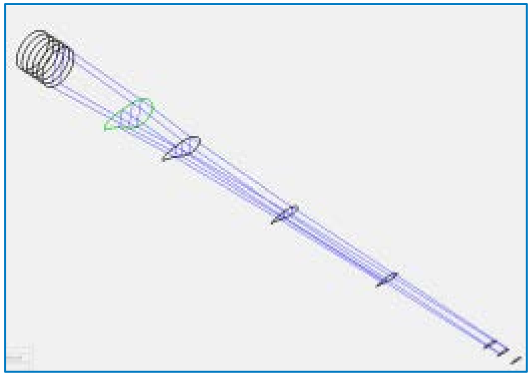


The Background:

Potential Advantages of Downwind Turbines:

1. Slenderer and softer blades (reduce tower strike constraint)
2. Increased efficiency with inclined flow

➔ Reduced LCOE?



The Method:

Analytic gradients

RotorSE+ CurveFEM
- Hub Struc
- Rotor Perf
- Rotor Struc
- Rotor Aero
- Blade Struc
- Section Aero
- Section Struc

TowerSE+ JacketSE
- Tower Struc
- Tower Aero
- Jacket Struc
- Tower Hydro
- Tower Soil

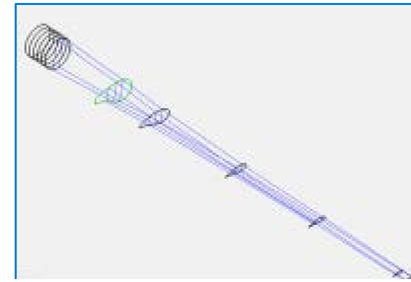
DriveSE
- LSS/HSS
- Gearbox
- Bearings
- Generator
- Bedplate
- Yaw System

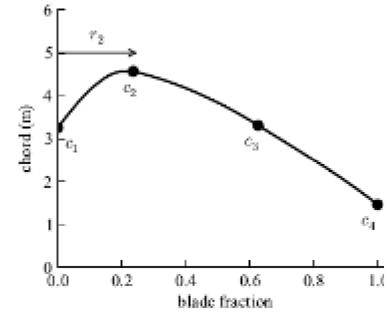
TurbineCostSE + Plant_EnergySE+ PlantCostsSE
- TCC
- O&M
- AEP
- BOS
- Finance

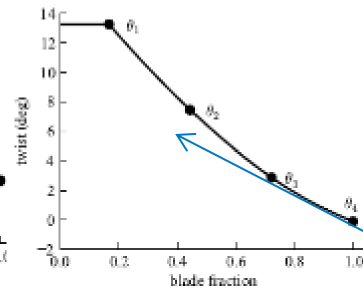
WISDEM^{TM} : TurbineSE – Downwind vs. Upwind

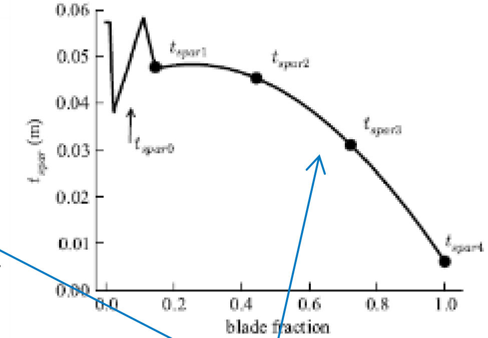
- 35 design variables
  - Chord +twist distribution
  - Spar-cap+aft panel thickness distribution
  - Precurve distribution
  - Tip-speed ratio
  - Bedplate I-beam dimensions
  - LSS length
  - Tower OD + wall thickness
  - Tower height
  - Tower waist location
- 100+ constraints
  - Natural frequency,
  - Deflections (tower clearance)
  - ULS strains/stresses
  - FLS damage
  - Max Tip speed (80 m/s)
  - Transportation (chord<=5.3 m)
- TowerSE + DriveSE…
  - Eurocode+GL buckling/strength requirements
  - Manufacturability and Weldability
  - …

- DLC 1.3, 6.2
- Constant laminate schedule (variable thickness)
- Deflection @70% V_{rated} for AEP









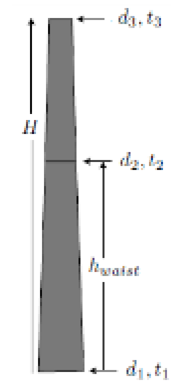
Akima Spline

$$f_0 \geq 1.1\, n_{blades} \Omega_{rated}$$

$$\delta_{tip}\, \eta_{dfl} \leq \delta_{max}$$

$$-\epsilon_{ult} \leq \epsilon\, \eta_{str} \leq \epsilon_{ult}$$

$$\epsilon \leq \epsilon_b \quad \epsilon_b = -\frac{N_{cr}}{T\, E}$$

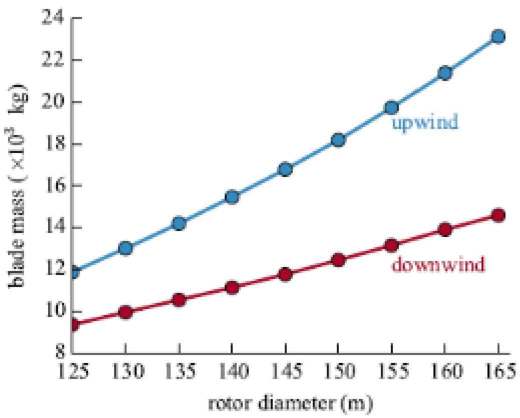


Objective function: m/AEP

WISDEM™ : TurbineSE – Downwind vs. Upwind

- SNOPT (optimizer) +analytic gradients
- nonlinear optimization problems using the sequential programming method, and
- the optimizations were formulated in the OpenMDAO framework

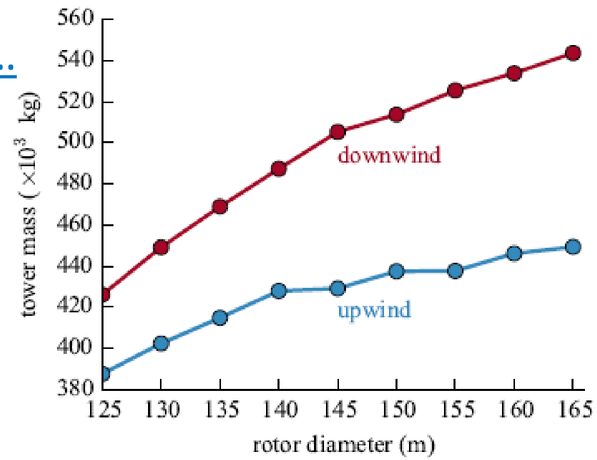
Class III 5 MW

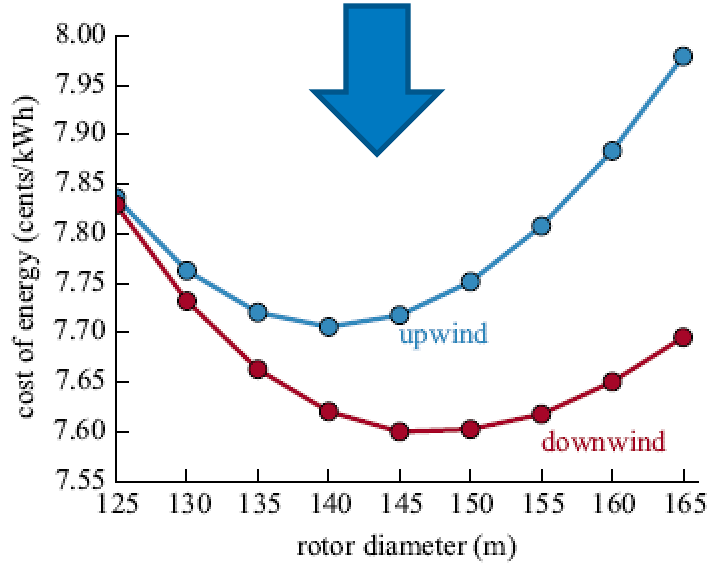


Blade Mass Reduced (30%) but…

Tower Mass increased

1% lower AEP





1.5% LCOE reduction at Larger Rotor Diameters and minimum LCOE with downwind rotors

Analytic Gradients

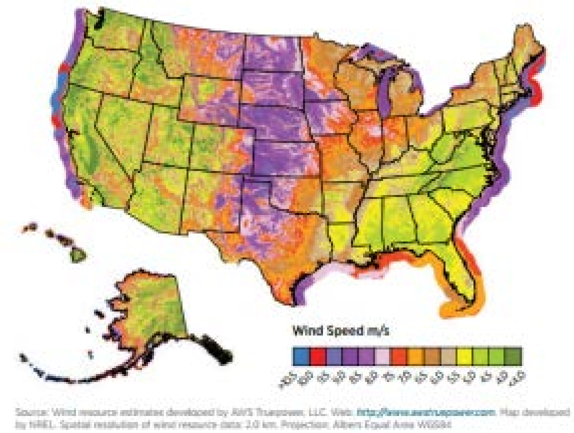
Integrated Plant Design

WISDEM^{TM} : Examples and Applications

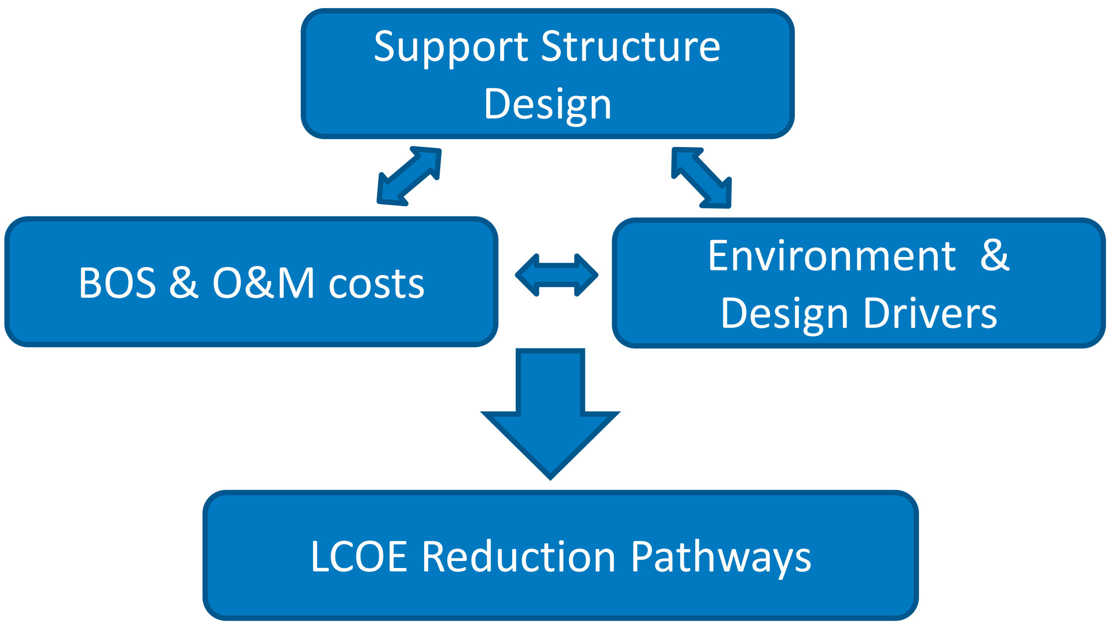
Offshore Support Structure Design

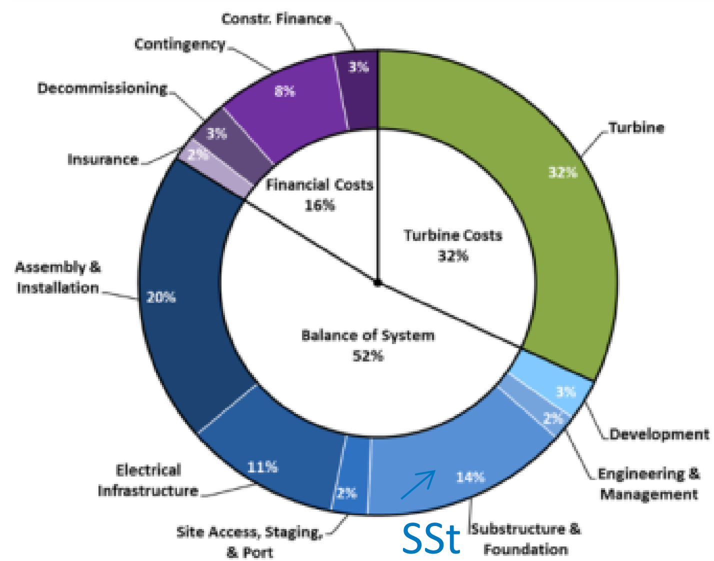
WISDEM™ : Monopile vs. Jacket Study

Background



- The U.S. DOE's Wind Vision → 86 GW of offshore wind capacity by 2050 is plausible for a high wind future
- The support structure is one of the largest cost drivers for offshore wind plants
- Need to understand link between:

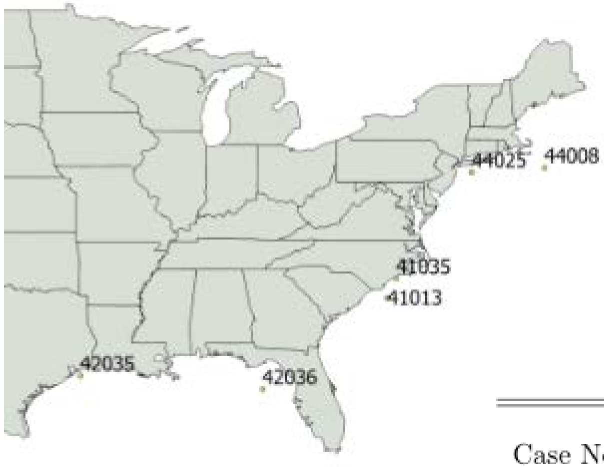




WISDEM™ : Monopile vs. Jacket Study

Background:

- Assess the viability of current technology **monopiles and jackets** for various "typical" US offshore locations
  - Monopiles dominant in European experience
  - Jackets →potential for larger turbines, deeper waters, and more extreme ocean environments



- 6 sites
- Metocean data: AWS Truepower + NOAA buoy system

Table 2. Key metocean parameters for the six sites analyzed.

Case No.	$WS^{(a)}$	Water Depth	$H_{s50}{}^{(b)}$	$H_{mx50}{}^{(b)}$	$T_{mx50}{}^{(c)}$	$HAT^{(d)}$	$\delta_{1000}{}^{(d)}$	$H_{mx1000}{}^{(b)}$	Deck Height
	$\mathrm{m\,s^{-1}}$	m	m	m	sec	m	m	m	m
1	9.74	23.50	10.82	18.33	13.34	1.26	1.25	18.33	13.20
2	8.06	12.80	7.24	9.98	10.91	0.47	6.00	9.98	13.00
3	9.33	40.80	9.48	17.63	12.48	0.33	2.50	23.26	16.00
4	9.52	9.70	10.46	7.57	13.11	0.83	0.90	7.57	7.00
5	9.26	65.80	12.15	22.60	14.13	0.79	1.54	28.31	18.00
6	7.58	50.60	7.63	14.19	11.20	0.84	1.50	17.81	12.70

WISDEM^{TM} : Monopile vs. Jacket Study

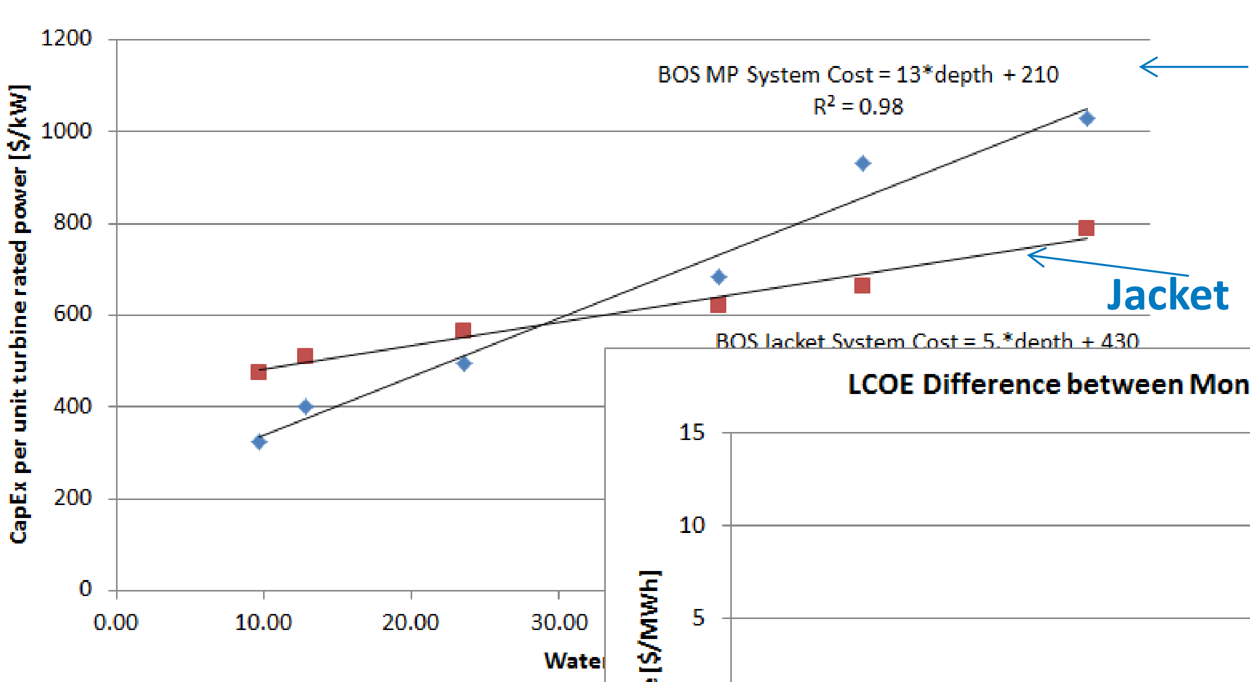
- NREL 5 MW (126 m rotor, 90 m hub height)
- RotorSE + DriveSE → turbine load estimates
- **TowerSE** (monopiles) + **JacketSE** (jackets) → optimize for minimum and cost
- PlantEnergySE +AWS Truepower's OpenWind →AEP
- TurbineCostsSE +PlantCostsSE →turbine+plant costs and LCOE

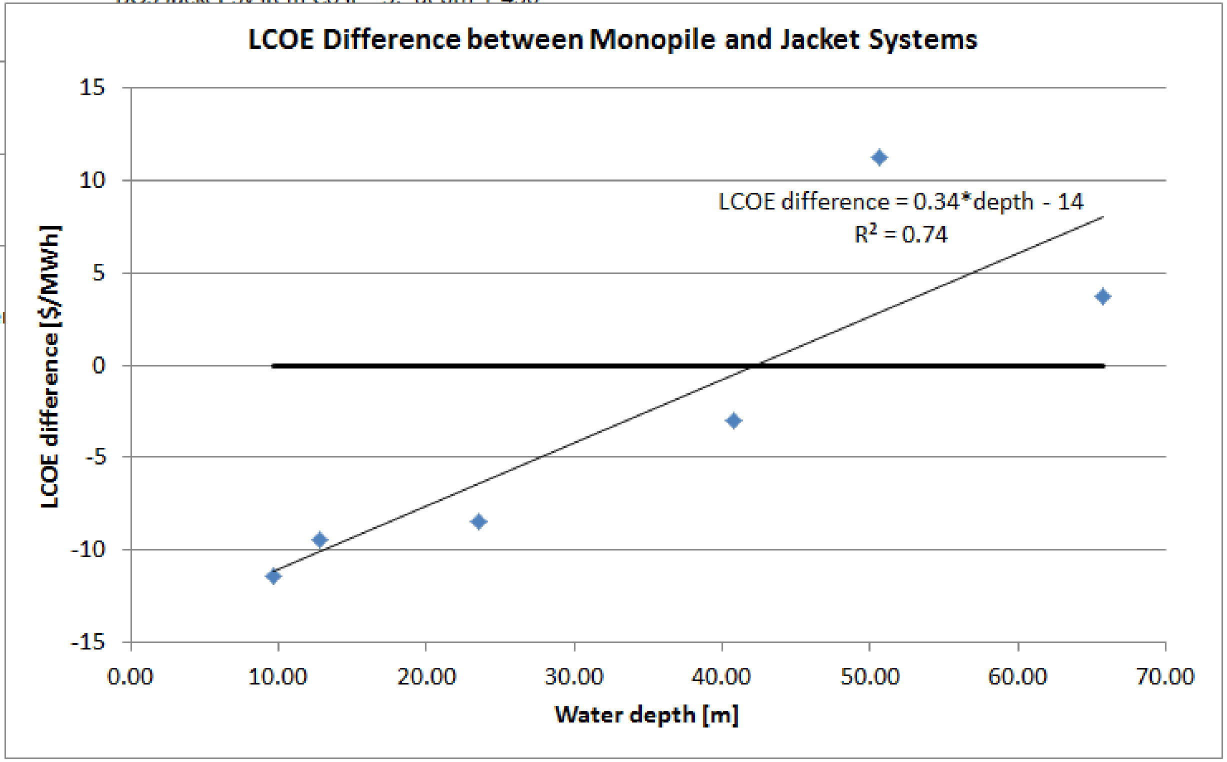
Table 5. Design variables and constraints for the jacket optimizations.

Description	Number of Variables	Number of Constraints
Tower ODs and $DTRs$	4	
Tower waist height	1	
TP girder ODs and ts	2	
TP deck width	1	
Jacket batter	1	
Jacket Leg, x-brace, mud-brace ODs, ts	6	
Pile OD, t, length	3	
Tower taper ratio (manufacturability)		1
Tower utilization against shell and global buckling		36
Tower utilization against strength		18
Tower and member $DTRs$ (manufacturability)		5
Batter range (manufacturability)		1
Maximum footprint		1
Minimum jacket brace angle		1
Jacket member additional structural criteria		10
Jacket member utilization		316
Jacket joint utilization		48
Pile length (manufacturability and axial capacity)		2
Eigenfrequency range		1

Jacket vs. Monopile: Results

Balance of System Cost: Jacket>Monopile for depths > 30m





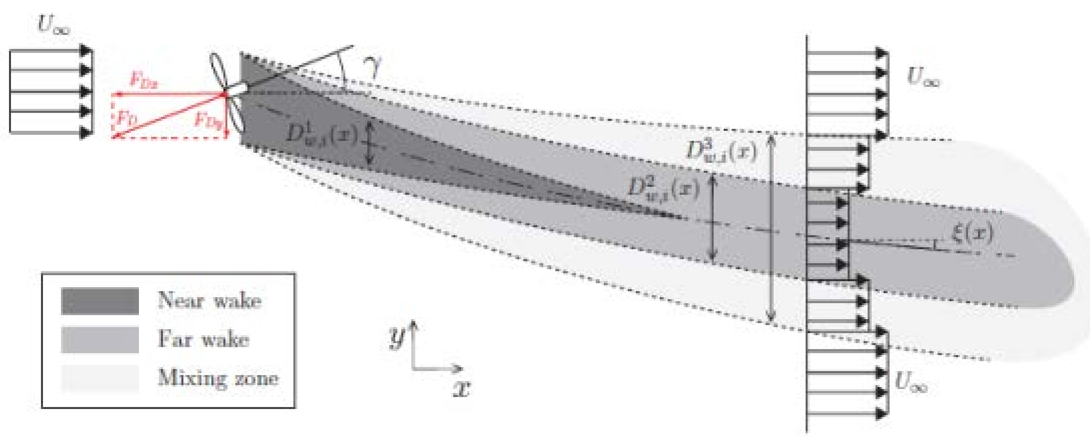
Analytic Gradients

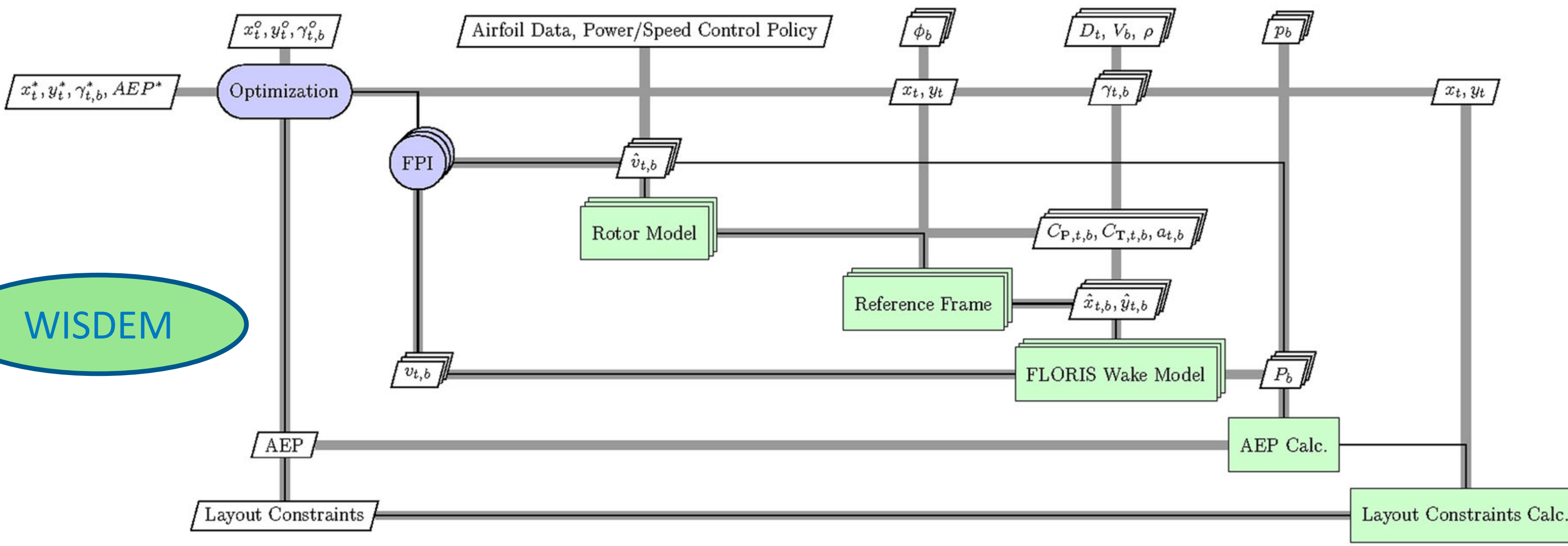
Integrated Plant Design

WISDEM™ : Examples and Applications

Plant Applications: Controls and Layout

Steady-state engineering model based on Jensen and Jimenez models with extensions

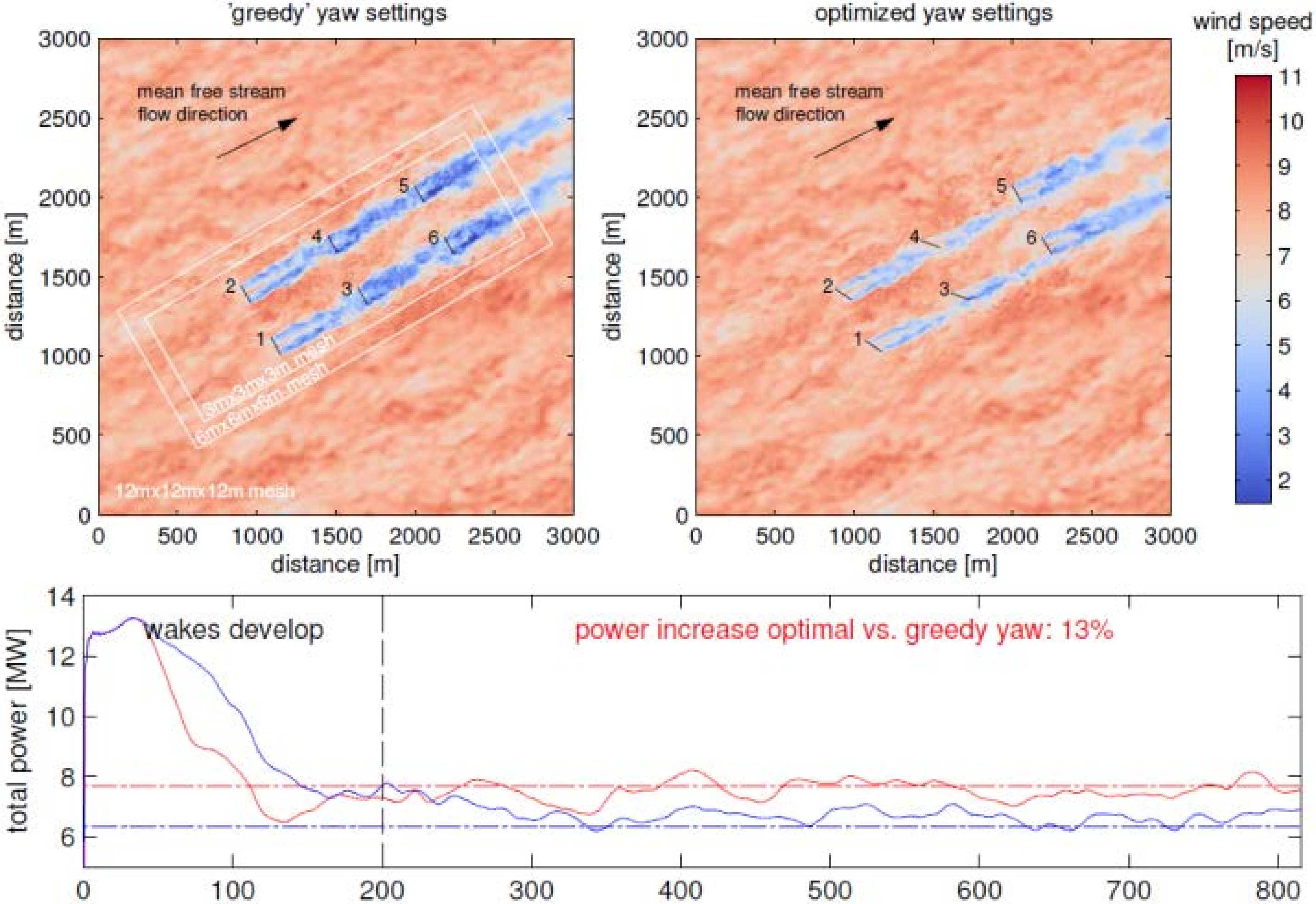




WISDEM

WISDEM^{TM}-FLORIS – SOWFA V&V (Simulator for On/Offshore Wind Farm Applications)

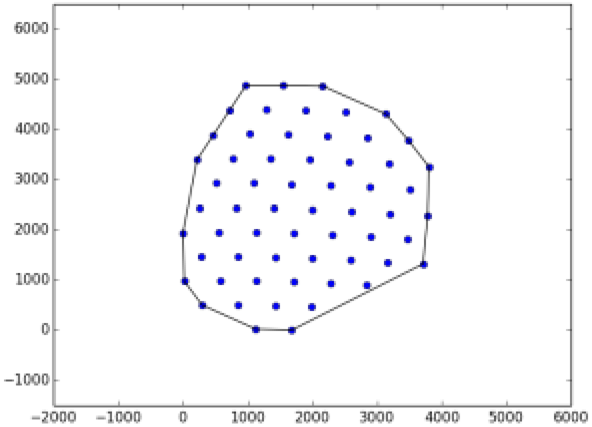
WISDEM-FLORIS COUPLING:
1. Real-time AEP optimization (O&M)
2. Wind Plant layout optimization (Development and Engineering)



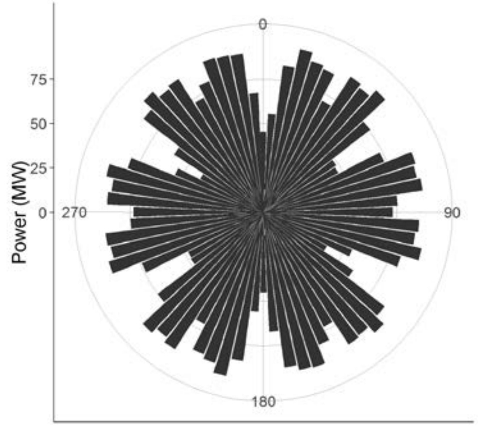
time

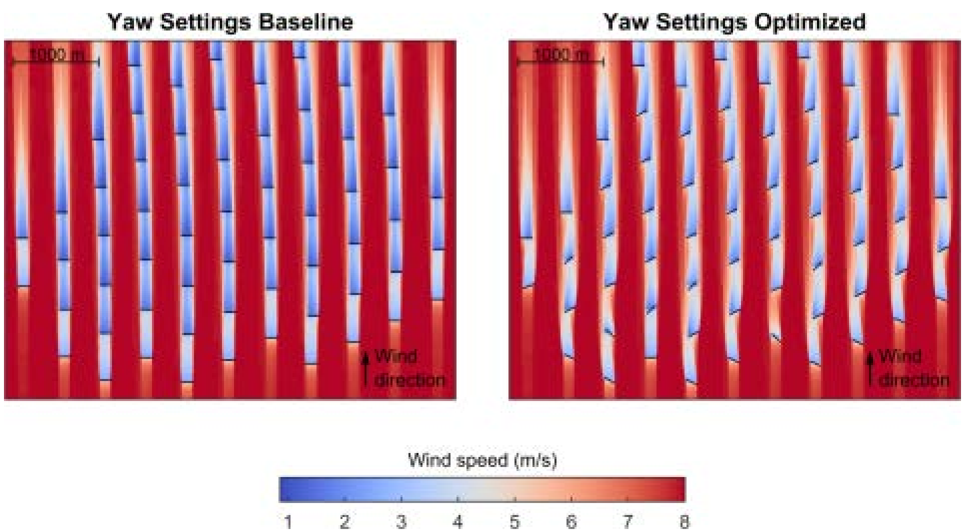
WISDEM^{TM} -FLORIS – CASE STUDY

Baseline Layout



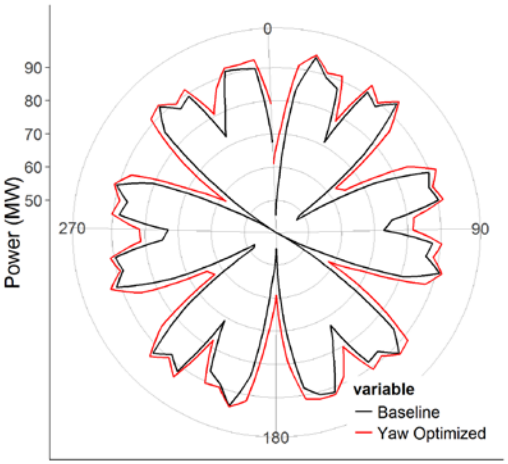
Baseline Power Production



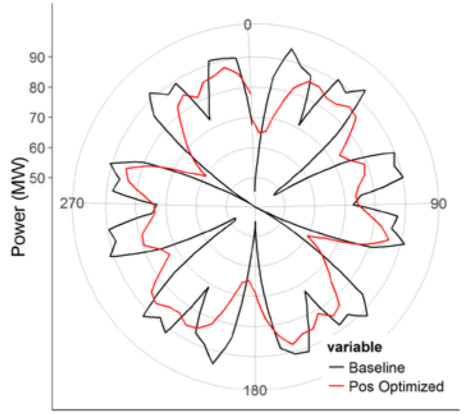


- **Baseline**: fixed (original) positions, turbines all yawed in mean wind direction
- **Optimized yaw**: fixed (original) positions, turbines optimally yawed for each wind direction
- **Optimized location**: position optimized, turbines all yawed in mean wind direction
- **Combined optimization**: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

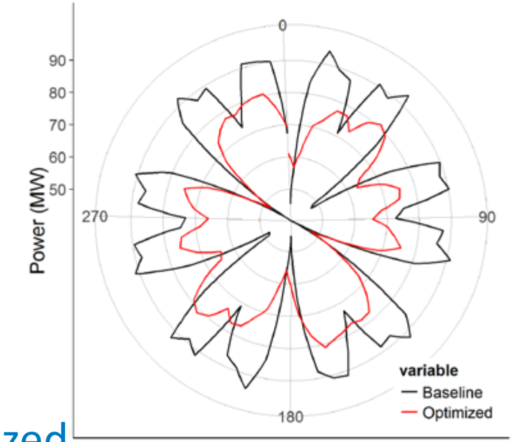
WISDEM^{TM} -FLORIS – CASE STUDY Results

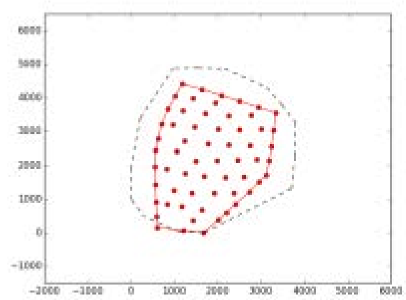


Yaw Optimized



Position Optimized



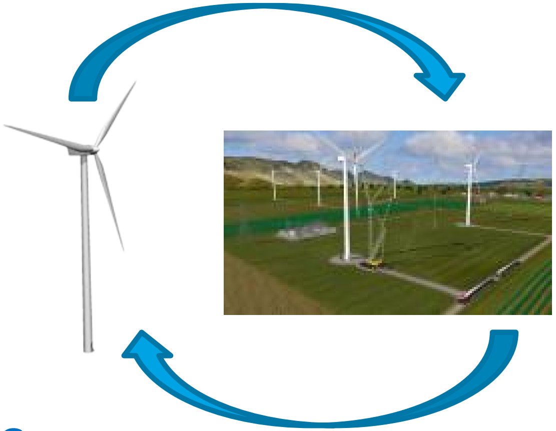


Combined

	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%)

Discrete Variables

Integrated Turbine / Plant Design



WISDEM™ : Examples and Applications

Plant Applications: Multi-turbine site design

WISDEM™ : Wind Plant Optimization with Multiple Turbines

- Addition of turbine type as a discrete variables transforms the plant layout optimization into a mixed-integer non-linear programming problem

- To address this problem, options include:
  - Turning the discrete variable into a continuous variable (difficult here – different Cp, Ct curves, etc.)
  - Reformulate model as algebraic, quadratic programs and use branch and bound techniques [3]
  - Incorporate a heuristic algorithm in the optimization

[3] P. Belotti. Mixed-integer nonlinear optimization. *Acta Numerica*, 22:1–131, 5 2013.

WISDEM^{TM} : Wind Plant Optimization with Multiple Turbines

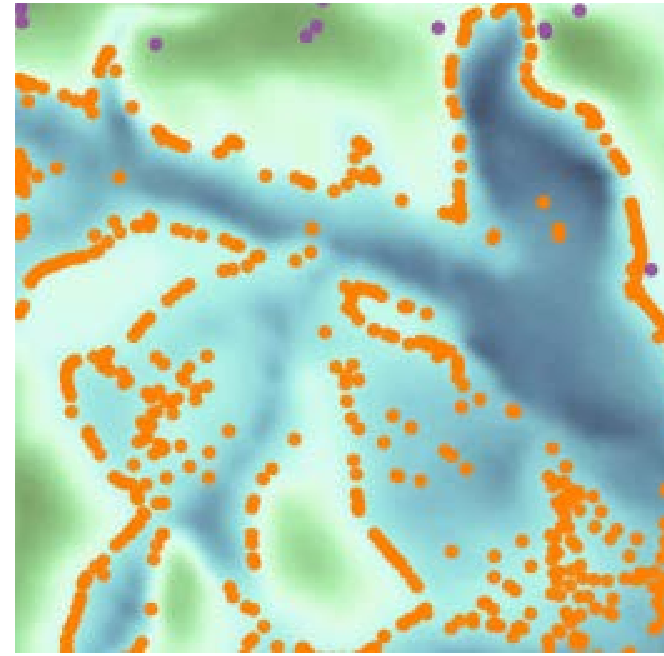
- Approach involves adding a heuristic algorithm along with a local search:
  1. Create an initial population of wind farms with varied turbine types and locations
  2. Run a heuristic (genetic) algorithm for a set number of iterations
     a) Evaluate population and select top-performers
     b) Cross and mutate top performers for new population
  3. Run a local search on turbine locations until converged
  4. Repeat steps 2 and 3 until “acceptable convergence” in overall performance is achieved

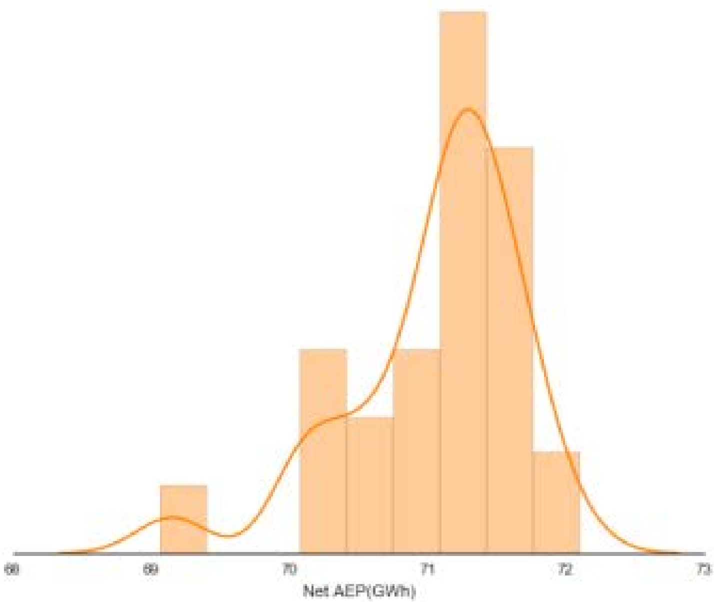
WISDEM™ : Methods: Objectives, design variables and constraints

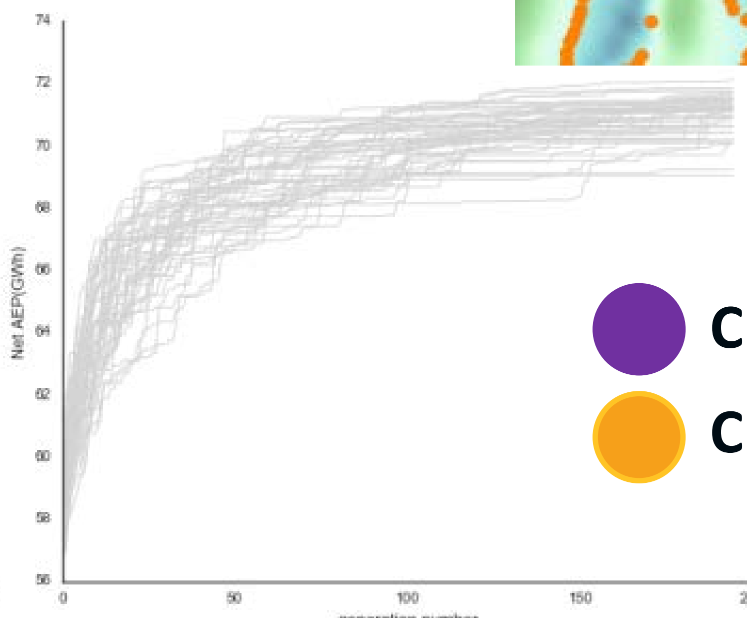
- Objective: annual energy production
- Design variables:
  - Discrete turbine type (choice of two) for each turbine
  - Continuous turbine position (x and y) for each turbine
- Constraints:
  - Minimum turbine distance
  - Minimum distance from site edge
  - Extreme wind constraint (site-suitability for each turbine at each location)
- Using real site data (but ignoring terrain) explore optimization with two turbine options of different IEC classes (I and III)
  - Enforce extreme wind constraint based on IEC 61400-1 to create class III turbine exclusion zones
  - Two cases run (16 and 64 turbines in a 7km x 5km site) with 80+ generations per case

Results: Real site, random initial positions, extreme wind constraint

- 16 turbine case
  - Significant convergence after 200 generations
  - Top performing population members include class III only turbines (relatively low-wind-speed site overall)
  - Turbine locations finding contours of the high-wind-speed exclusion zones





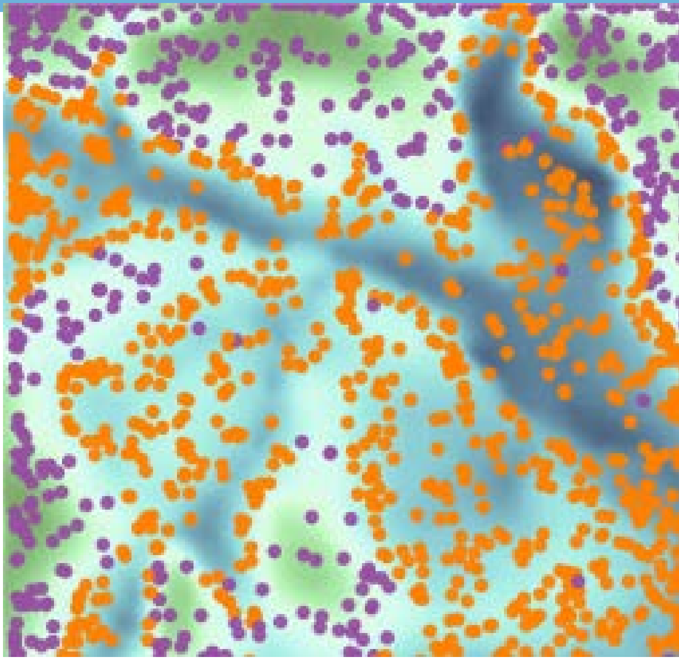


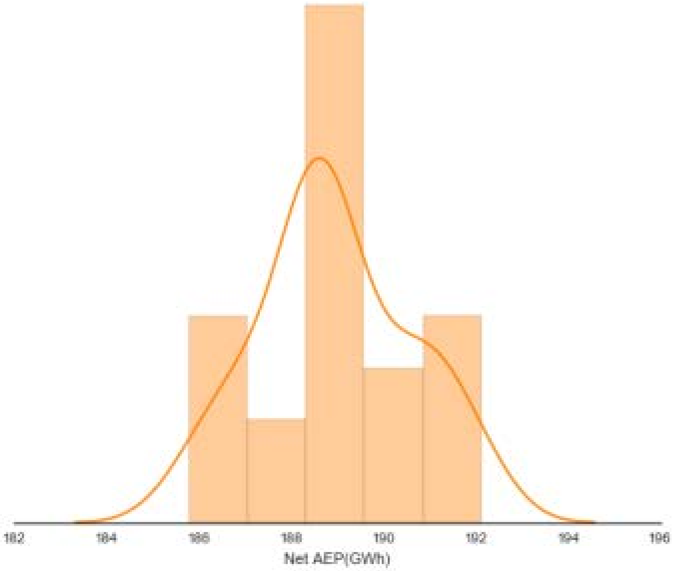
Class I (high WS)

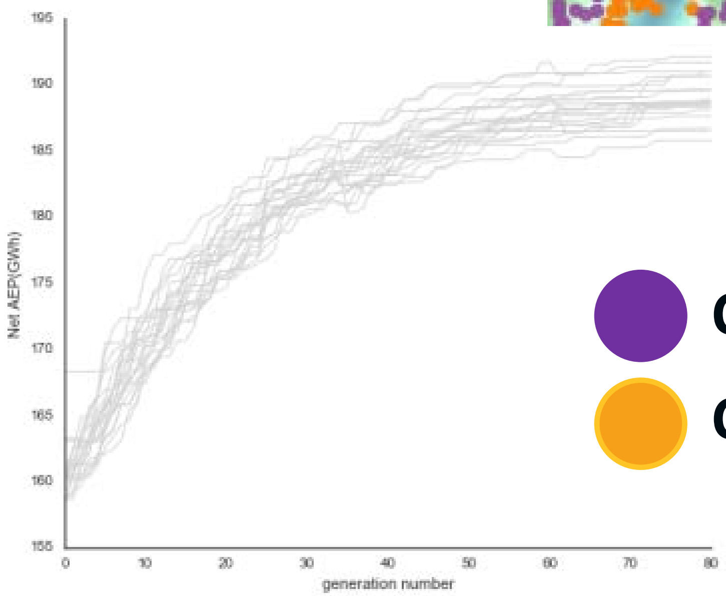
Class III (low WS)

Results: Real site, random initial positions, extreme wind constraint

- 64 turbine case
  - Ran for 80 generations
  - Top performing population members include both class I and III turbines (minimum spacing and losses)
  - Turbine locations partitioned into lower and higher wind-speed areas







Class I (high WS)

Class III (low WS)

Adjoint Techniques

Integrated Plant Design

WISDEM^{TM} : Examples and Applications

Plant Applications: CFD based wind plant layout design

WISDEM^{TM} – WindSE Approach using CFD and Adjoints

- Layout optimization to reduce levelized cost of energy.
  - Layout optimization w.r.t. annual energy production
- High-fidelity flow models with accurate turbulence physics.
  - CFD flow model using 3D turbulent RANS equations
- Multidisciplinary systems engineering optimization approach.
  - Integration into NREL's sys. engineering tool WISDEM
- Efficient optimization algorithms.
  - Gradient-based optimization using adjoints

WISDEM[TM] – WindSE Approach using CFD and Adjoints

- AEP optimization with constraints on spacing:

Adopt a PDE-constrained optimization approach:

$$
\begin{aligned}
\text{minimize} \quad & J(\mathbf{u}, \mathbf{m}) \\
\text{subject to} \quad & \mathcal{R}(\mathbf{u}, \mathbf{m}) = 0 \\
& h(\mathbf{m}) = 0 \\
& g(\mathbf{m}) \leq 0
\end{aligned}
$$

$J(\mathbf{u}, \mathbf{m}) \in \mathbb{R}$ is the objective function – power

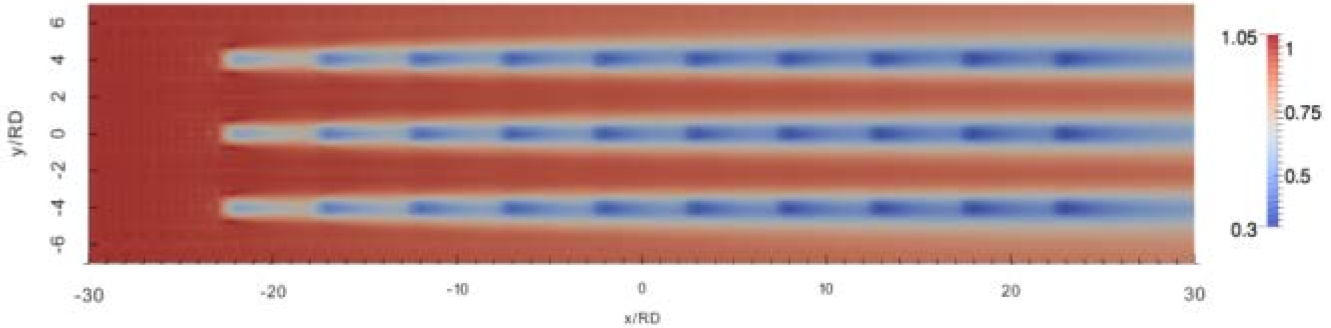
$\mathbf{u} \in \mathbb{R}^n$ are the states – velocities, pressure

$\mathbf{m} \in \mathbb{R}^m$ are the control inputs – locations

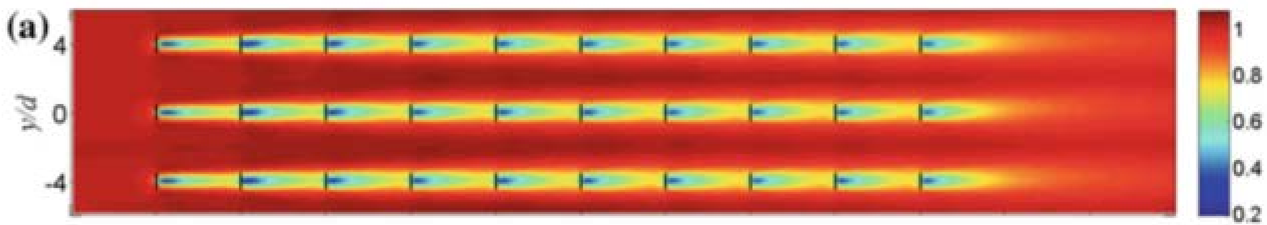
$\mathcal{R}$ are the governing equations – 3D RANS equations

h and g are constraints – site boundaries, turbine spacing

- RANS Model Testing



WindSE 3D RANS results at hub height.

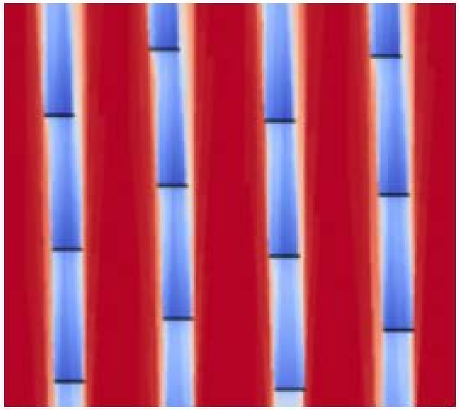


Time-averaged LES at hub height[1].

[1]Wu and Porté-Agel, Boundary Layer Meteorology, 2013.

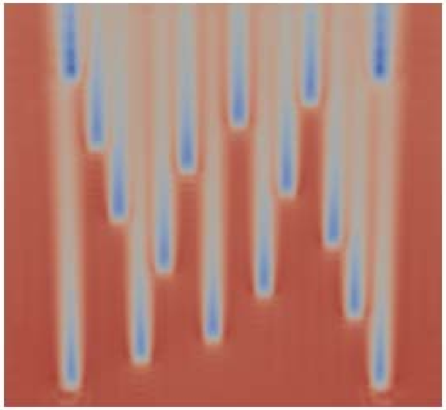
WISDEM™ – WindSE Approach using CFD and Adjoints

- Nonlinear wake effects



Industry wake model.

Horns Rev wind farm.



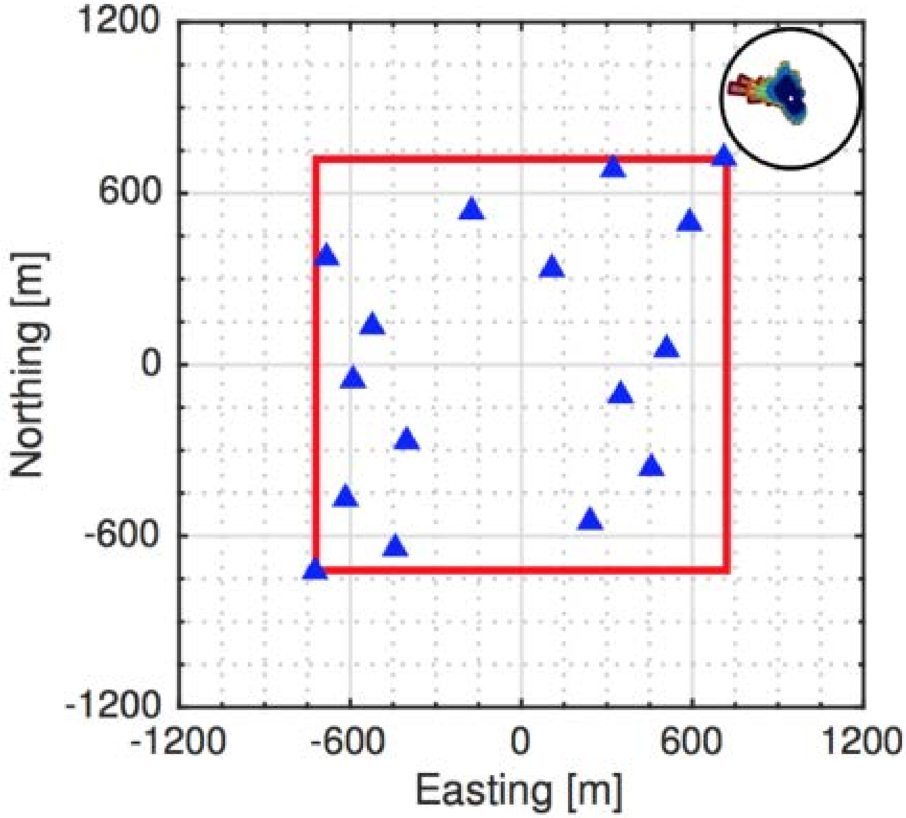
WindSE flow model.

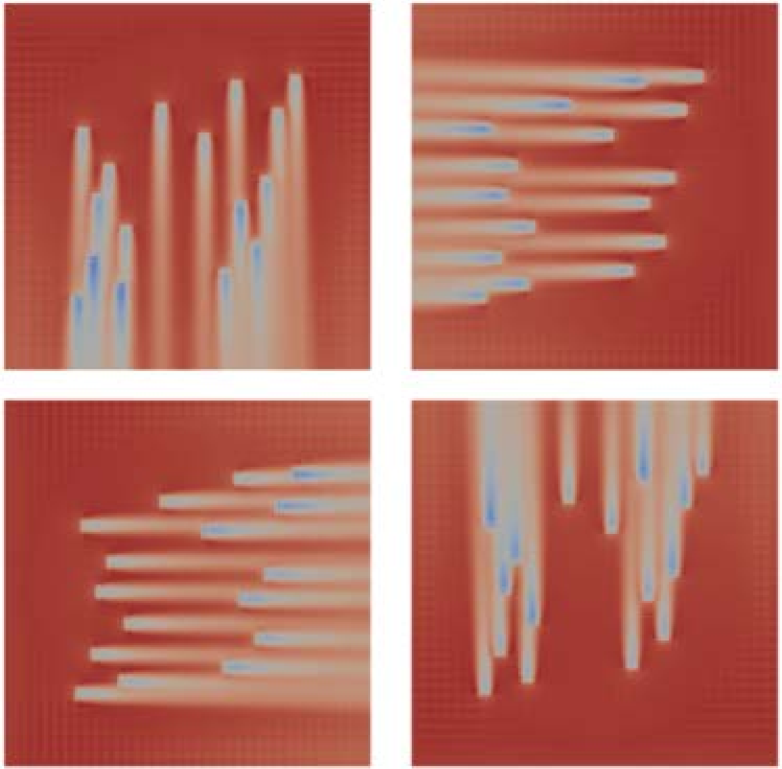
Nonlinear wake effects – flow curvature and wake redirection – are not predicted by industry wake models but do exist in real flows.

Implications for yaw control and wake steering.

WISDEM™ – WindSE Approach using CFD and Adjoints

- Full AEP Optimization (36 directions, 5 wind speeds)





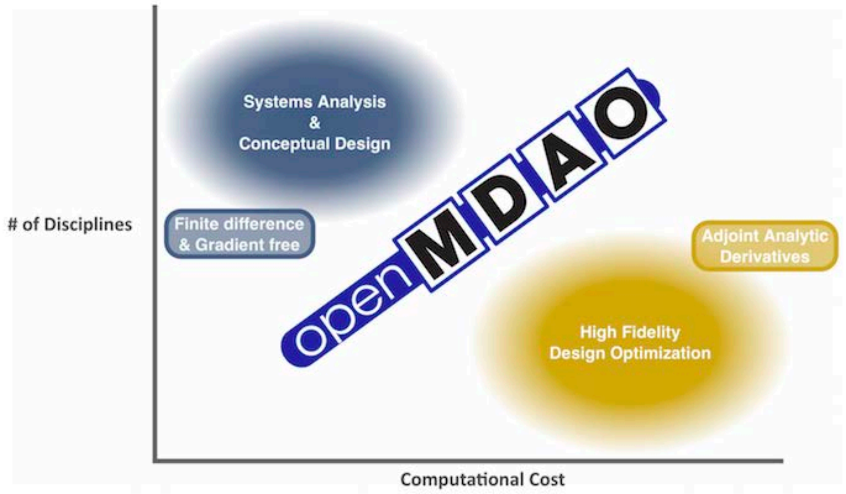
Optimization Under Uncertainty

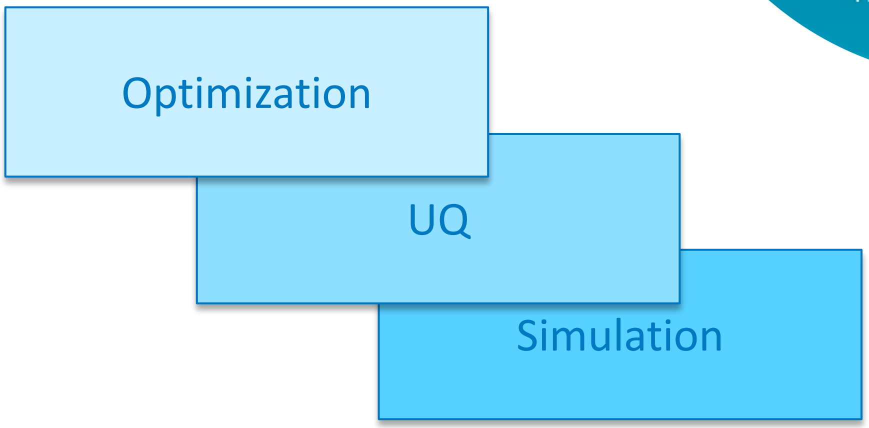
Integrated Plant Design

WISDEM™ : Examples and Applications

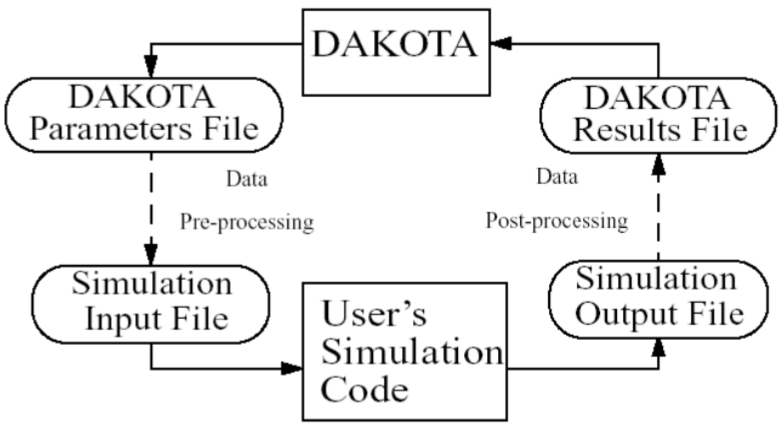
Plant Applications: Controls and Layout

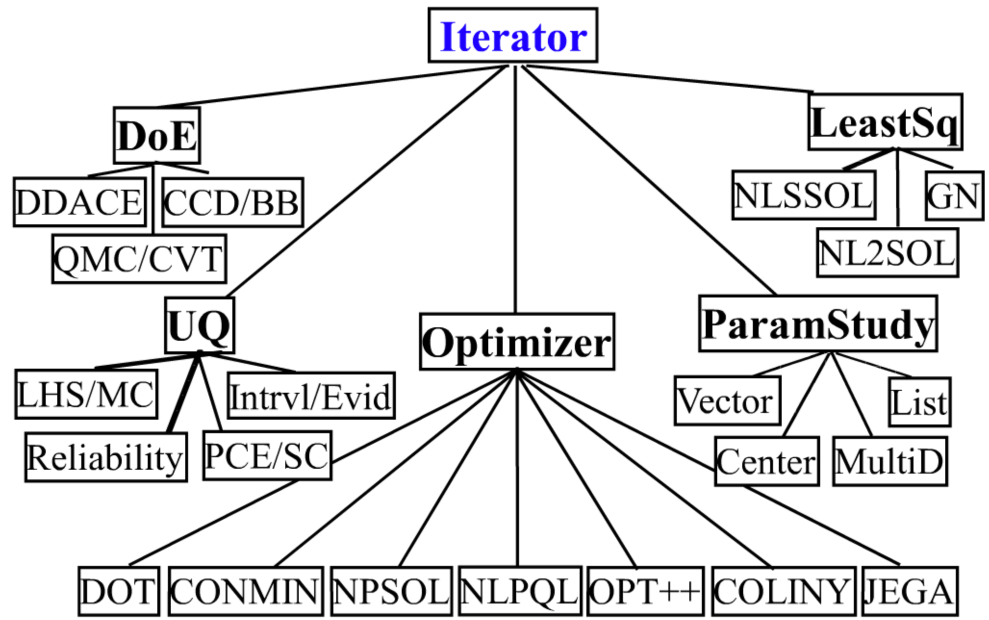
Overview of OpenMDAO-DAKOTA Optimization Under Uncertainty (OUU)

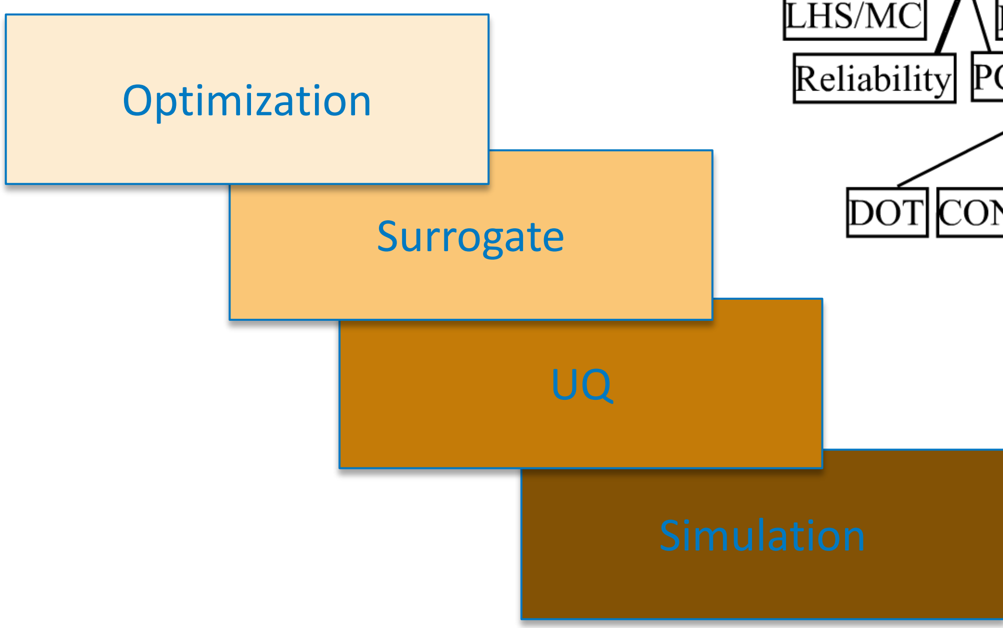




WISDEM^{TM} -pyDAKOTA

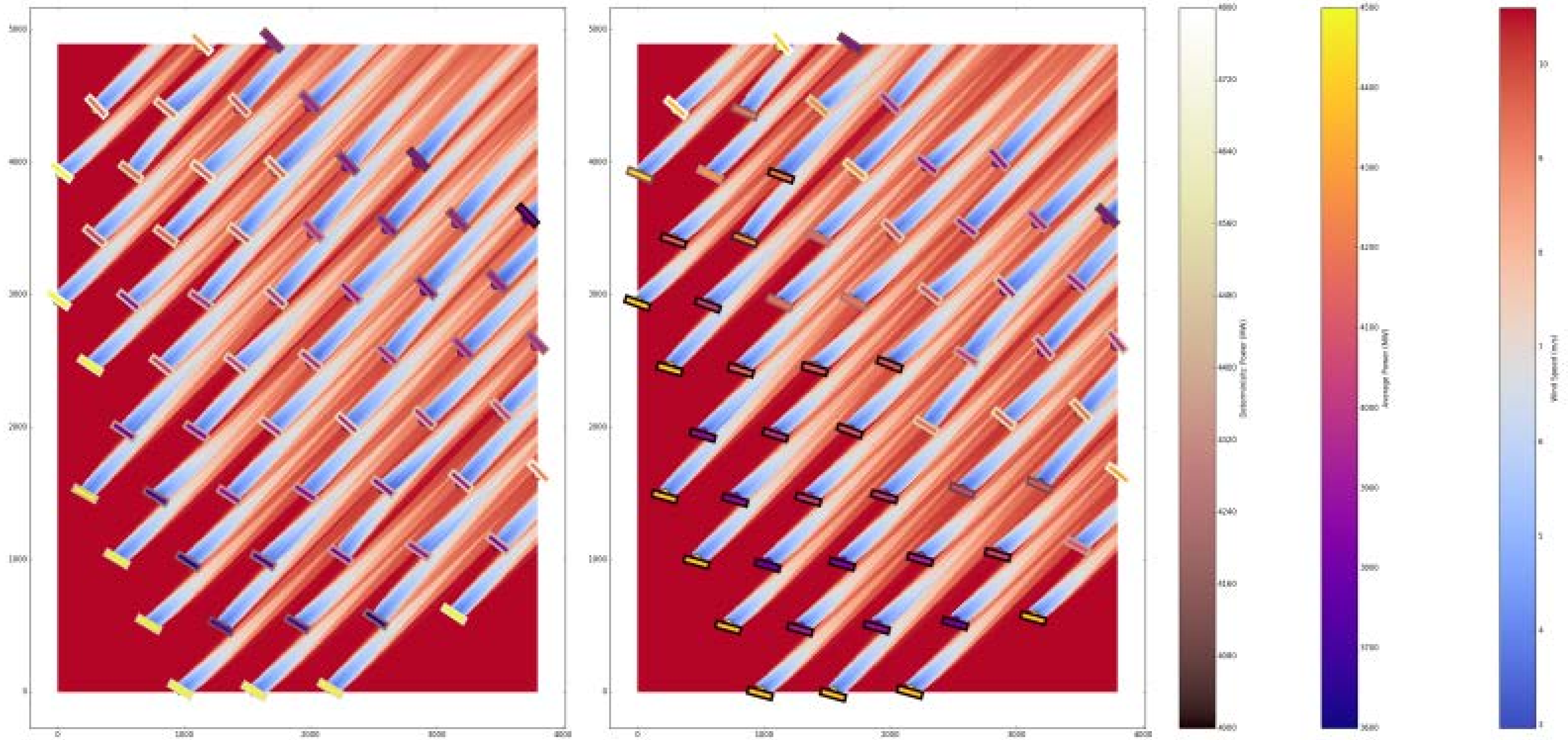




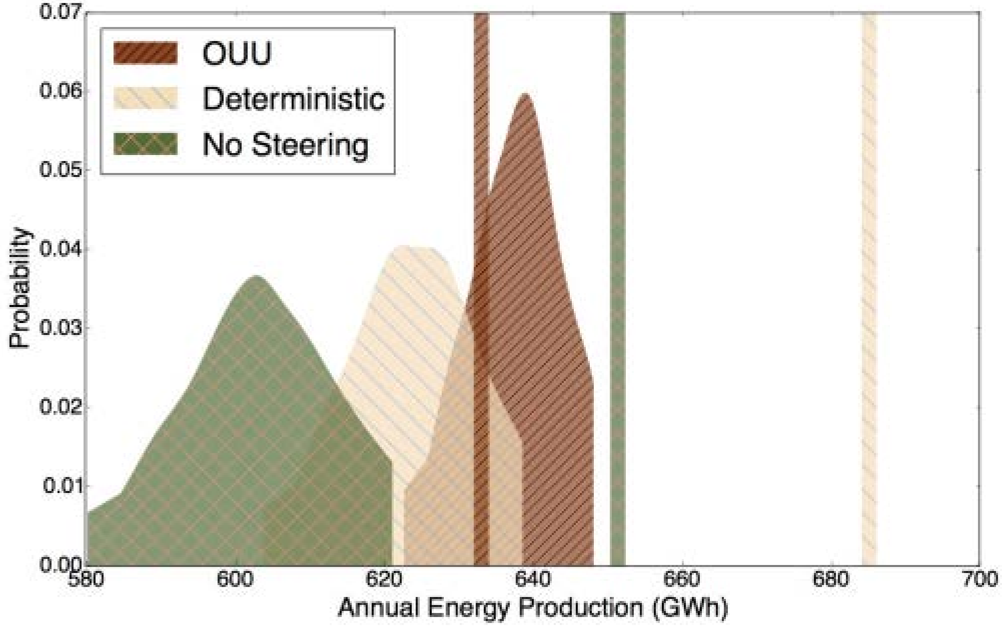


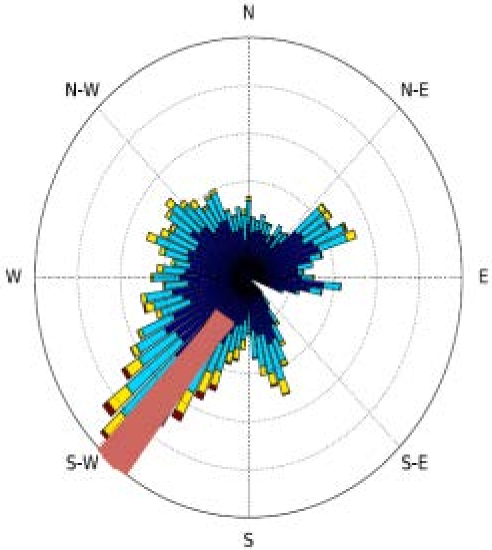
WISDEM™ – OUU with uncertainty in yaw position

- Deterministic and OUU results for wake steering with uncertainty in the nacelle yaw sensor measurement



WISDEM™ – OUU with uncertainty in yaw position





	Deterministic AEP	Expected AEP
OUU Solution	173.7	168.2
Deterministic Solution	179.3	166.0

Summary & Conclusions

Conclusions

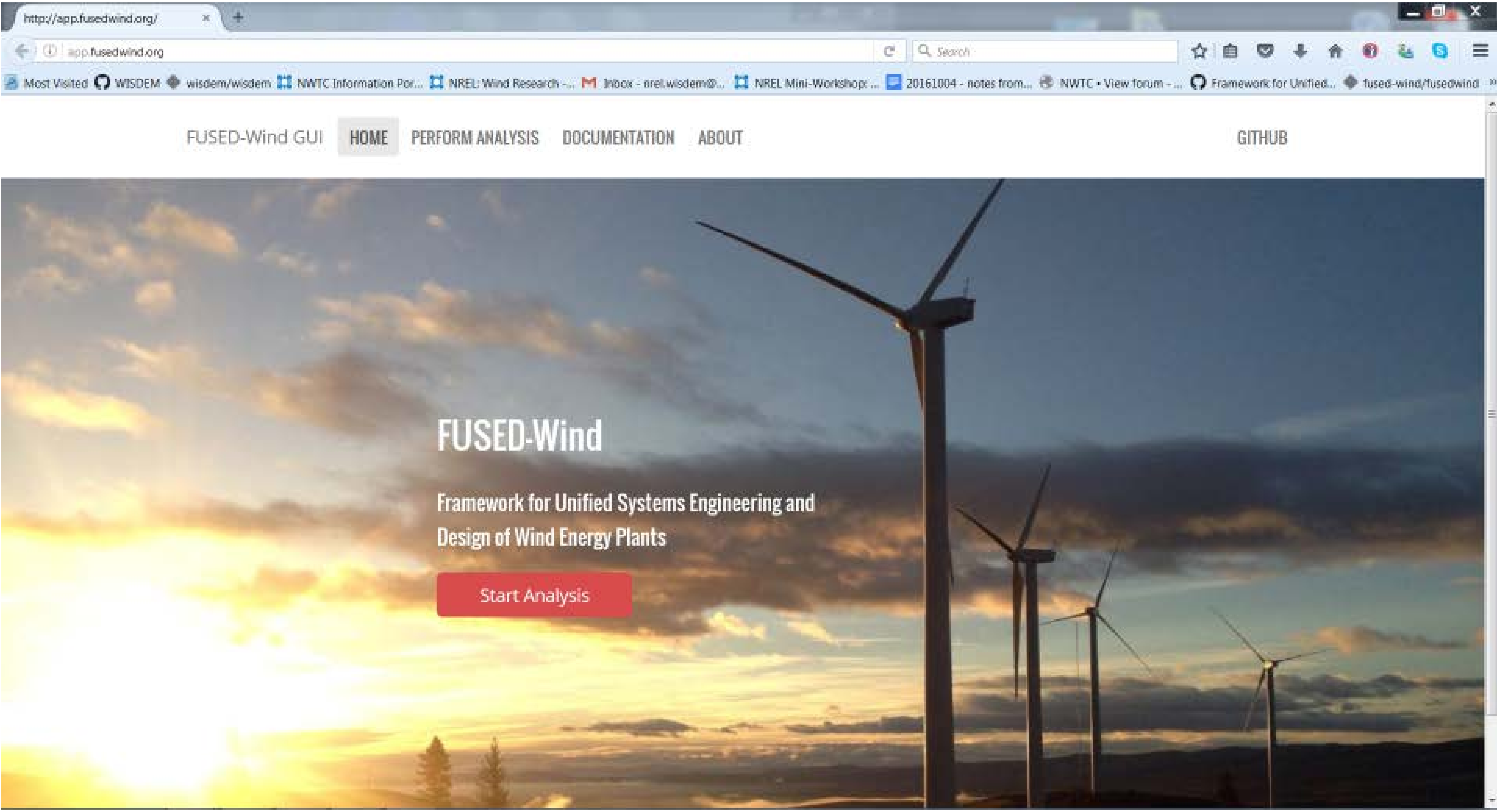
- WISDEM™ a robust Systems Engineering tool toward integrated design of complex wind systems
- Exploration of innovation space and LCOE impact (plug and play your model and rely on WISDEM)
- Design Optimization with analytic gradients, discrete variables, uncertainty, adjoints
- Trade-off studies: Pre and Post-Construction (O&M) optimization
  - Integrated urbine design
  - Integrated plant design and operations
  - Integrated turbine and plant design and operations

IEA Wind Task 37

- Recognition of importance for integrated system modeling / systems engineering growing in industry and research organizations

- IEA Wind Task 37 formed in 2016 with three complementary activity areas:
  - Framework guidelines for wind turbine and plant model integrated modeling
  - Reference wind energy systems for MDAO research
  - Demonstration cases of MDAO applied to wind turbine and plant applications

FUSED Wind the App



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Thank you!

www.NREL.gov/wind/systems-engineering.html

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