Wind Power Plant Optimization State-of-the-Art

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5th Wind Energy Science Workshop
Oct 2-4, 2019
Pamplona, Spain

Outline

- ModSim Book
- Wind Plant Optimization - Background and Motivation
- Historical Developments in Wind Power Plant Optimization (2000 – 2015)
  - Manual Approaches
  - From AEP to LCOE
- Recent Trends (2015 – Present)
  - More advanced LCOE optimization
  - Multiple turbine types
  - Control strategies
- Current and Future Opportunities
  - High-fidelity / multi-fidelity
  - Optimization Under Uncertainty / Stochastic Optimization
  - Data-driven modeling
  - Site suitability and loads surrogates
  - The holy grail of reliability and O&M
  - Beyond LCOE & Hybrid power plants
- Collaboration Opportunities
  - IEA Wind Task 37

ModSim

Coming in Fall 2019: *Modeling and Simulation in Wind Plant Design*, edited by Paul Veers, NREL, IET Publications

Volume 1: Atmosphere and Plant	
Chapter Title	**Full Author Name(s)**
Introduction	Paul Veers
Looking forward: The promise and challenge of exascale computing	Michael Robinson, Michael Sprague
Blade-resolved modeling with fluid-structure interaction	Ganesh Vijayakumar and Jim Brasseur
Mesoscale modeling of the atmosphere	Sue Haupt; Jared Lee; Pedro Jimenez; Branko Kosovic
Mesoscale to Microscale Coupling for High-Fidelity Wind Plant Simulation	Jeff Mirocha
Atmospheric turbulence modelling, synthesis, and simulation	Jacob Berg
Modeling and Simulation of Wind Farm Flows	Matt Churchfield and Pat Moriarty
Wind Plant Controller Design	Jan-Willem von Wingerden, Bart Doekemeijer, Paul Fleming
Forecasting for Wind Power Production and Grid Operations	John Zack
Cost of Wind Energy Modeling	Maureen Hand

Volume 2 Turbine and System	
Chapter Title	**Full Author Name(s)**
Introduction	Paul Veers
Aerodynamics: turning wind into mechanical motion	Martin O.L. Hansen
Wind turbine aero-servo-elasticity and dynamics	Morten Hansen
Rotor design and analysis	Carlo Bottasso, Pietro Bartolotti
Drivetrain Analysis for Reliable Design	Zhiwei Zhang and Yi Guo
Offshore turbines with bottom-fixed or floating substructures	Denis Matha
Wind Turbine Control Design	Alan Wright
Systems Engineering and Optimization of Wind Turbines and Power Plants	**Andrew Ning, Katherine Dykes, Julian Quick**
Wind Plant Electrical Systems	Ed Muljadi and Vahan Gevorgian
Grid Modeling with Wind Plants	Nicholas Miller

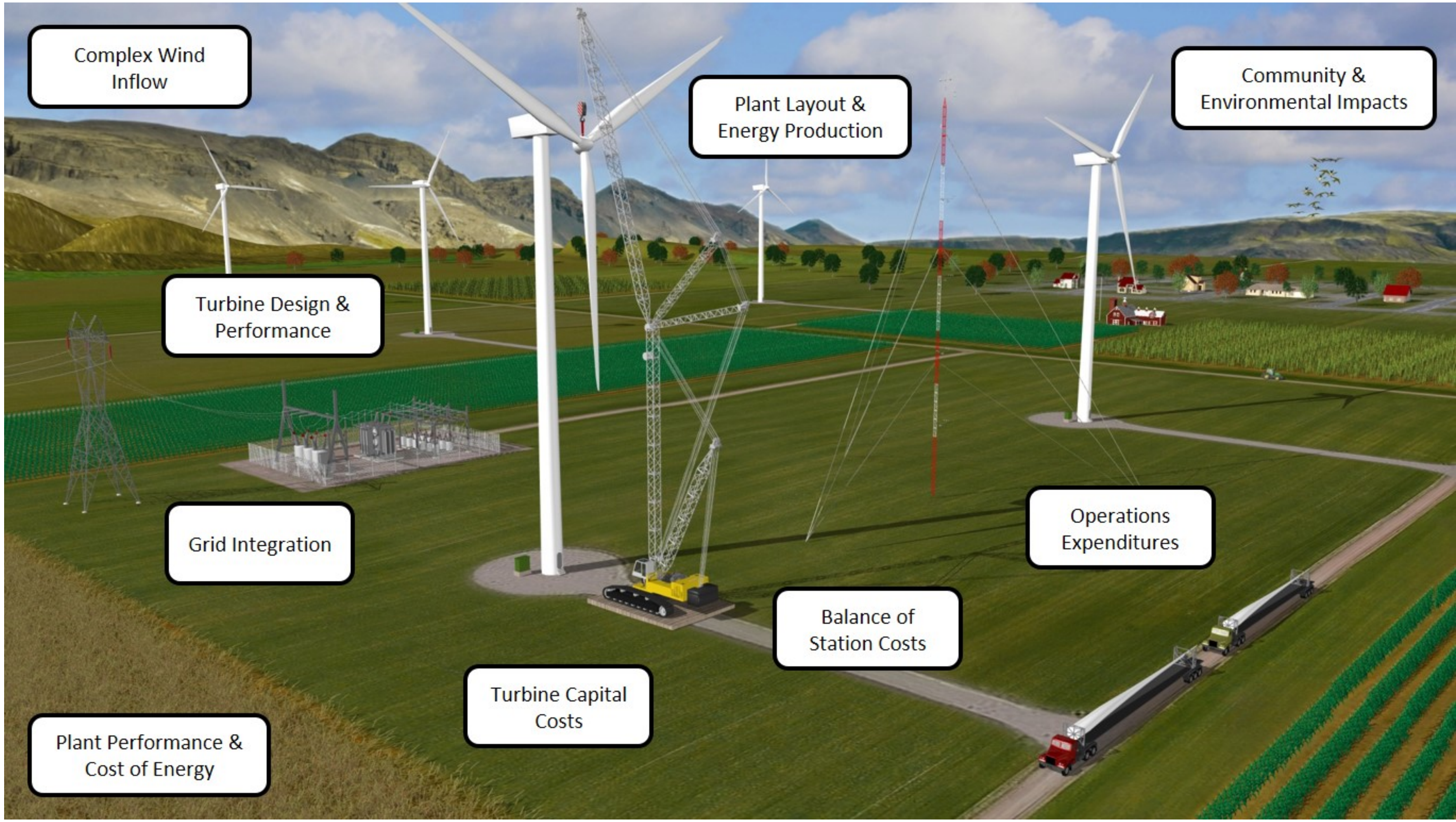
ModSim

- **Systems Engineering and Optimization of Wind Turbines and Power Plants**
  - **Design-Based Optimization**
  - **Wind Turbine Design Optimization**
    - **Unique Challenges in Wind Turbine Optimization**
    - **Higher Fidelity Approaches and Unsteady Aeroelstic Modeling**
    - **Research and Industry Applications of Wind Turbine Optimization**
  - **Wind Power Plant Design Optimization**
    - **Unique Challengs in Wind Power Plant Optimization**
    - **Higher Fidelity Approaches and Addressing Uncertainty**
    - **Research and Industry Applications of Wind Power Plant Optimization**

Background and Historical Developments

Wind Plant Optimization
Background and Motivation

Wind energy systems are complex and couple many sub-systems and components together, described by numerous physical phenomena and disciplines (from the atmosphere to the electrons)



Wind Plant Optimization
Background and Motivation

Plant designers addressed this complexity historically in various ways:

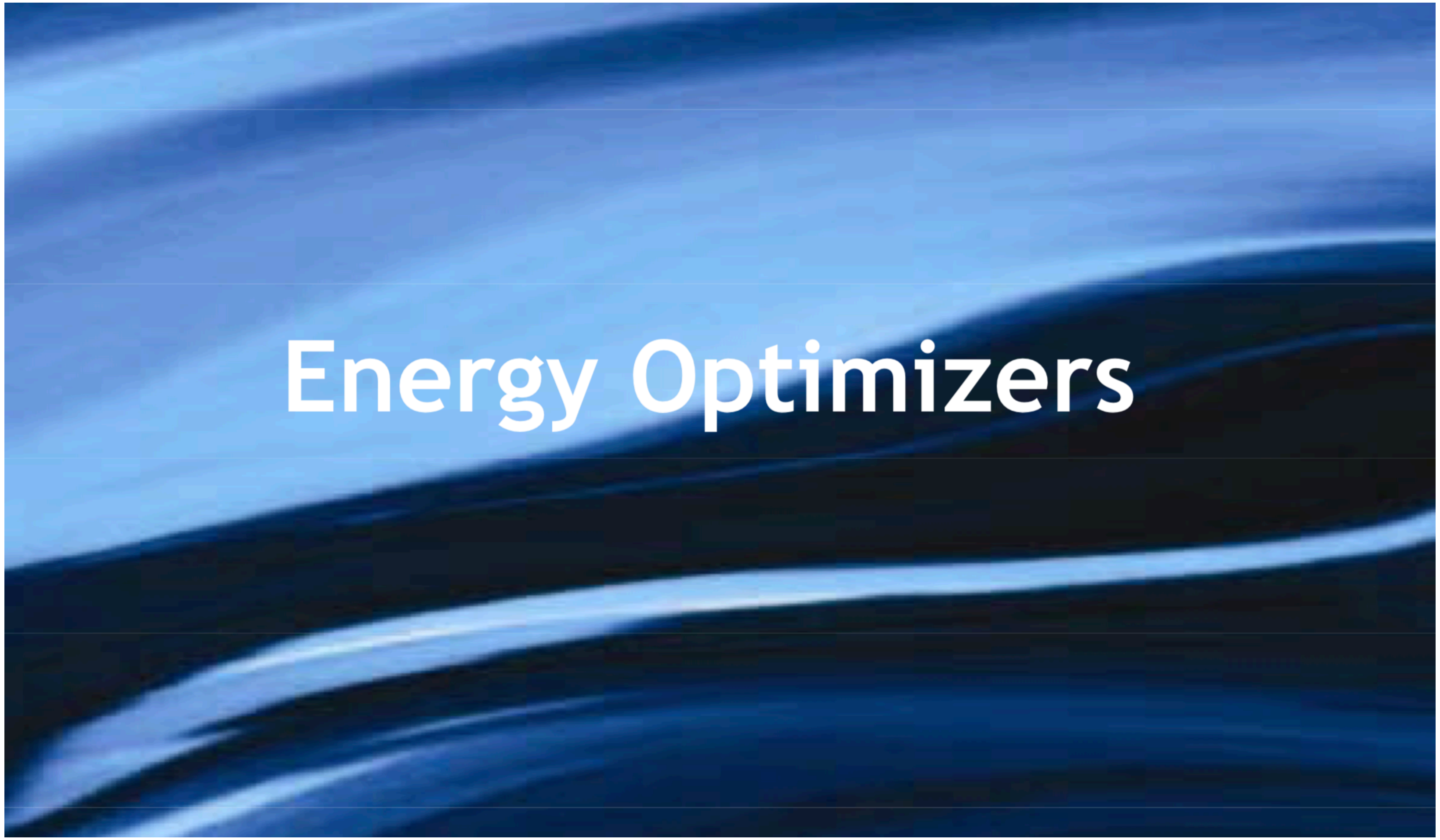
1. Skip optimization and rely on experience

2. Use optimization for basic design with emphasis on AEP (layout) and maybe some elements of LCOE (crude infrastructure models)

3. Develop strong dependence on optimization and include increasing levels of scope (more system elements) and fidelity (more accurate models)
    - Leveraging abundant computational resources and advanced multi-disciplinary design, analysis and optimization (MDAO) techniques

Historical Wind Plant Optimization

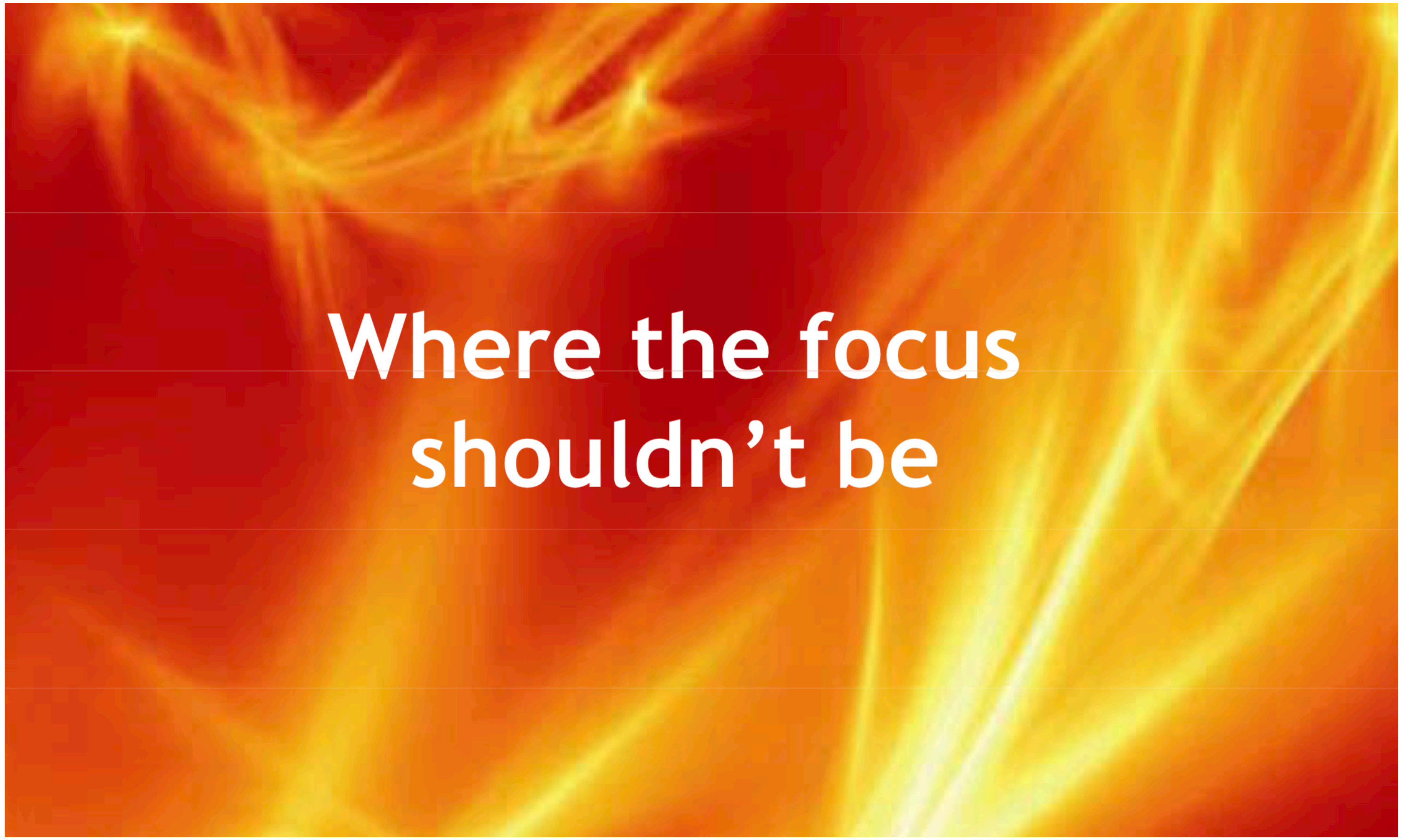
Manual Design Process



1st Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf

Historical Wind Plant Optimization

Manual Design Process



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https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf

Historical Wind Plant Optimization

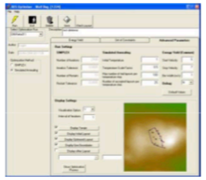
Manual Design Process

AMERICAS

Energy Optimization Software: A bad idea in practice

- RES has developed various optimization software over the years

SIMPLEX ALGORITHM (> 10 years ago) → GENETIC ALGORITHM (8 years ago) → SIMULATED ANNEALING (7 years ago) → SOFTWARE DISCONTINUED (2010)



- Why did we discontinue it?
  - Complex site constraints
    - Software could deal with this, but very time consuming entering all into software
    - Inevitably some 'real world' constraint missed (less value in the optimization)
      - Contractual: E.g. Landowner 'A' has stipulation of minimum MW
      - ALTA survey (late in dev. cycle) reveals pipelines, easements, microwaves, etc
      - Many times governed by noise constraints: Complex analysis in itself
  - Wake models and wind flow models don't have required level of accuracy
    - See following slides: Can't do an optimization if the inputs (models) aren't correct
  - Many layouts end up 'designing themselves' and when they don't ....
  - .... an experienced practitioner can get extremely close to the optimized solution

1st Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se_workshop_oliver.pdf

Historical Wind Plant Optimization (2000 – 2015)

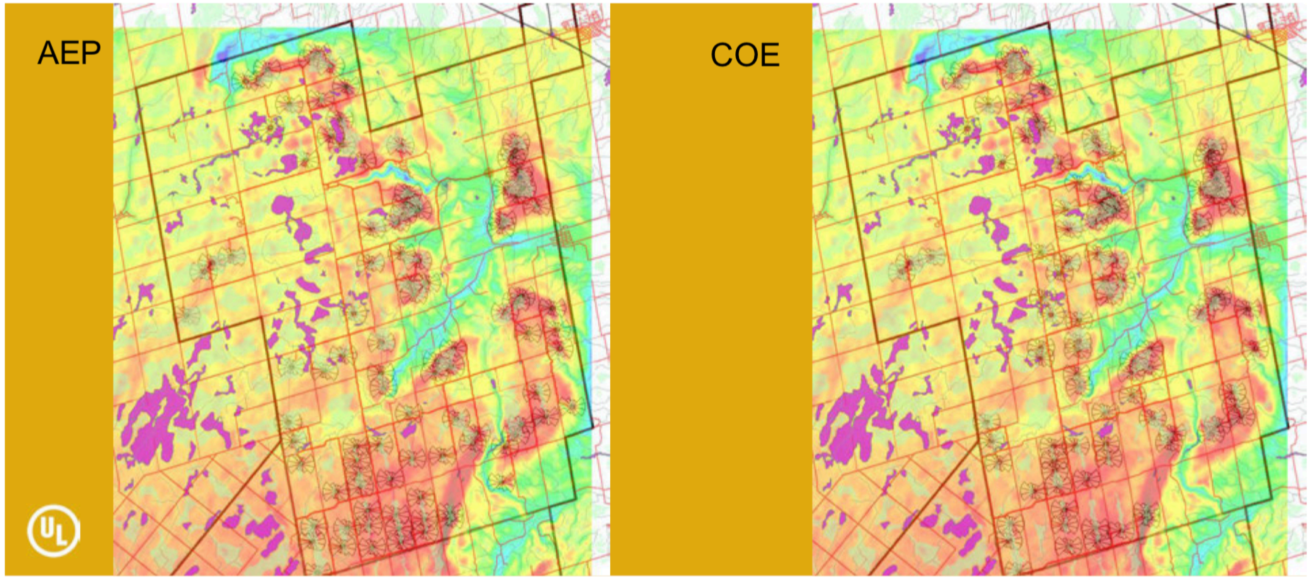
From AEP to LCOE

- Slowly built trust in optimization with research and industry experience
- AEP optimization insufficient but cost models are cumbersome
- Compromise: simple models for major cost elements (electrical and road infrastructure)

Openwind®

Objective Function	Net Energy [GW]	BOP Cost [$]	LCOE [$/MW]
AEP	1101 100%	51 100%	38.49 100%
COE	1096 99.6%	46 90.2%	38.3 99.5%
IRR	1094 99.4%	46 90.2%	38.38 99.7%

Results



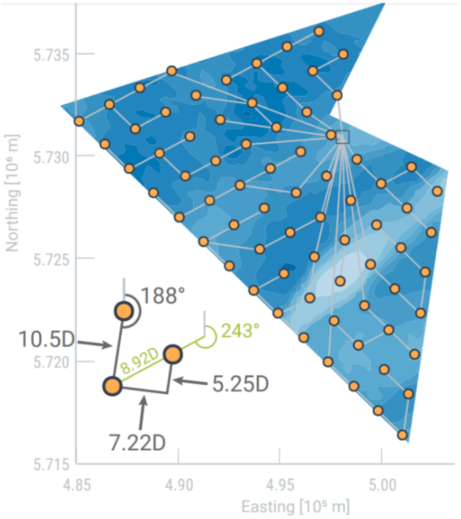
4th Wind Energy Systems Engineering Workshop Presentation
https://www.nrel.gov/wind/assets/pdfs/se17-8-ul-renewables.pdf

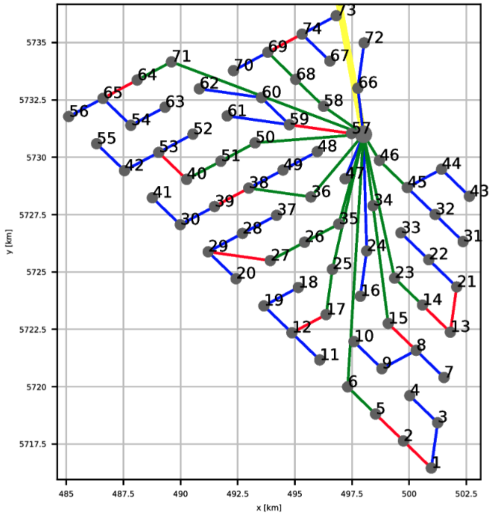
Recent, Current and Future Trends

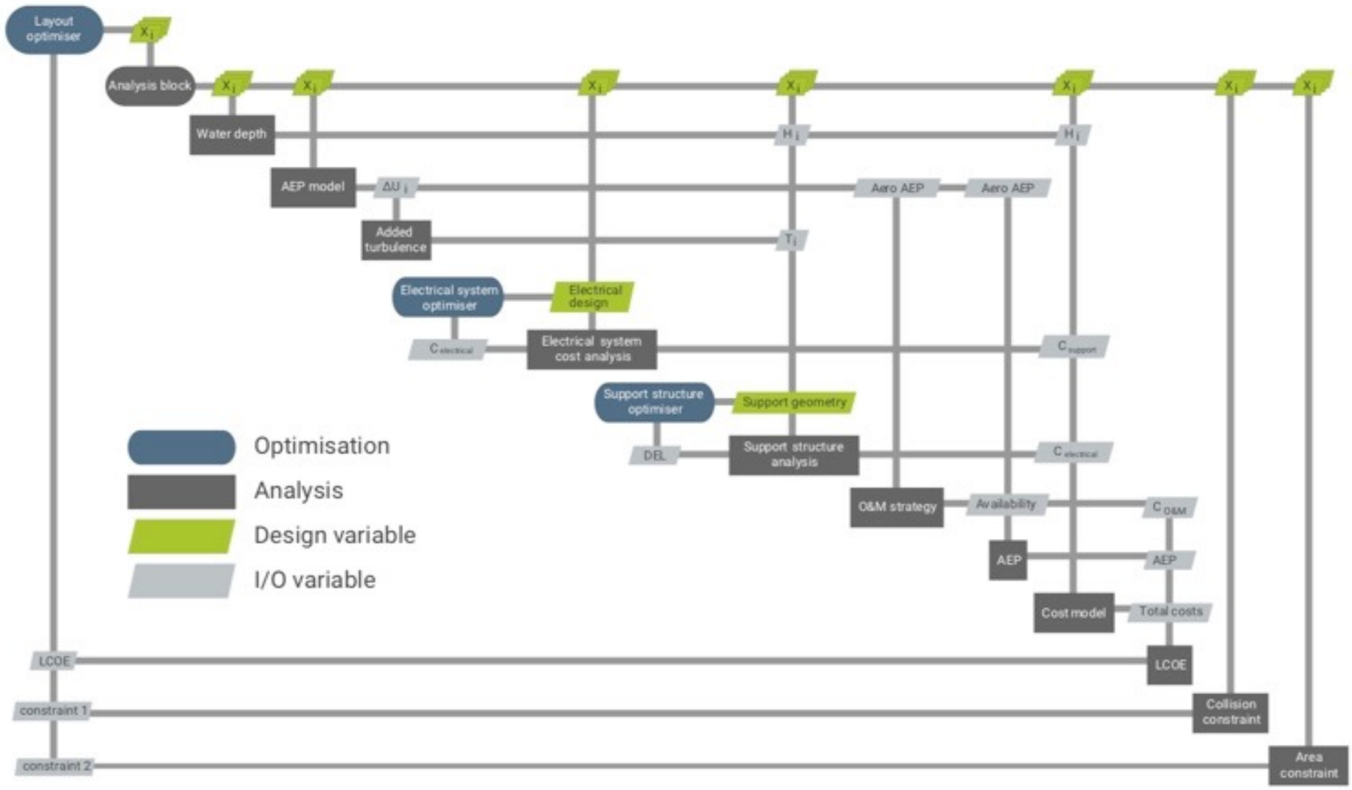
Recent Wind Plant Optimization

More advanced LCOE optimization

- Optimization use in site design now widespread
- Emphasis shifts to more advanced modeling of LCOE components – and also addressing offshore sites





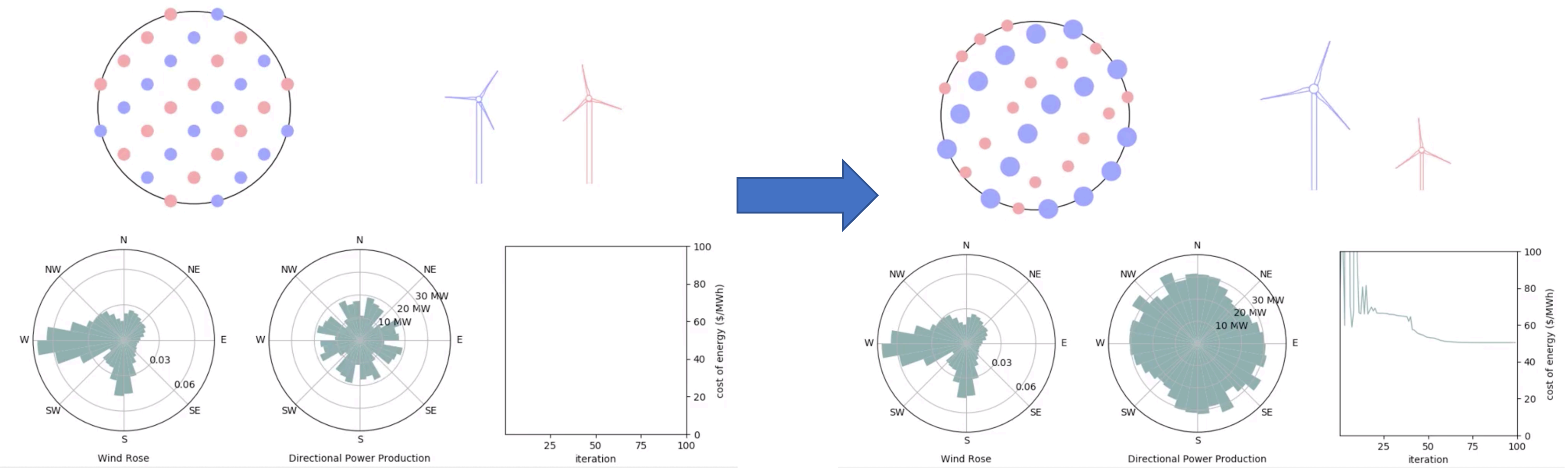


Example wind plant layout optimization workflow for an offshore reference wind plant (Source: Sanchez Perez-Moreno et al 2017)

Recent Wind Plant Optimization

Multiple Turbine Types

- Increasing trend towards modular turbine platforms with varied hub heights, rotor diameters and even power ratings



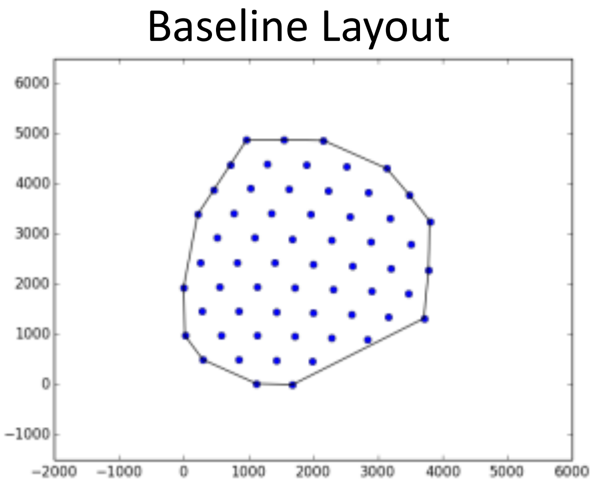
Stanley, A. P. J., and Ning, A., "Coupled Wind Turbine Design and Layout Optimization with Non-Homogeneous Wind Turbines," *Wind Energy Science*, Vol. 4, No. 1, pp. 99–114, Jan. 2019. doi:10.5194/wes-4-99-2019

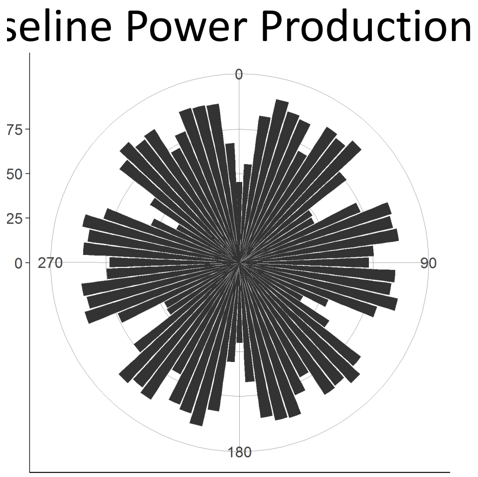
Stanley, APJ; Ning, A.; Dykes, K. (2019) Optimization of Turbine Design in Wind Farms with Multiple Hub Heights, Using Exact Analytic Gradients and Structural Constraints. *Wind Energy*. 22: 605–619.

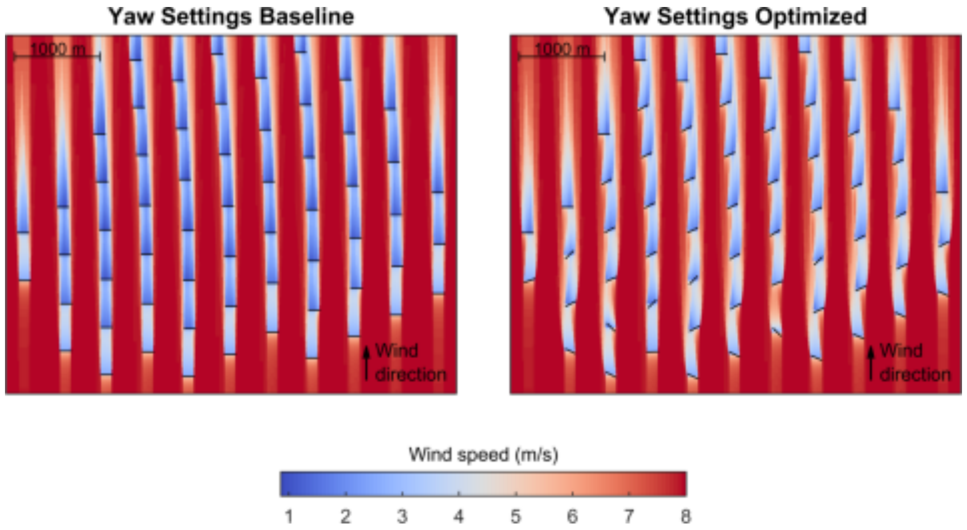
Stanley, A.P.J.; Thomas, J.; Ning, A.; Annoni, J.; Dykes, K.; Fleming, P. (January 2017) Gradient-Based Optimization of Wind Farms with Different Turbine Heights. AIAA SciTech Forum Grapevine, Texas, doi:10.2514/6.2017-1619.

Recent Wind Plant Optimization
Control strategies

- As control paradigm shifts from turbine to plant, so do opportunities to consider plant control strategies in the upfront design process







- **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.

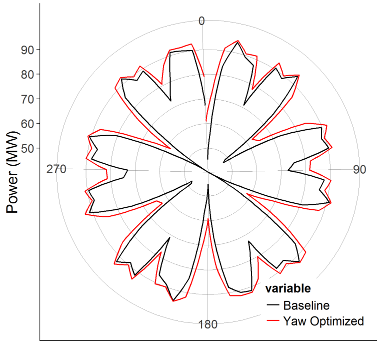
Recent Wind Plant Optimization

Control strategies

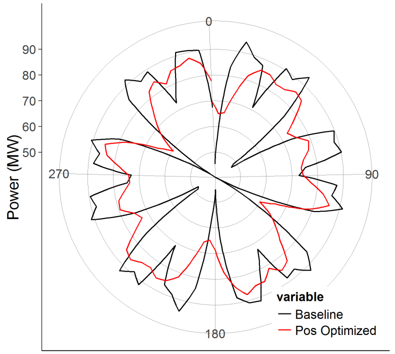
- Considering wake steering strategies in the design process can increase AEP, reduce costs, or both

	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%)

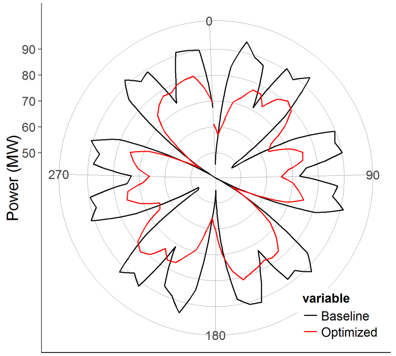
Yaw Optimized

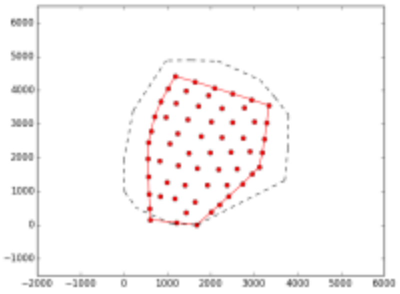


Position Optimized



Combined





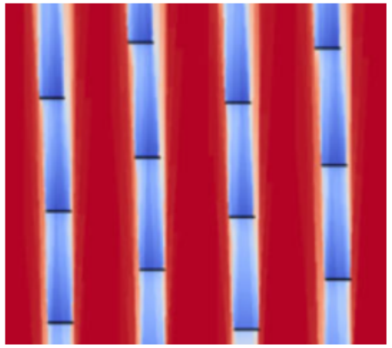
Final versus initial layout perimeter with higher power density

Gebraad, P.; Thomas, J.; Ning, A.; Fleming, P.; Dykes, K. (May 2016) Maximization of the Annual Energy Production of Wind Power Plants by Optimization of Layout and Yaw-Based Wake Control. Wind Energy, doi:10.1002/we.1993.
Fleming, P.A.; Ning, A.; Gebraad, P.M.O.; Dykes, K. (2015). Wind plant system engineering through optimization of layout and yaw control. Wind Energy.

Current and Future Opportunities

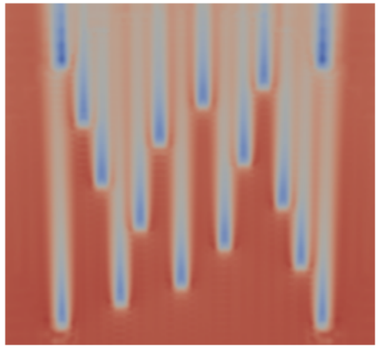
High / Multiple Fidelity Levels

- Using higher fidelity models address more complex flow phenomena including influence of controls on flow, atmospheric stability, complex terrain, etc

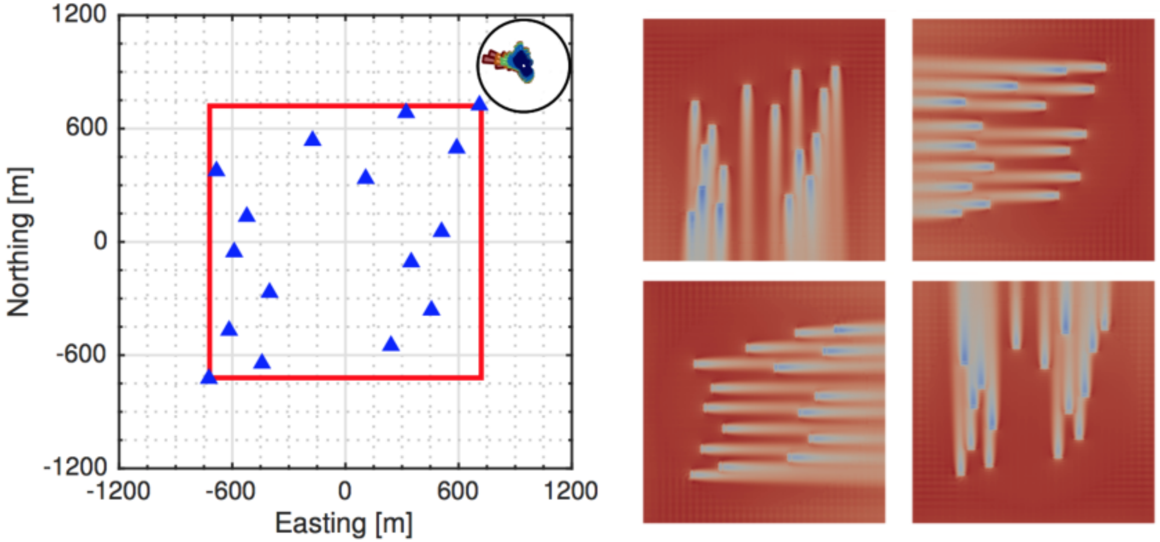


Industry wake model.

Horns Rev wind farm.



WindSE flow model.

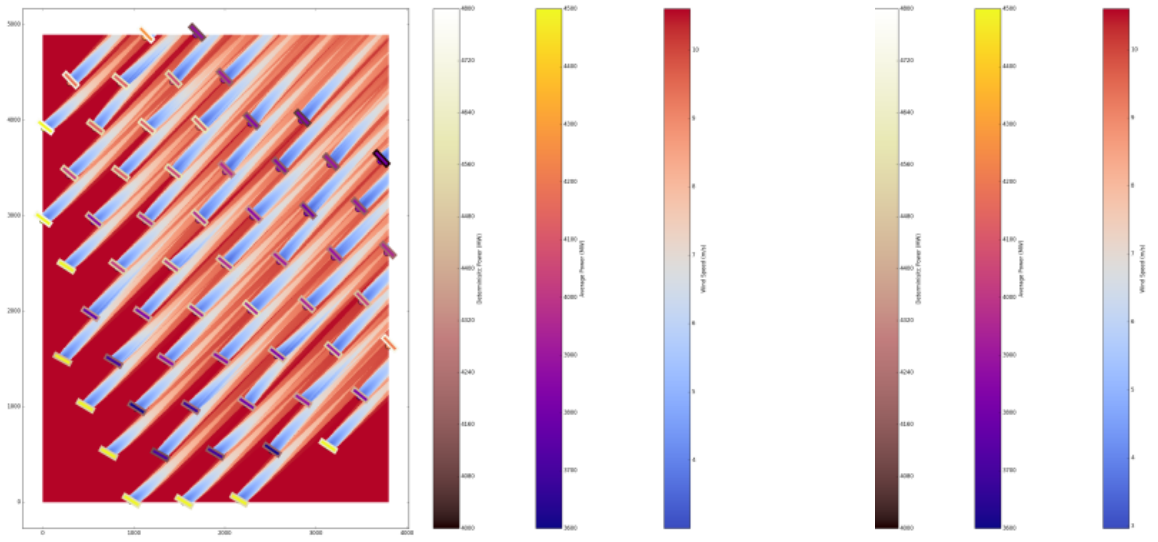


Full AEP Optimization (36 directions, 5 wind speeds)

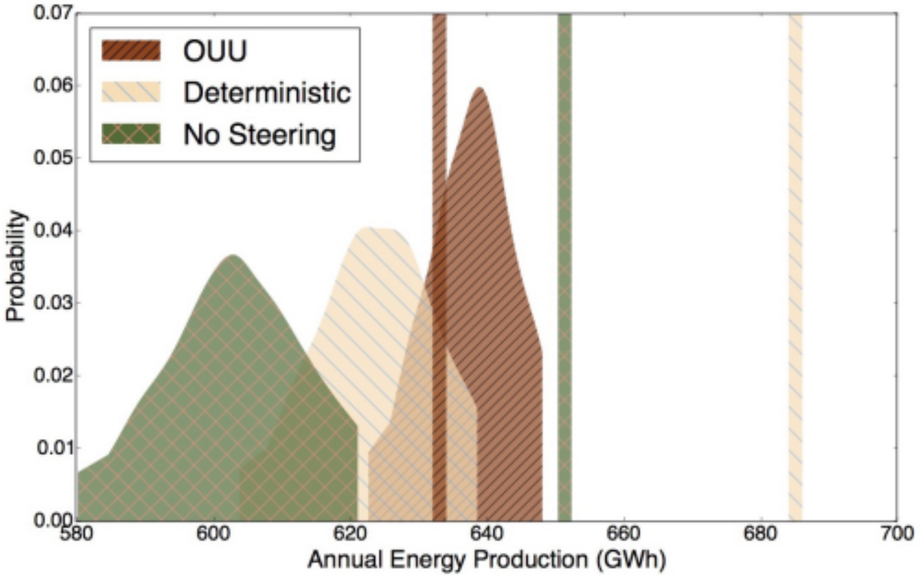
King, R.N.; Hamlington, P.E.; Graf, P.; Dykes, K. (2017) Optimization of Wind Plant Layouts Using an Adjoint Approach. Wind Energy Science, doi:10.5194/wes-2-115-2017.

Current and Future Opportunities
Stochastic Optimization

- Explicitly addressing uncertainty can lead to more robust plant design and operational / control strategies



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

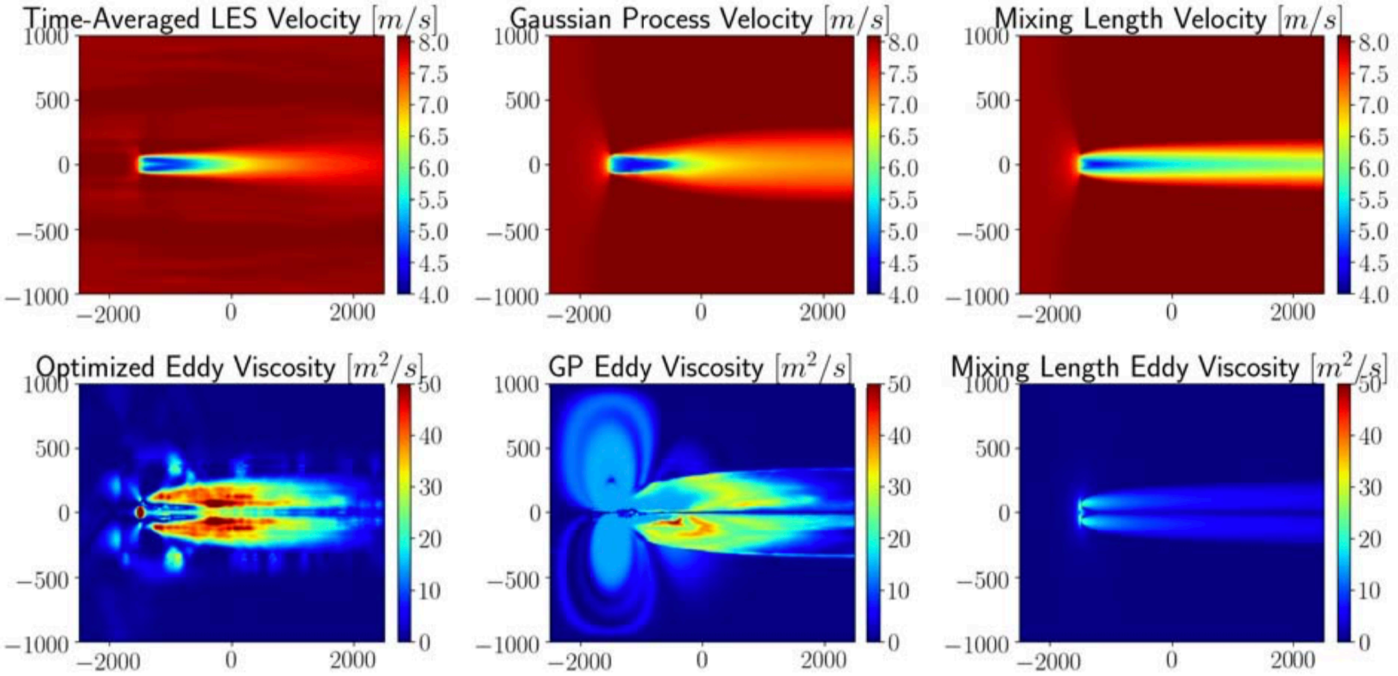


	Deterministic AEP	Expected AEP
OUU Solution	173.7	168.2
Deterministic Solution	179.3	166.0

Quick, J.; Annoni, J.; King, R.; Dykes, K.; Fleming, P.; Ning, A. (2017) Optimization under uncertainty for wake steering strategiesPDF. Wake Conference 2017, Visby, Sweden. NREL/CP-5000-68185.

Current and Future Opportunities
Data-driven modeling

- Using data from high-fidelity simulations or experimental data, we can improve accuracy of optimization models while preserving computational efficiency

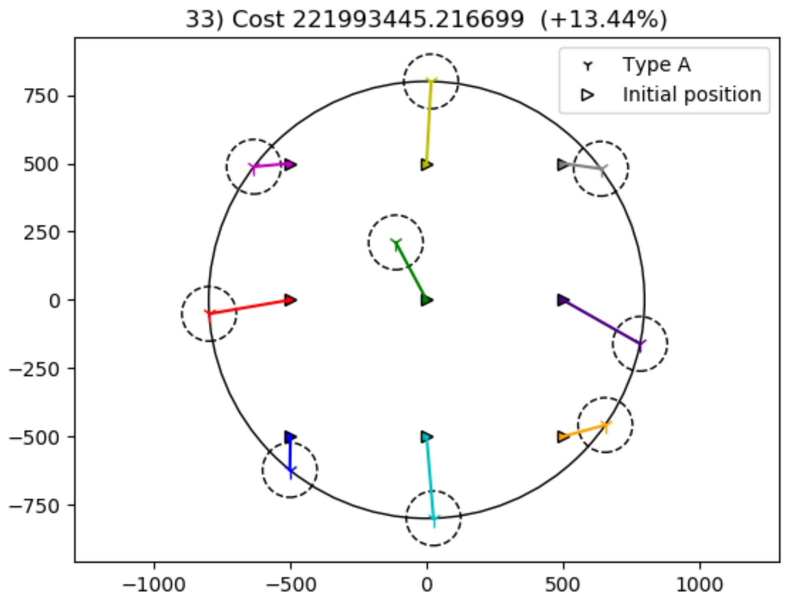


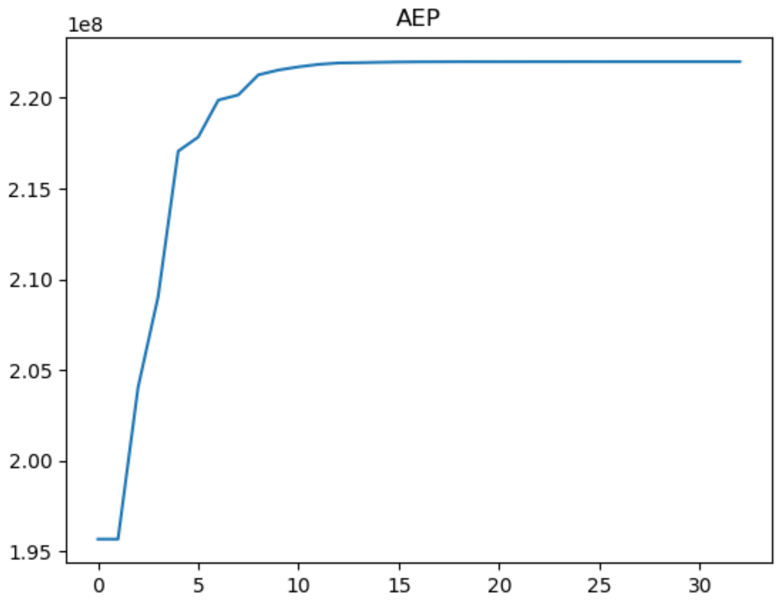
R. N. King *et al* 2018 *J. Phys.: Conf. Ser.* **1037** 072004

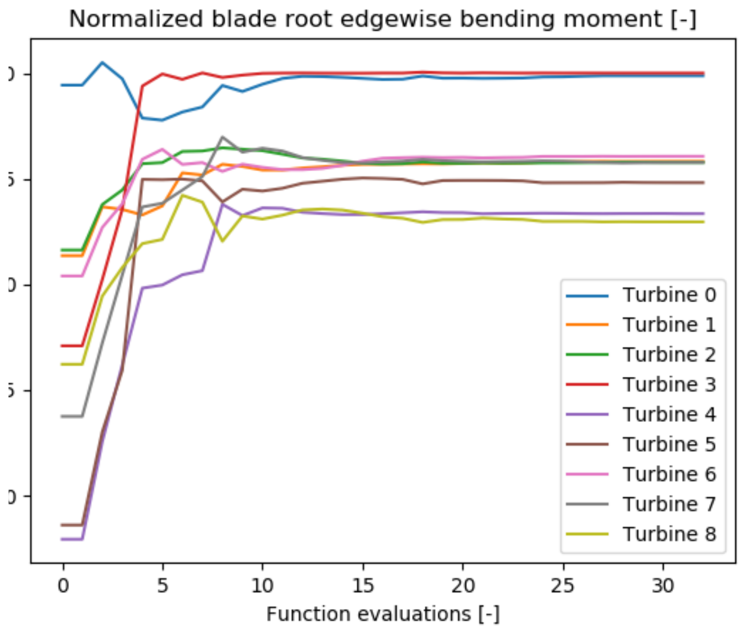
Current and Future Opportunities

Site suitability and loads surrogates

- Using data and higher fidelity simulations to develop surrogates of loads to address site suitability concerns



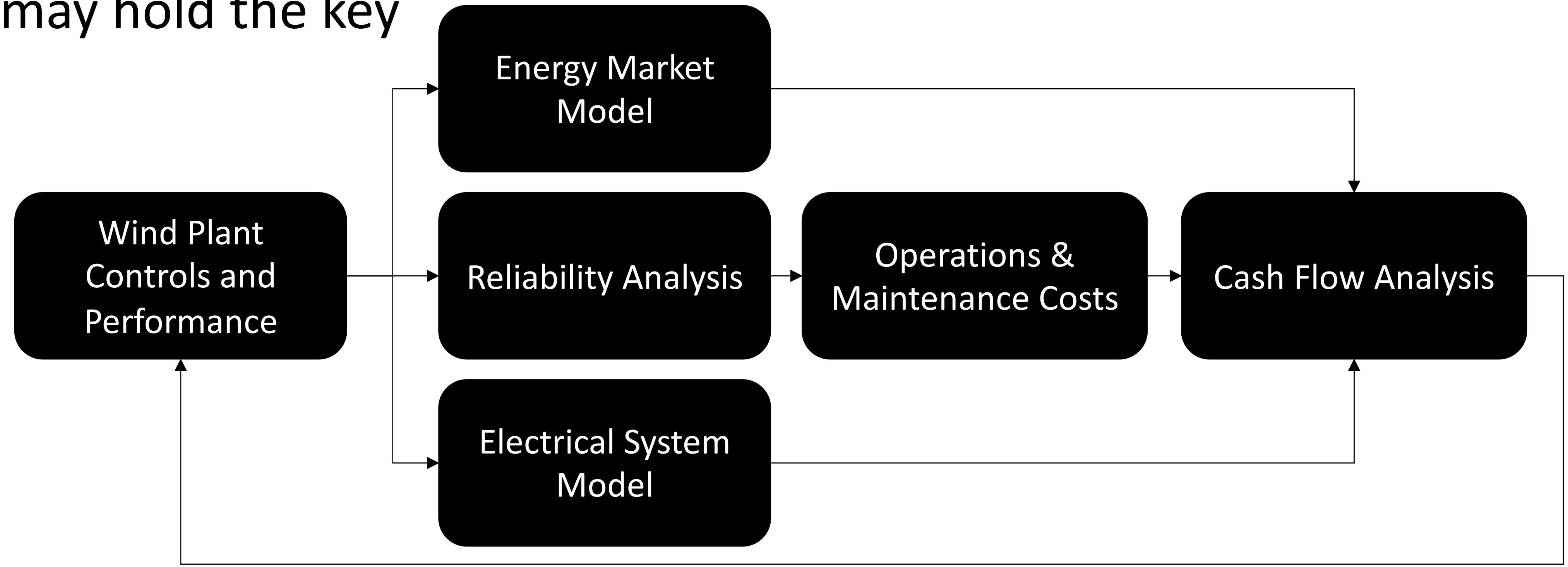




Unpublished Topfarm results using IEA Wind Task 37 case study 1 9 turbin case

Current and Future Opportunities
The Holy grail of O&M and reliability

- Long term assessment of reliability and associated costs includes high levels of uncertainty
- Leverage data-driven techniques and physics-based modeling together may hold the key



Current and Future Opportunities
Beyond LCOE & Hybrid Power Plants

- Shifting from fixed purchase price for renewable energy to participation in energy, capacity and service markets

Ahlstrom et al. 2017 IEEE Power & Energy Magazine

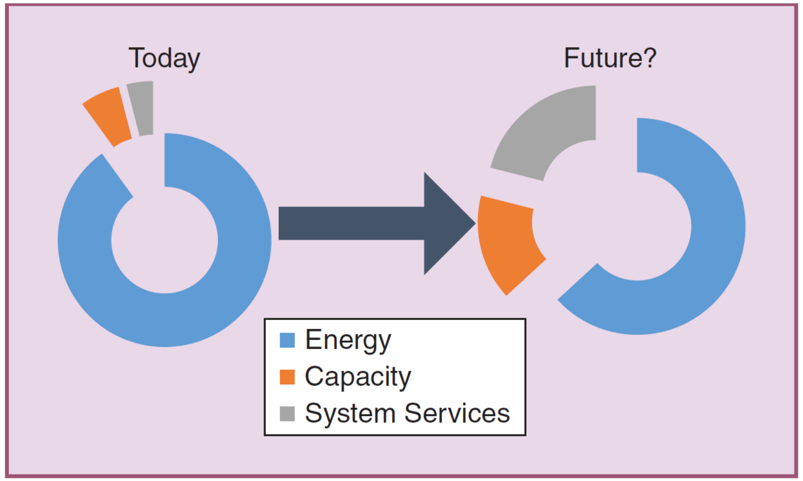
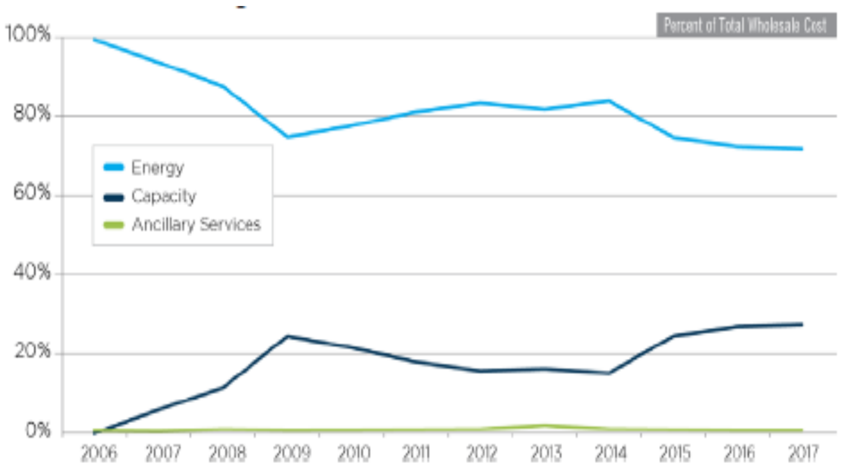
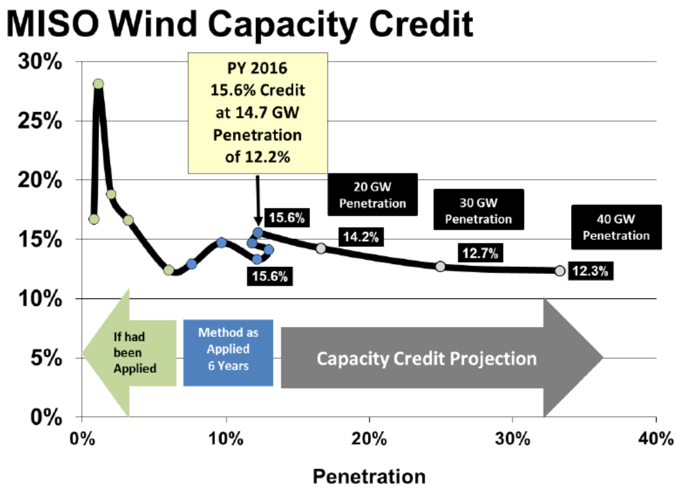


figure 1. A conceptual view of the possible shift from energy to system services. (Courtesy of EPRI.)



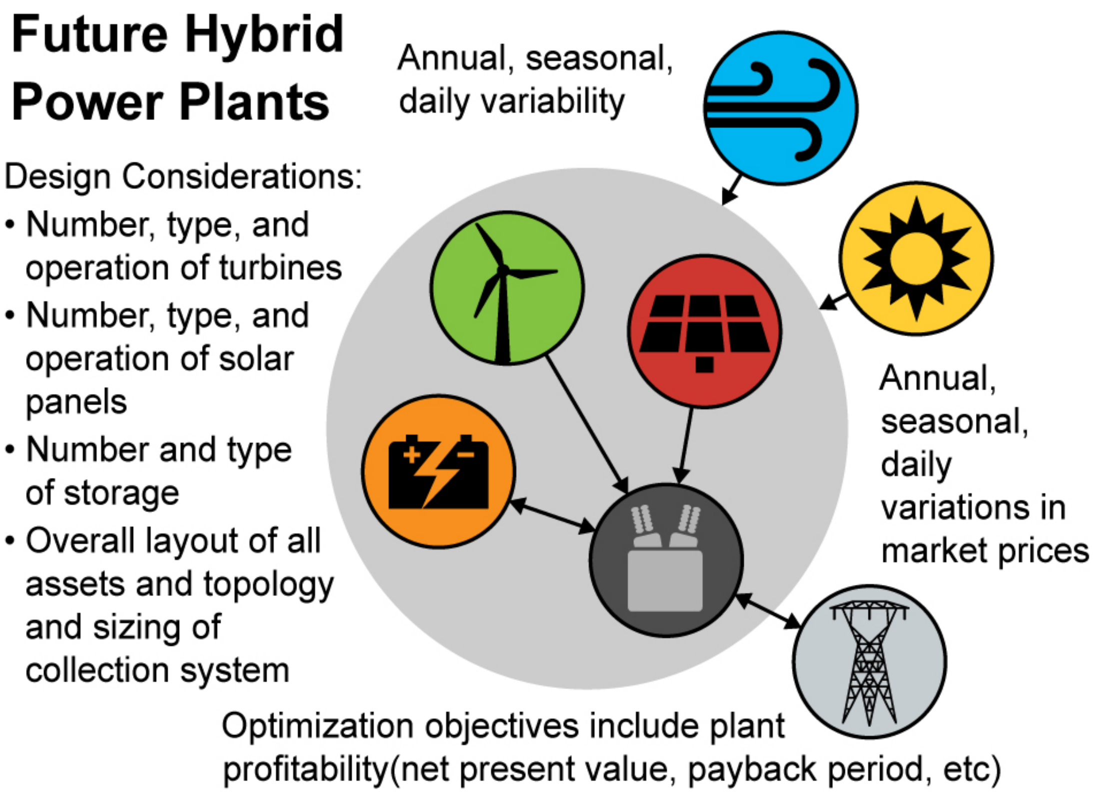
PJM market trends through 2017 (Source: PJM 2017)



Declining wind capacity credits (Source: MISO 2015)

Current and Future Opportunities
Beyond LCOE & Hybrid Power Plants

- Design wind power plants for shifting revenue streams
- Integrate solar and storage into hybrid power plant energy solutions

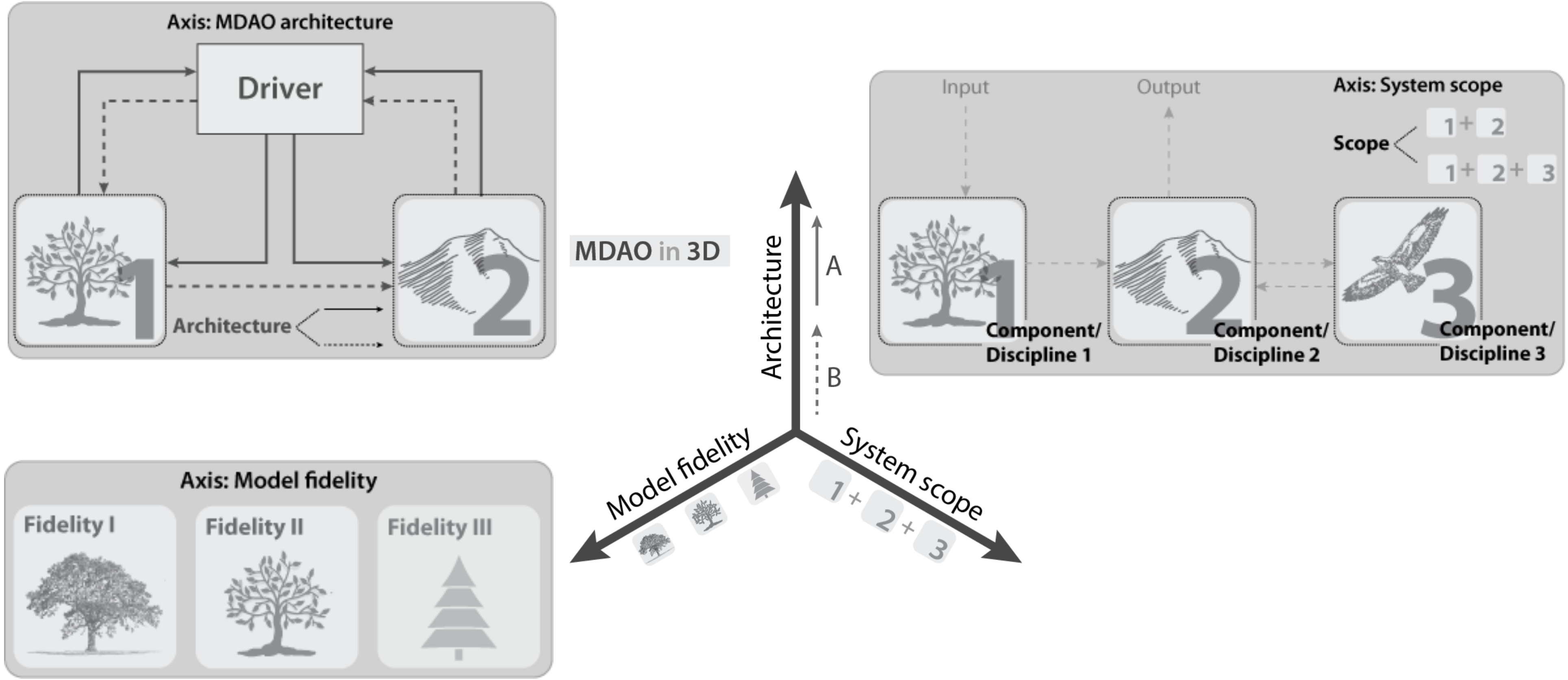


IEA Wind Task 37

IEA Wind Task 37

Overview

What model fidelity and disciplinary couplings must be captured in a design process? What is the best possible architecture of the design process?



Perez-Moreno, S.; Zaaijer, M.; Bottasso, C.; Dykes, K.; Merz, K.; Rethore, P.; Zahle, F. (2016) Roadmap to the multidisciplinary design analysis and optimisation of wind energy systems. Journal of Physics, doi:10.1088/1742-6596/753/6/06

IEA Wind Task 37
Overview

Project Objectives and Outcomes

- Improve quality of systems engineering by practitioners through development of best practices and benchmarking exercises
- Promote general knowledge and value demonstrations of systems engineering tools and methods applied to wind energy RD&D

Target audience

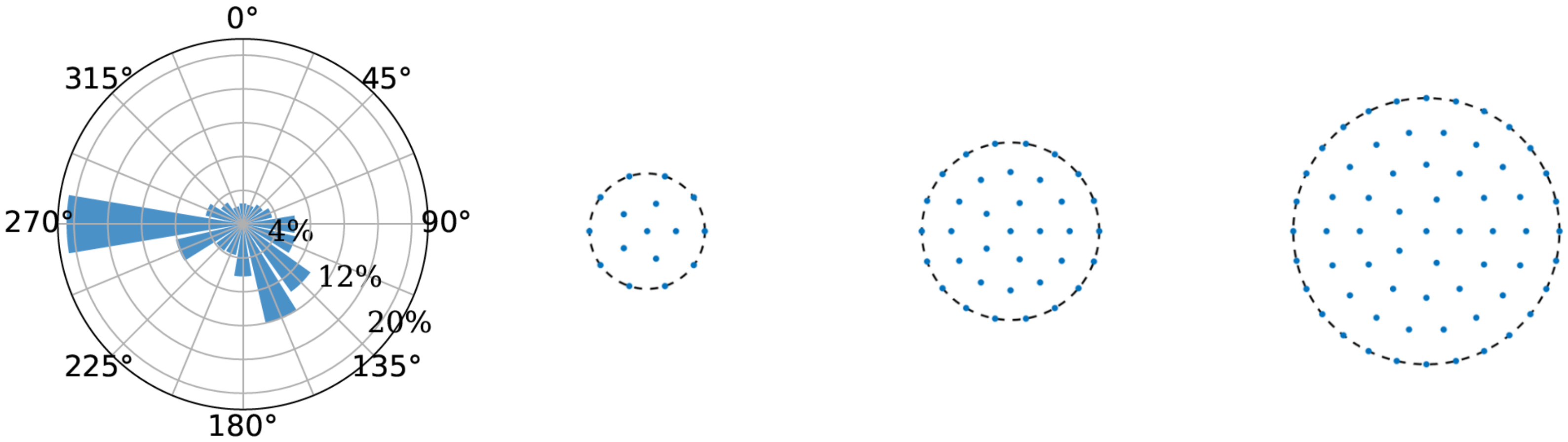
- wind turbine OEMs, developers, owner/operators, consultancies, and research community

IEA Wind Task 37

Case Studies

WP3.2 Plant MDAO case study

- **Phase 1**: participants provided with the same software workflow and asked to execute optimization for 3 different problems
- **Phase 2**: participants use their own software on high-simplified optimization problem and results compared to high-fidelity code



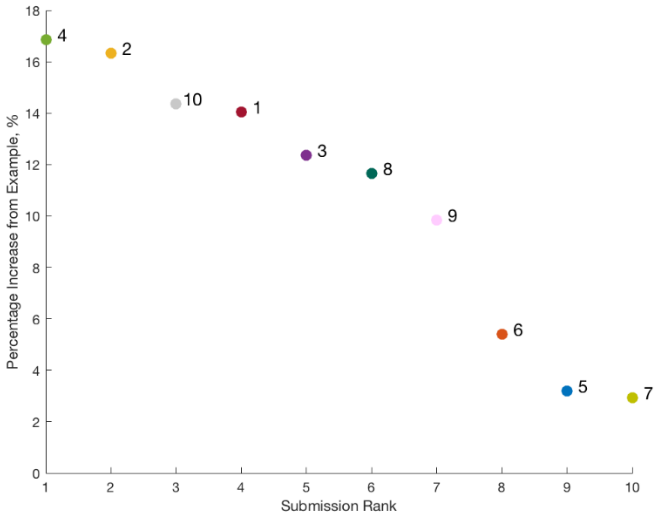
IEA Wind Task 37

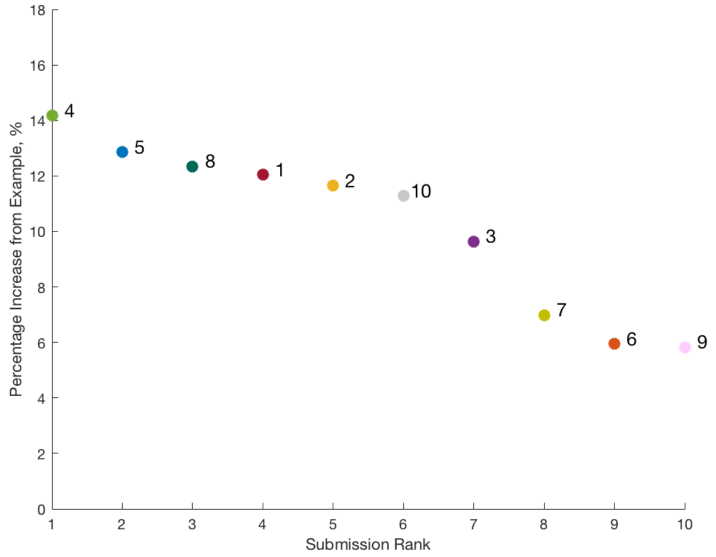
Case Studies

WP3.2 Plant MDAO case study

- Main findings: Despite use of same exact model, part 1 of the case study still had a significant spread in results (which increased with increasing turbine number)

sub#	Algorithm	Grad.
1	SNOPT	G
2	Preconditioned Sequential Quadratic Programming	G
3	Full Pseudo-Gradient Approach	GF
4	SNOPT+WEC	G
5	fmincon	G
6	Simple Particle Swarm Optimization	GF
7	Basic Genetic Algorithm	GF
8	SNOPT	G
9	Simple Pseudo-Gradient Approach	GF
10	Multistart Interior-Point	G



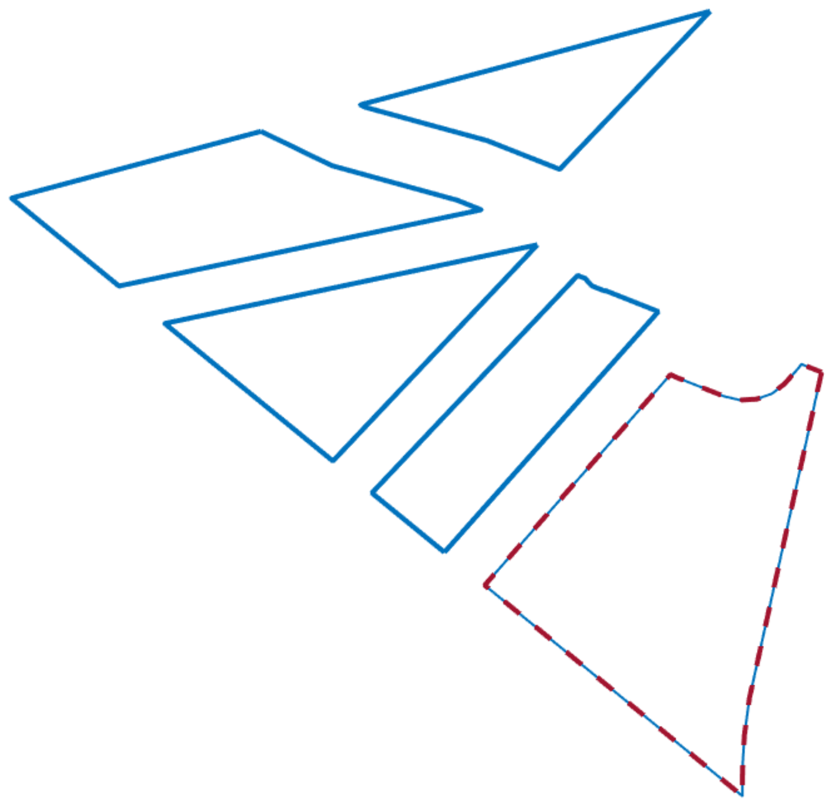


Nicholas F. Baker, Andrew P.J. Stanley, Jared J. Thomas, Andrew Ning, Katherine Dykes. "Best Practices for Wake Model and Optimization Algorithm Selection in Wind Farm Layout Optimization: Preprint.": 17 pp. 2019. https://www.nrel.gov/docs/fy19osti/72935.pdf .

IEA Wind Task 37

Case Studies 3 and 4 – In Process

Study: Realistic boundaries that gradient-based methods struggle with.



Case Study 3:

- Single region
- Non-uniform
- Concavities

Case Study 4:

- Multiple regions
- Discontinuities

https://github.com/byuflowlab/iea37-wflo-casestudies/tree/master/cs3-4

Summary and Outlook

Summary and Outlook

- We’ve come a long way!
- Still so much more to go… uncertainty, data, increased fidelity and scope, beyond LCOE and hybrids
- Join us in the journey!
  - IEA Wind Task 37 (contact me at kady@dtu.dk for info)

Thank you!

Past SE workshop materials can be found at:

https://www.nrel.gov/wind/systems-engineering-workshops.html

Other references:

https://www.nrel.gov/wind/systems-engineering-publications.html