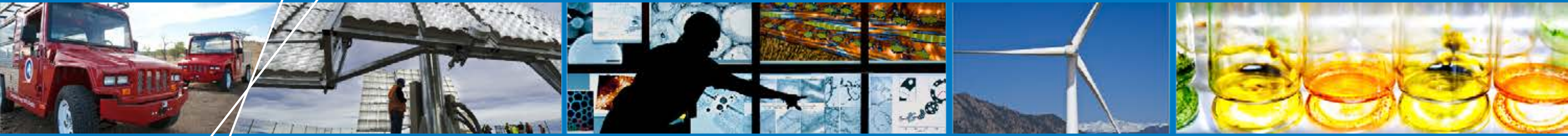
A Vision for Systems Engineering Applied to Wind Energy



Fort Felker and Katherine Dykes
National Renewable Energy Laboratory/National Wind Technology Center

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Outline

- **Why systems engineering?**
  - Wind as a complex system
- **A vision for systems engineering applied to wind energy**
- **Application of systems engineering approaches to wind energy research and development (R&D).**

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Why Systems Engineering?

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Wind Energy System Cost of Energy

- **Wind energy systems are often assessed via a cost of energy (COE) metric:**

$$\boldsymbol{COE = \frac{Financing\ Rate * (Capital\ Expenditures) + Operational\ Expenditures}{Net\ Annual\ Energy\ Production}}$$

  - Most system design parameters affect all COE contributors *and* have secondary impacts on other system design parameters, which have impacts on COE contributors, and so on…

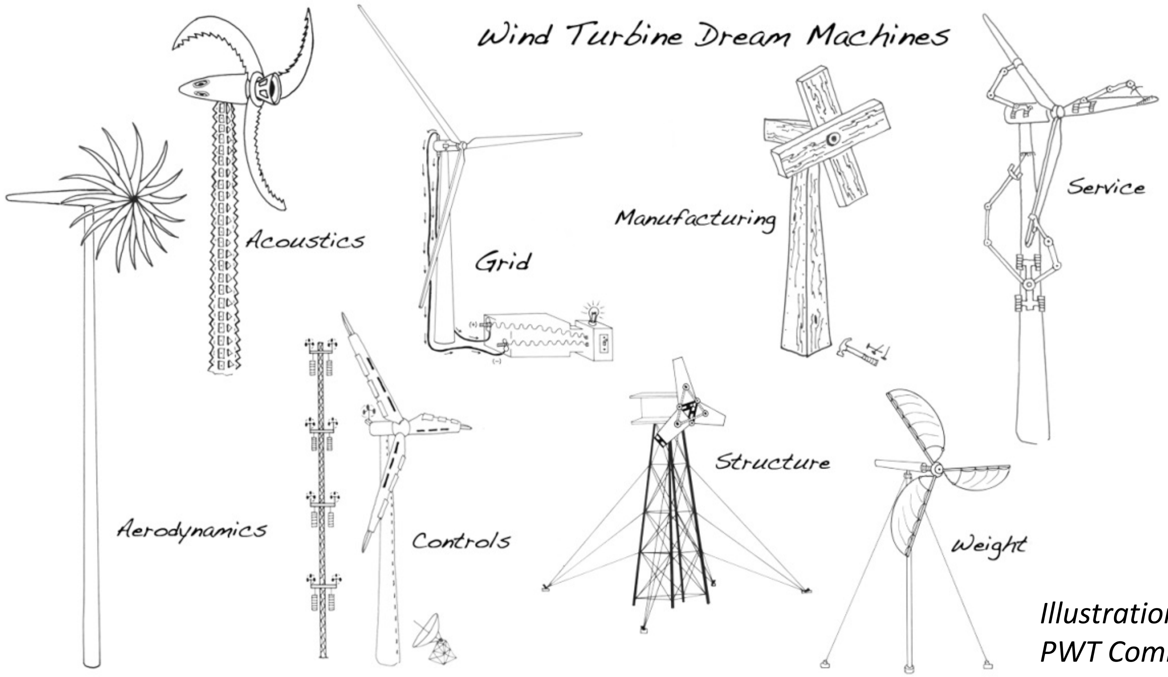
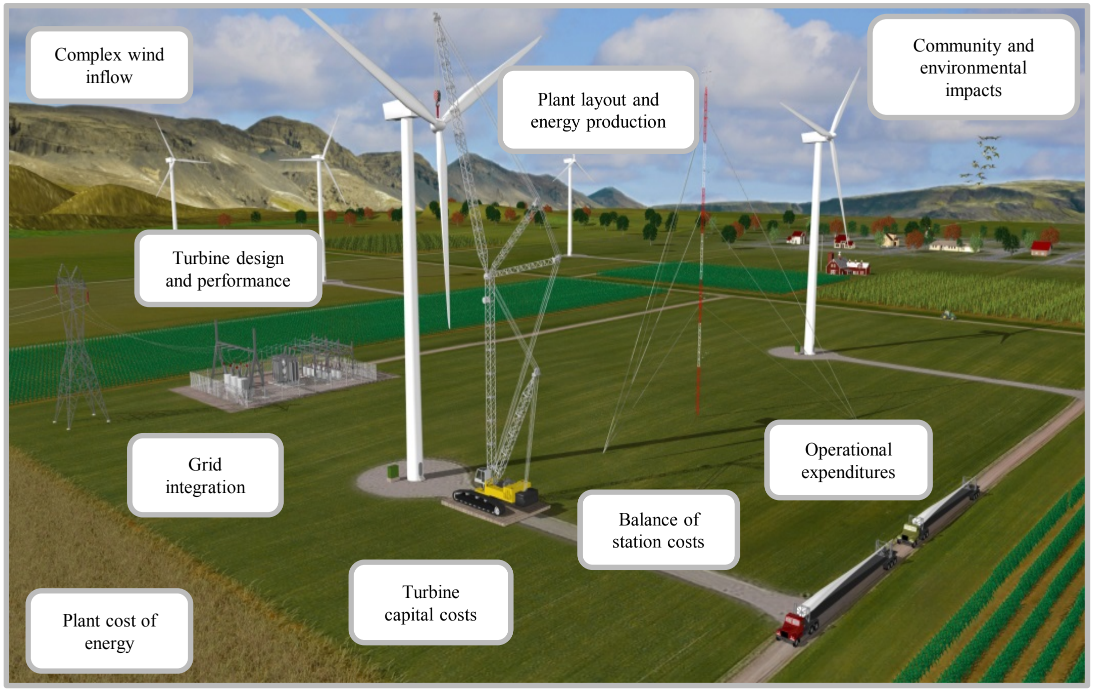


Illustration by Rick Hinrichs, PWT Communications

Wind Energy as a Complex System

- **Wind energy systems are complex and integrated**
- **There is an increasing level of awareness of the need to model the complete system to understand:**
  - The potential of design innovations and new technologies
  - The value of nonphysical or system-level design characteristics (i.e., turbine and plant-level controls).



Dykes, K.; Meadows, R. (2011). *Applications of Systems Engineering to the Research, Design, and Development of Wind Energy Systems.* NREL/TP-5000-52616. Golden, CO: National Renewable Energy Laboratory. Accessed February 12, 2015: http://www.nrel.gov/docs/fy12osti/52616.pdf

A Vision for Systems Engineering

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NREL Wind Energy Systems Engineering

The National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory (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*.

Wind Energy System Engineering

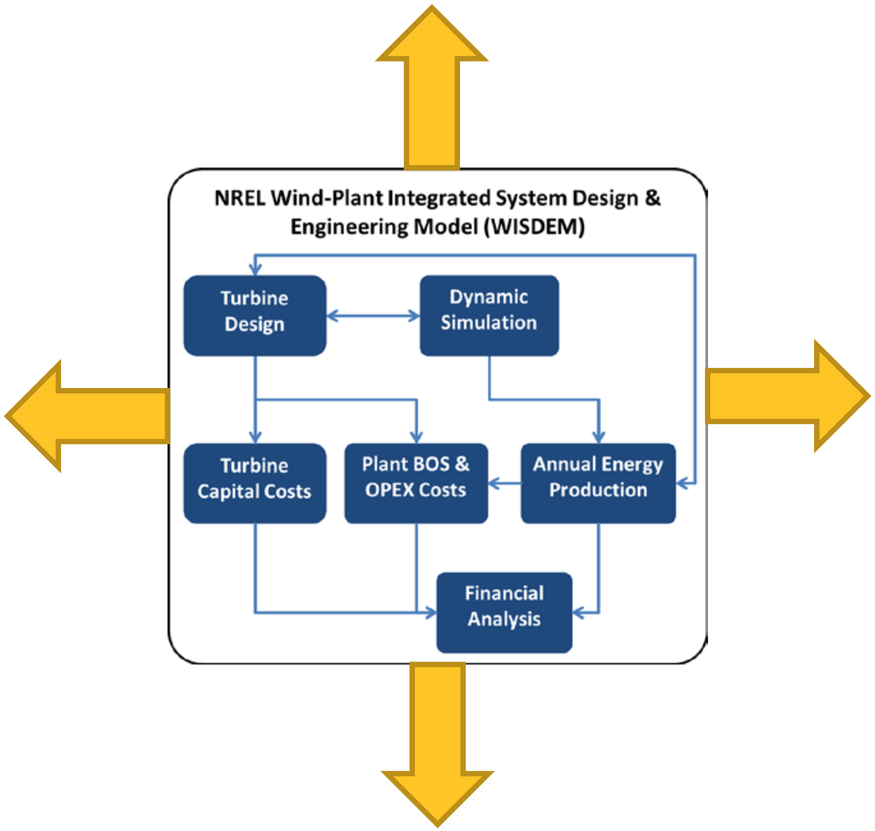
- **Key goals of a wind energy systems engineering effort:**
  - Integrate wind plant engineering performance and cost software modeling to enable full system analysis at multiple levels of fidelity
  - Apply a variety of advanced analysis methods in multidisciplinary design analysis and optimization (MDAO) and related fields
  - Develop a common platform and toolset to promote collaborative research and analysis among national laboratories, industry, and academia.

Integrated Wind System Modeling

Various uses for the system:

Innovation and technology assessment

System uncertainty and risk analysis



Scenario, trade, and concept studies

MDAO

Systems Engineering Within Atmosphere to Electrons

- **Atmosphere to Electrons (A2e)–a new approach for U.S. Department of Energy wind research**
- **Integrated multiyear plans**
- **Research will focus on the wind *plant* as a system**
- **Systems engineering will be a key component of integrating analysis and research across the full wind plant—from components to turbines to plant performance and cost.**

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Application of Systems Engineering Approaches to Wind Energy R&D

Initial Analysis Work

1. **Comparison across wind plant COE models with different fidelity levels**

2. **Investigation into impacts of tip speed on turbine design and plant COE.**

For complete publications visit: http://www.nrel.gov/wind/systems_engineering/publications.html

Reference Project

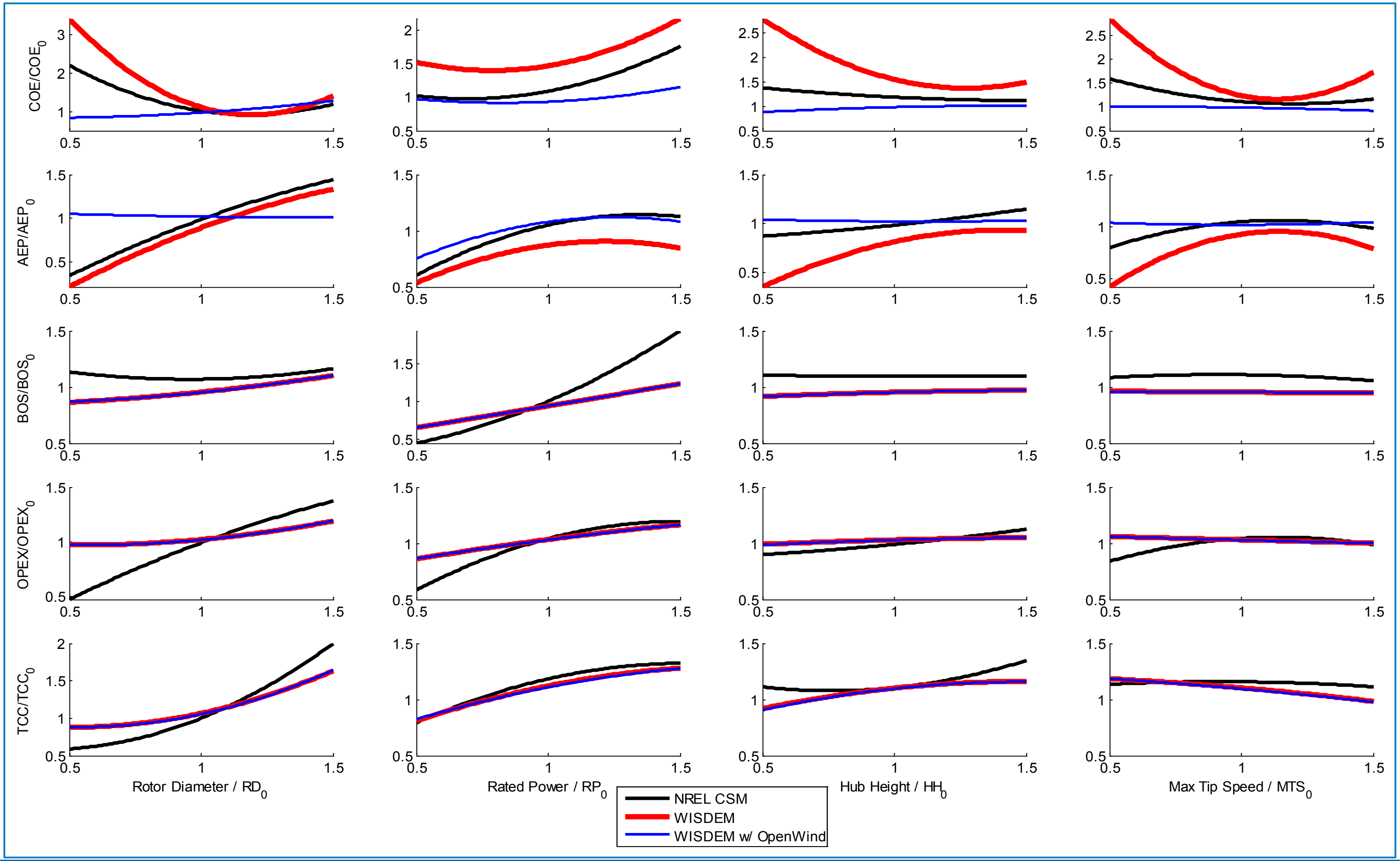
- **Any analysis requires both turbine *and* plant design inputs:**
  - Studies used NREL 5-megawatt (MW) reference turbine model and offshore reference site.

NREL 5-MW Reference Turbine Parameter Value	
Rotor:	
Rotor diameter	126 meters (m)
Rated wind speed	12.1 meters/second (m/s)
Cut-in [cut-out] wind speeds	3 m/s [25 m/s]
Maximum allowable tip speed	80 m/s
Tower:	
Hub height	90 m
Tower [monopile] lengths	60 m [30 m]
Tower-top [base] diameters	3.87 m [6.0 m]
Tower	
Drivetrain configuration	3-stage geared (epicyclic-epicyclic-parallel)
Rated power	5 MW
Gearbox ratio	97:1
Drivetrain efficiency at rated power	94.4%

Offshore Site Conditions	
Distance to shore	30 kilometers (km)
Sea depths	20 m
Wind speed at 90 m	Mean = 8.65 m/s Weibull shape = 2.1
Design wave height	10-year extreme = 6.0 m 50-year extreme = 8.0 m
Design wave period	10-year extreme = 20 seconds

Sensitivity Analysis: Comparison

- **Overall global sensitivities were increased by moving from the NREL cost and scaling model (NREL CSM) to Wind-Plant Integrated System Design and Engineering Model (WISDEM™) with SE models.**



Initial Analysis Work

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Tip Speed Investigations

- **Primary benefits of increasing tip speed expected to be reductions in drivetrain gearbox mass and cost**

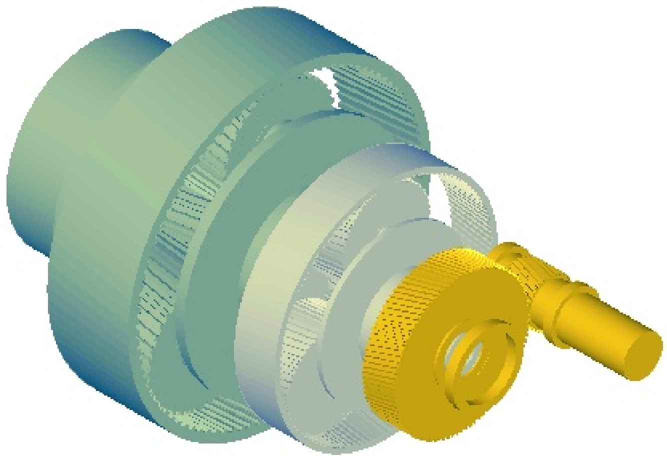
- **Two studies performed:**
  - Sequential optimization of the wind turbine followed by plant-level COE analysis
    - Higher fidelity rotor optimization
  - Integrated system-level optimization with overall COE objective.

Study 1: Sequential Optimization

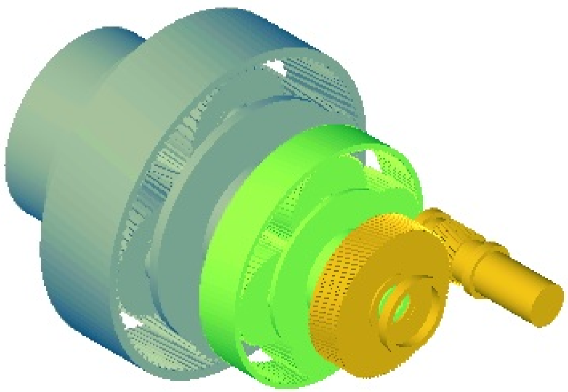
- **Collaborative effort with Sandia National Laboratories**
  - High-fidelity rotor modeling by Sandia followed by WISDEM-based drivetrain, tower design, and system cost analysis by NREL

- **COE reduction of ~1.5% mainly due to reduction in gearbox size**

- **Blade dimensioning and weight have a significant trade-off with energy production and drivetrain dimensioning and weight.**



Baseline gearbox at 80-m/s tip speed



Reduced size gearbox at 100-m/s tip speed

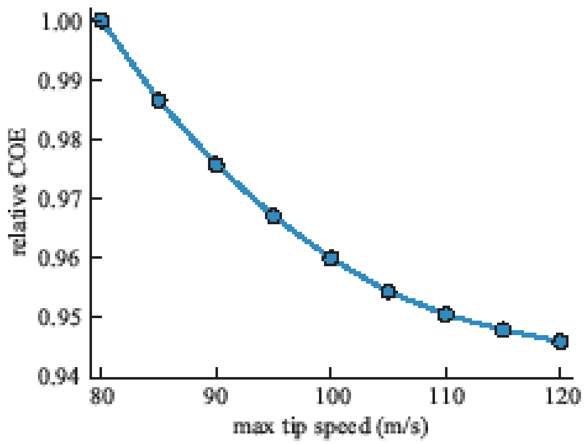
Dykes, K.; Resor, B.; Platt, A.; Guo, Y.; Ning, A.; King, R.; Parsons, T.; Petch, D.; Veers, P. (2014). *Effect of Tip-Speed Constraints on the Optimized Design of a Wind Turbine.* NREL/TP-5000-61726. Golden, CO: National Renewable Energy Laboratory. Accessed February 12, 2015: http://www.nrel.gov/docs/fy15osti/61726.pdf

Study 2: Integrated System Optimization

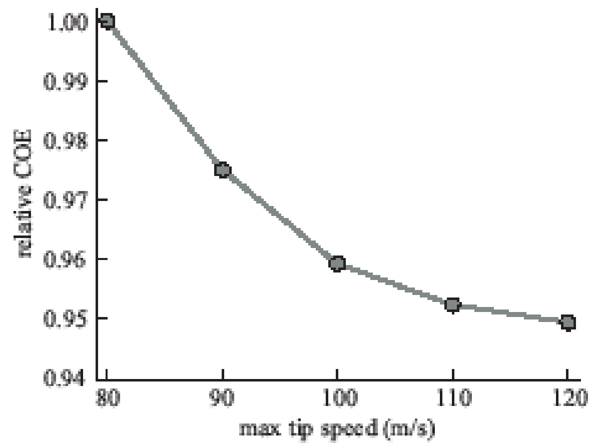
- **Rotor, drivetrain, and tower designed in simultaneous process using COE as overall system objective**
  - Used full set of models for WISDEM version 1.0

- **Analysis used lower fidelity tool but explored design space over a range of tip speeds, turbine classes, site conditions, rotor diameters, and hub heights**

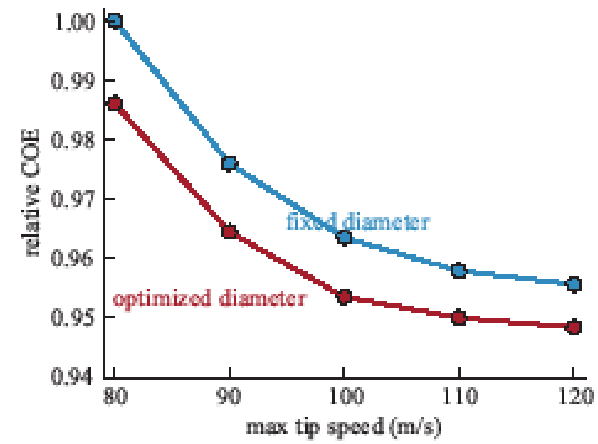
- **Cost reductions of ~5% seen for a variety of turbine/site configurations.**



a) Class IB turbine



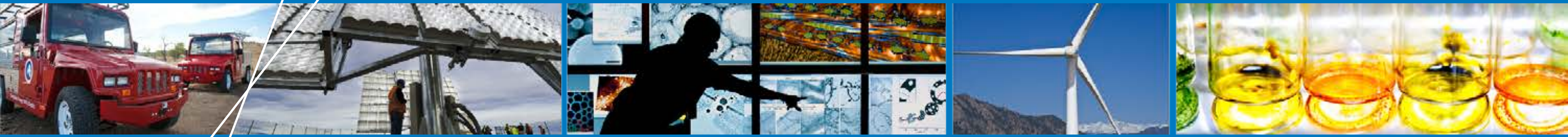
b) Class IIIB turbine



c) Class 1B variable rotor size

5% COE reduction possible at very high tip speeds of 120 m/s

Ning, A.; Dykes, K. (2014). “Understanding the Benefits and Limitations of Increasing Maximum Rotor Tip Speed for Utility-Scale Wind Turbines.” *Journal of Physics: Conference Series.* (524:1); 10 pp. http://dx.doi.org/10.1088/1742-6596/524/1/012087



Summary and Future Work

Summary

1. WISDEM is a capability for modeling integrated wind plant systems for performance and cost—with the ability to select model fidelity for different parts of the system

2. Initial work showed an improved ability to capture system interactions and perform a variety of system-level analyses such as sensitivity studies and optimization

3. WISDEM provides the ability to investigate the effects of system changes and innovations on overall COE

4. Research design (model selection, variable, and constraint specifications, and so on) becomes critical with a flexible system-level model.

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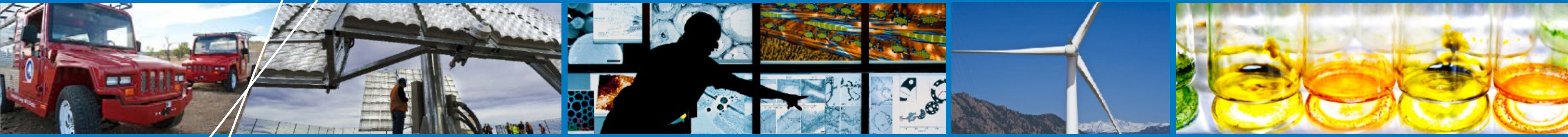
http://www.nrel.gov/wind/systems_engineering



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Contact: systems.engineering@nrel.gov