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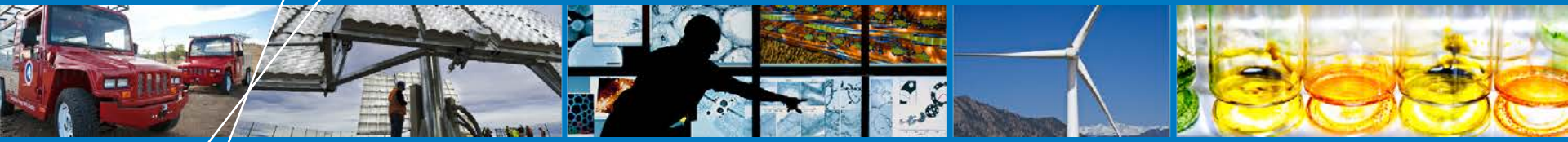
Introducing WISDEM

Integrated System Modeling for Wind Turbines and Plants



October 8th, 2014

Katherine Dykes, Peter Graf, George Scott, Andrew Ning, Ryan King, Yi Guo, Taylor Parsons, Rick Damiani, and Paul Veers

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.

Outline

- NREL NWTC Wind Energy Systems Engineering Program and Software
  - Integrated Wind Turbine and Plant Modeling
  - Software Platform
  - Initial Analysis Work
  - Summary and Future Work

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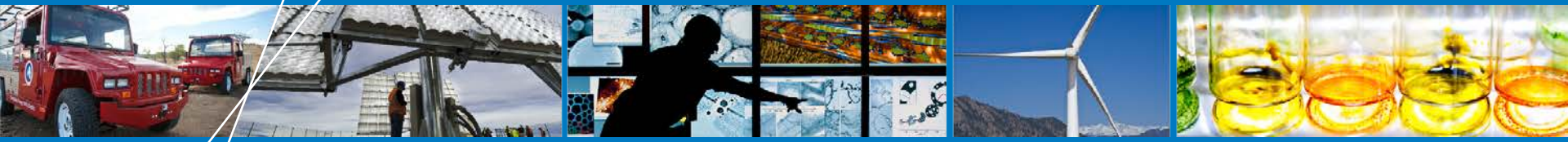

Integrated Wind Turbine and Plant Modeling

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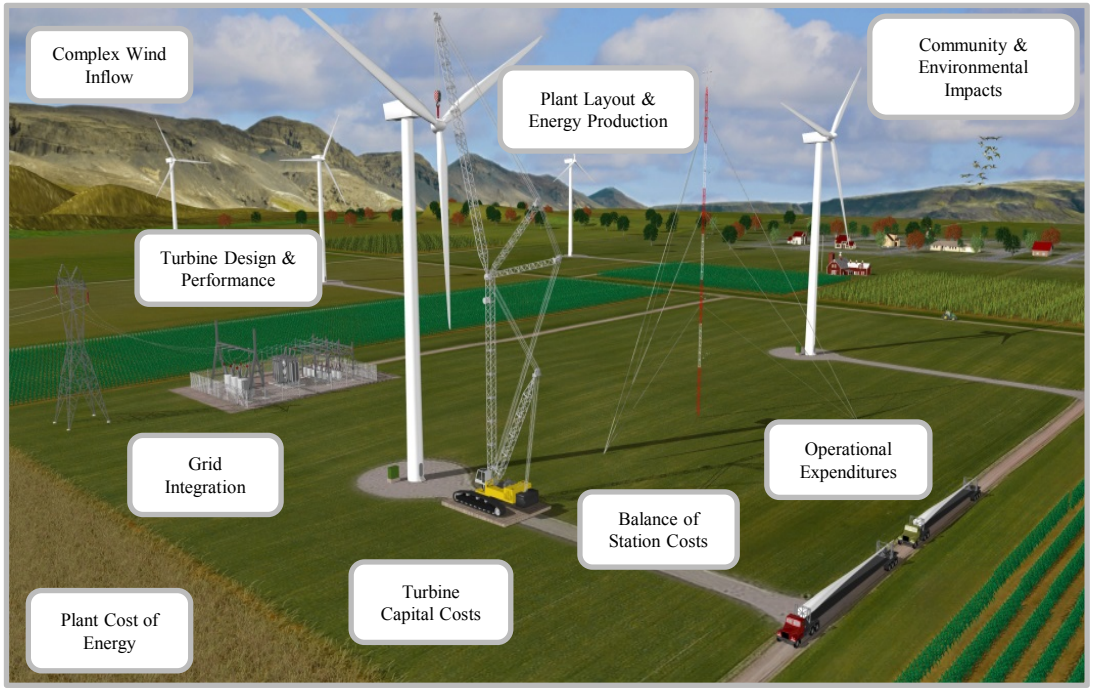
Introduction

- **Wind energy systems are complex and integrated**

- **There is an increasing level of understanding for the need to model the complete system to understand:**
  - Potential of design innovations and new technologies
  - Value of non-physical or system-level design characteristics (i.e. turbine and plant level controls)



Wind Energy System Cost of Energy

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

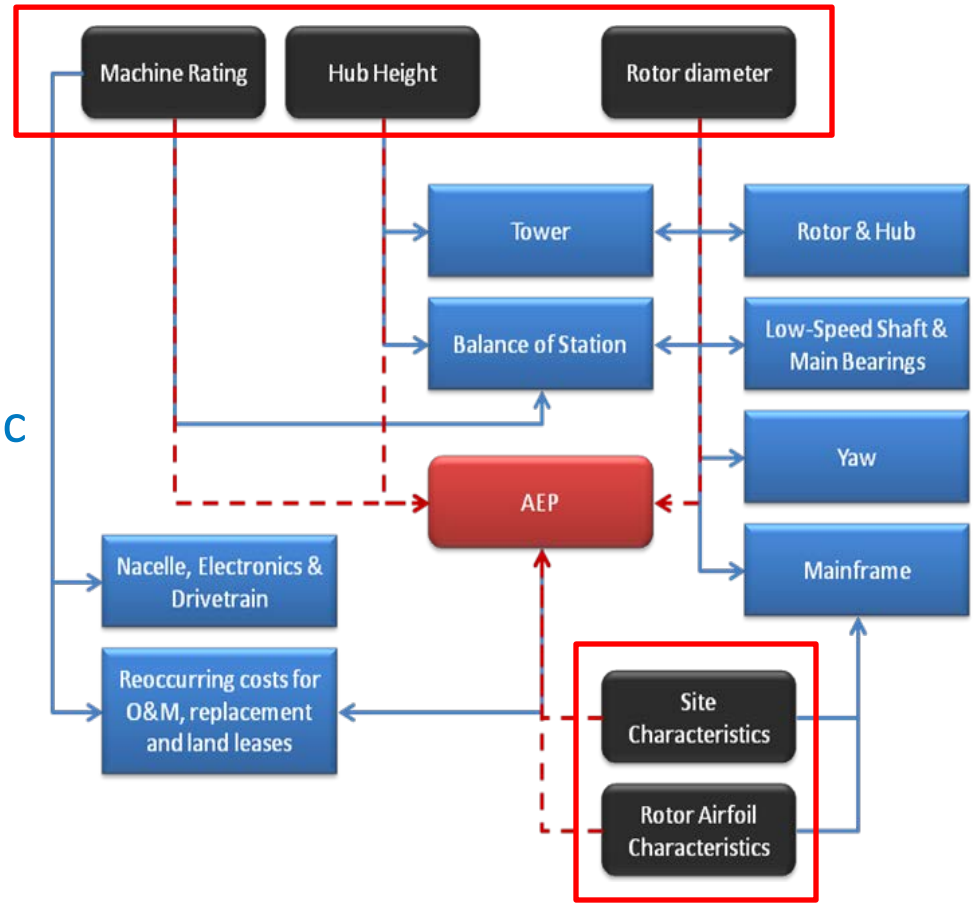
$$COE = \frac{F * (CAPEX) + OPEX}{AEP}$$

  - Where COE is cost of energy, CAPEX is the sum of BOS is Balance of Station cost, TCC is Turbine Capital Cost (for full project), F is the financing rate to annualize investment costs, OPEX are the annual operating expenses and AEP is the net annual energy production

Determining Wind Cost of Energy

- **Current "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

Current structure of cost model



NREL Wind Energy System Engineering

The National Wind Technology Center (NWTC) 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*.

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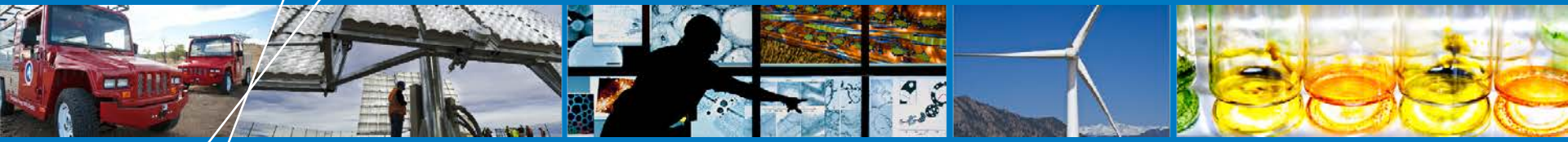

Software Platform

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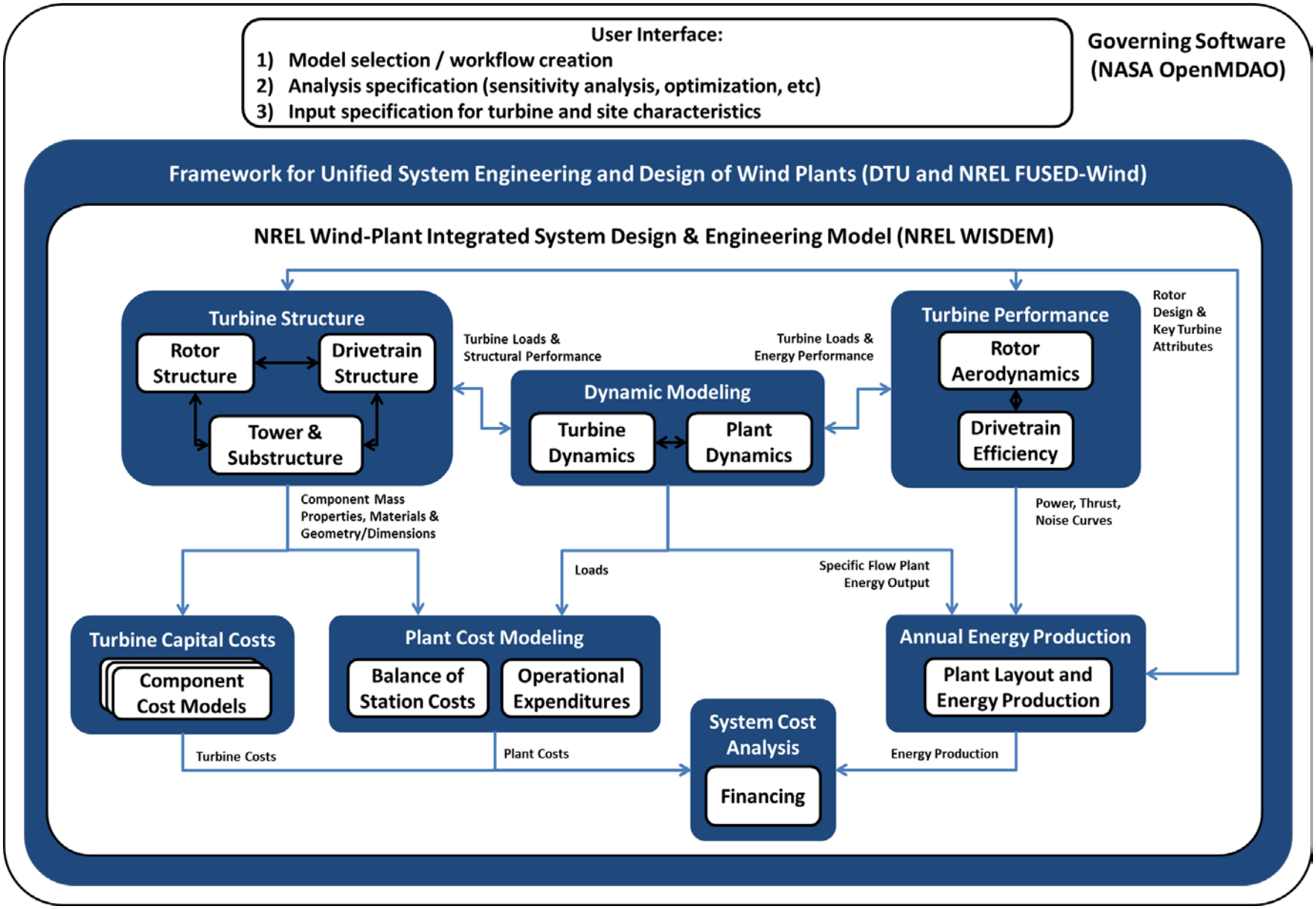
NREL Wind Energy System Engineering

- **NREL has a Systems Engineering effort to develop, maintain, and apply a software platform to:**
  - Integrate wind plant engineering performance and cost software modeling to enable full system analysis.
  - Apply of 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.

Systems Engineering Software Framework



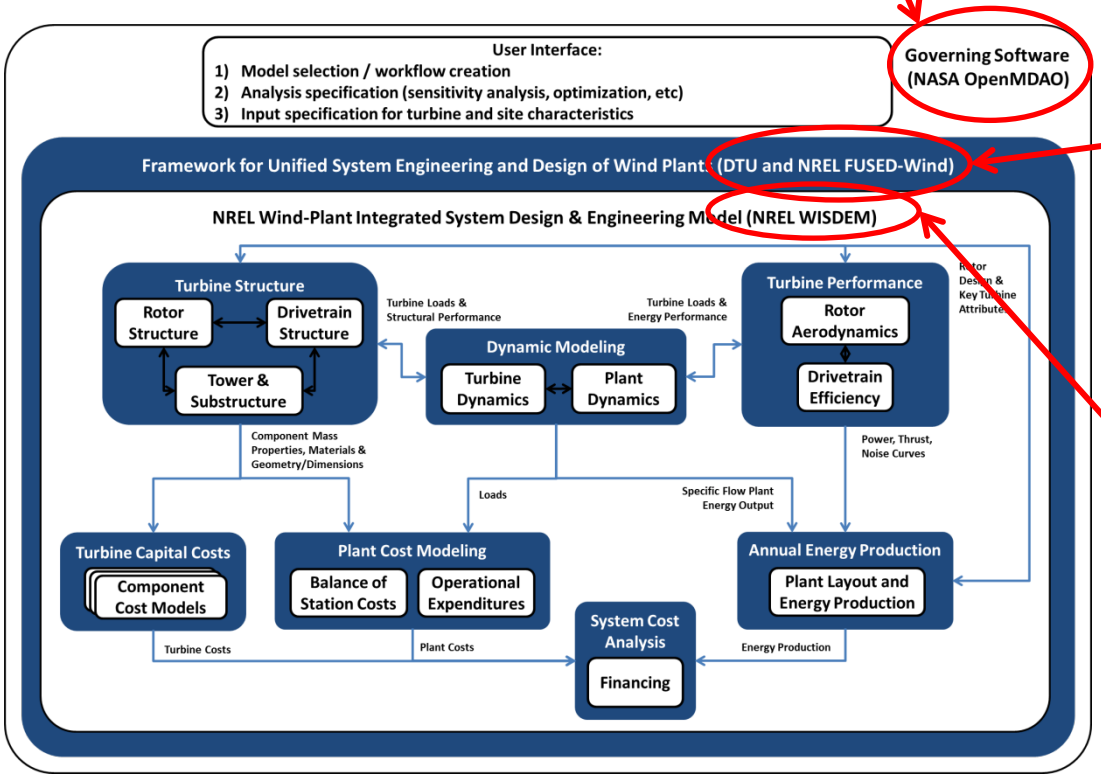
Systems Engineering Software Framework

OpenMDAO:

- Work flows integrate models together in structured ways (use of NASA's OpenMDAO software)
- Easily reconfigured (model selection and analysis structure)

FUSED-Wind:

- Support software for structured interface of wind turbine and plant modeling tools into OpenMDAO
- Allows interchange of models, sharing of common turbine and plant input descriptions



NREL WISDEM:

- Collection of NREL engineering and cost turbine and plant analysis tools integrated into FUSED-Wind and OpenMDAO
- Full wind turbine and plant model set planned for release

Systems Engineering Software Framework

- **FUSED-Wind (http://fusedwind.org)**
  - Independently programmed collaboration between DTU Wind Energy and NREL (with efforts to engage Sandia National Laboratories and other groups as well)
  - Focused on standardizing interfaces between models as well as creating common representations of turbines and plants for various model archetypes (i.e. aeroelastic codes, structural design codes, etc)

Systems Engineering Software Framework

- Integration of models into FUSED-Wind based WISDEM includes several areas:
  1. Turbine component structure and cost models
  2. Plant energy production and cost models
- For each area, multiple levels of fidelity possible

Rotor Aero	Rotor Structure	Nacelle Structure	Tower Structure	Turbine Costs	Plant BOS Costs	Plant OPEX	Plant Energy Production	Plant Finance
NREL CSM				NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM
RotorSE	RotorSE	NacelleSE (with DriveSE option)	TowerSE	Turbine_ CostsSE	NREL Onshore / Offshore BOS	NREL OPEX / ECN Offshore O&M Model	AWS Truepower openWind	NREL System Advisor Model

NREL WISDEM Current Status

- **Version 1.0 Beta-Relase:**
  - Physics-based design and sizing tools for a wind turbine (RotorSE, DriveSE, TowerSE)
  - Empirical cost tools for wind turbine and plant (Turbine_CostsSE, Plant_CostsSE, Plant_FinanceSE)
  - Basic energy production models (Plant_EnergySE) as well as a wrapper for AWS Truepower openWind
  - Basic wrapper for FAST v. 7.0 (AeroelasticSE)

Turbine Level Models

- **Turbine models for design and sizing of major wind turbine components:**
  - RotorSE
  - DriveSE/DriveWPACT
  - TowerSE
- **Wrapper for FAST aeroelastic code:**
  - AeroelasticSE

RotorSE (with CCBlade, PreComp and pBEAM)

- **Strengths:**
  - Guaranteed convergence in aerodynamics
  - Flexibility to plug in additional aerodynamic codes
  - Analytic gradients for all aerodynamic methods
  - Also includes classical laminate theory and beam FEM
- **Current limitations**
  - Doesn't handle large deflections
  - Aero/structural coupling still in development
  - Only cursory assessment of fatigue
  - Ability to map detailed layup description to cross-sectional properties

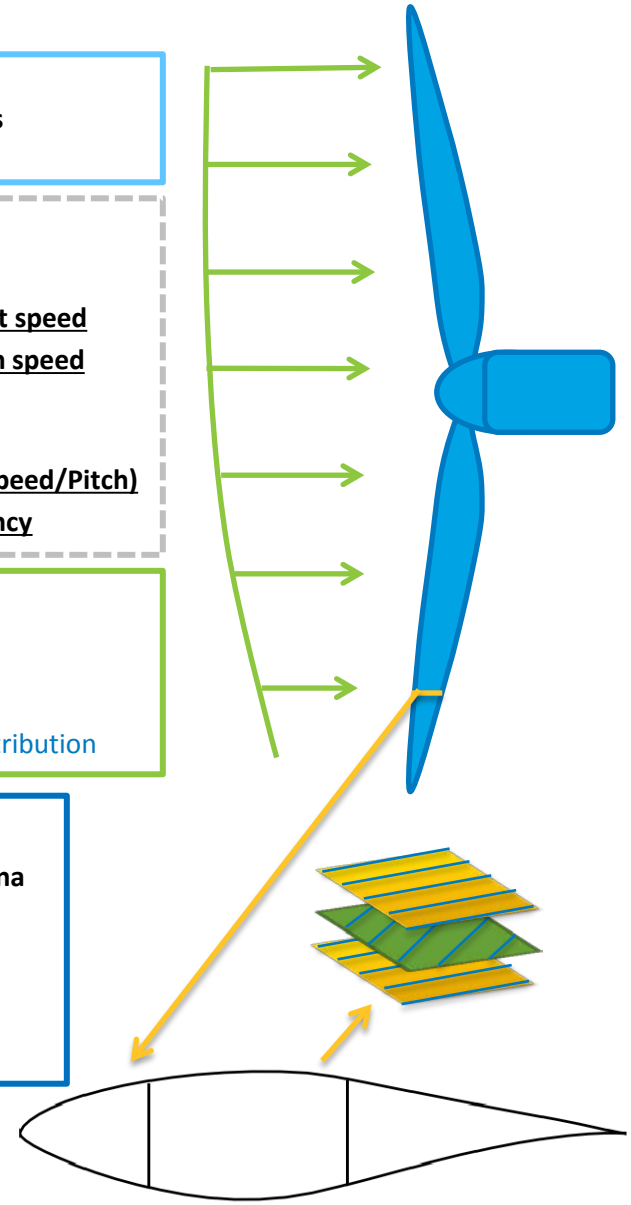
<<< INPUTS

ROTOR INPUTS
- Number of blades
- Precone, tilt

TURBINE INPUTS
- Hub Height
- Cut-in and cut-out speed
- Min/max rotation speed
- Rated power
- Machine type (Fixed/Variable Speed/Pitch)
- Drivetrain Efficiency

ATMOSPHERE
- Density
- Viscosity
- Shear exponent
- Wind speed distribution

LAMINATE STACK
- Sequence of lamina
- Number of plies
- Ply thickness
- Ply orientation
- Ply material



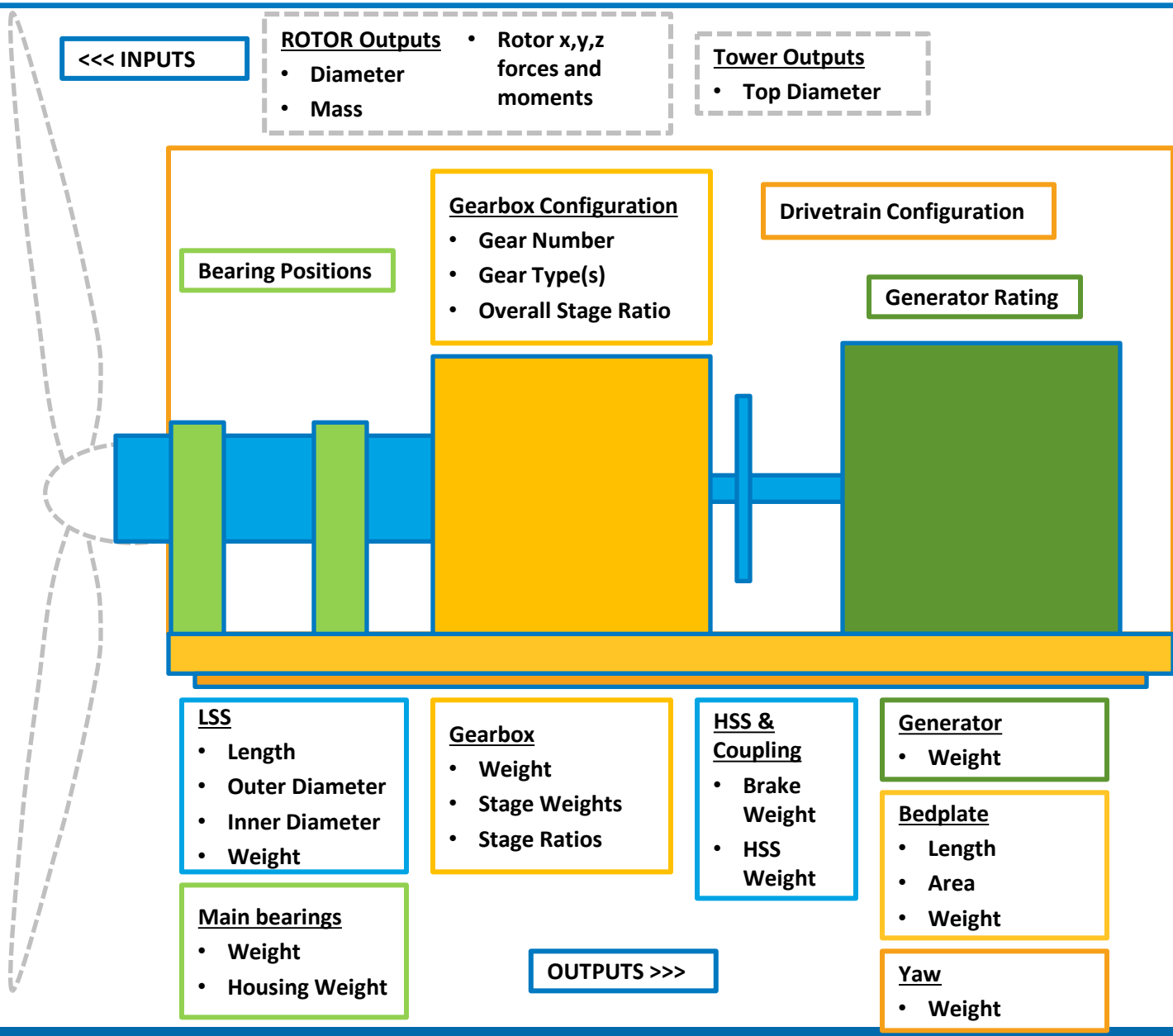
OUTPUTS >>>

ROTOR STRUCTURE & PERFORMANCE
- Blade mass and moments of inertia
- Cost
- Power curve
- Turbine AEP
- Hub loads
- Sound power level
- Natural frequencies
- Blade displacements
- Panel buckling loads
- Axial and shear stress

AIRFOIL
- Radial location, chord, twist
- Profile shape
- Lift curves and drag polars (Parameterized by Re and t/c)
- Web locations

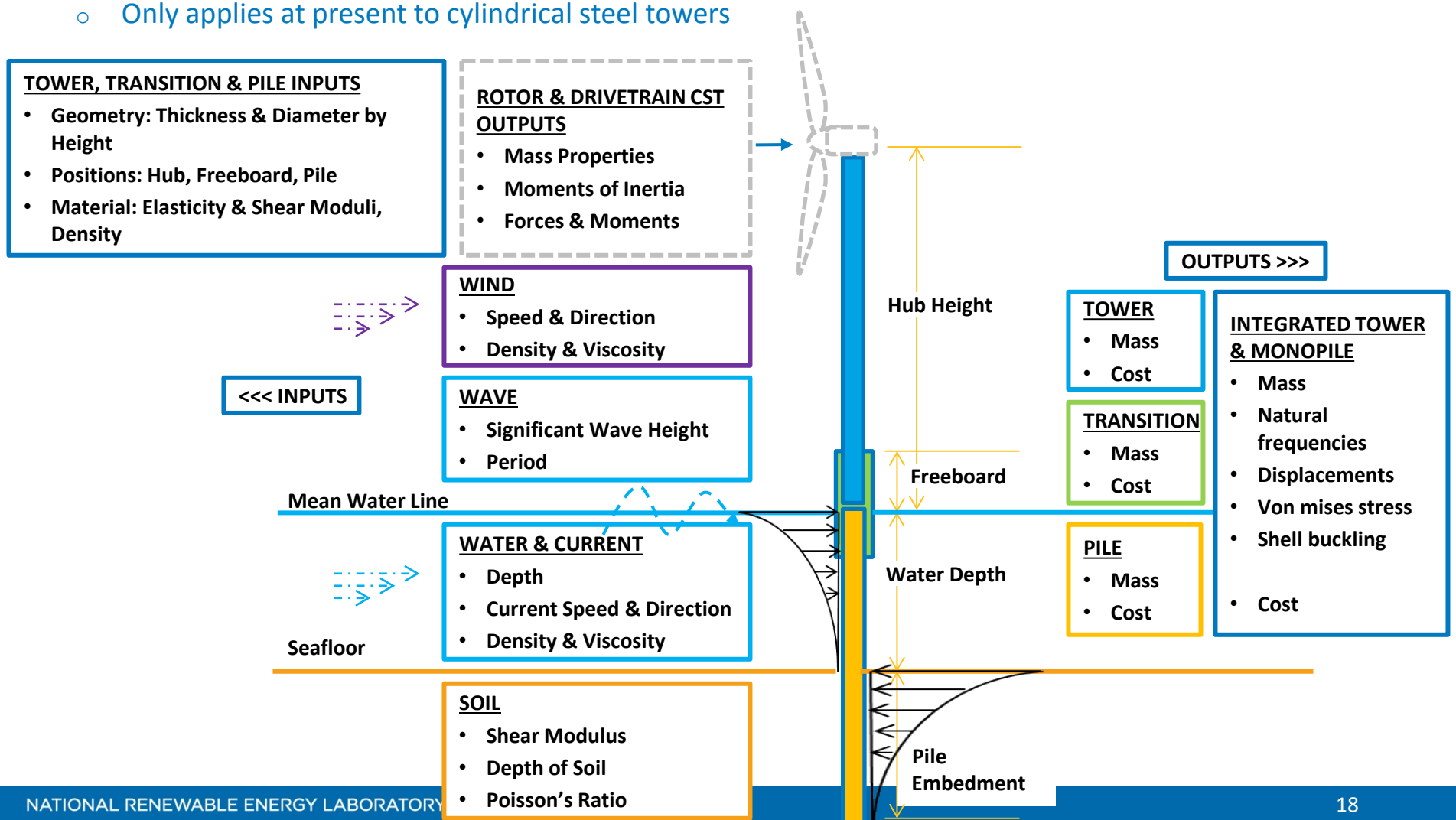
DriveSE / DriveWPACT

- **Strengths:**
  - Implicit sizing of drivetrain components for different configurations based on rotor loads
  - Sizing of low-speed shaft and main bearings based on both extreme and fatigue loads
- **Current limitations:**
  - Handling non-traditional configurations for all main drivetrain components
  - Physics-based models for electrical components including generator



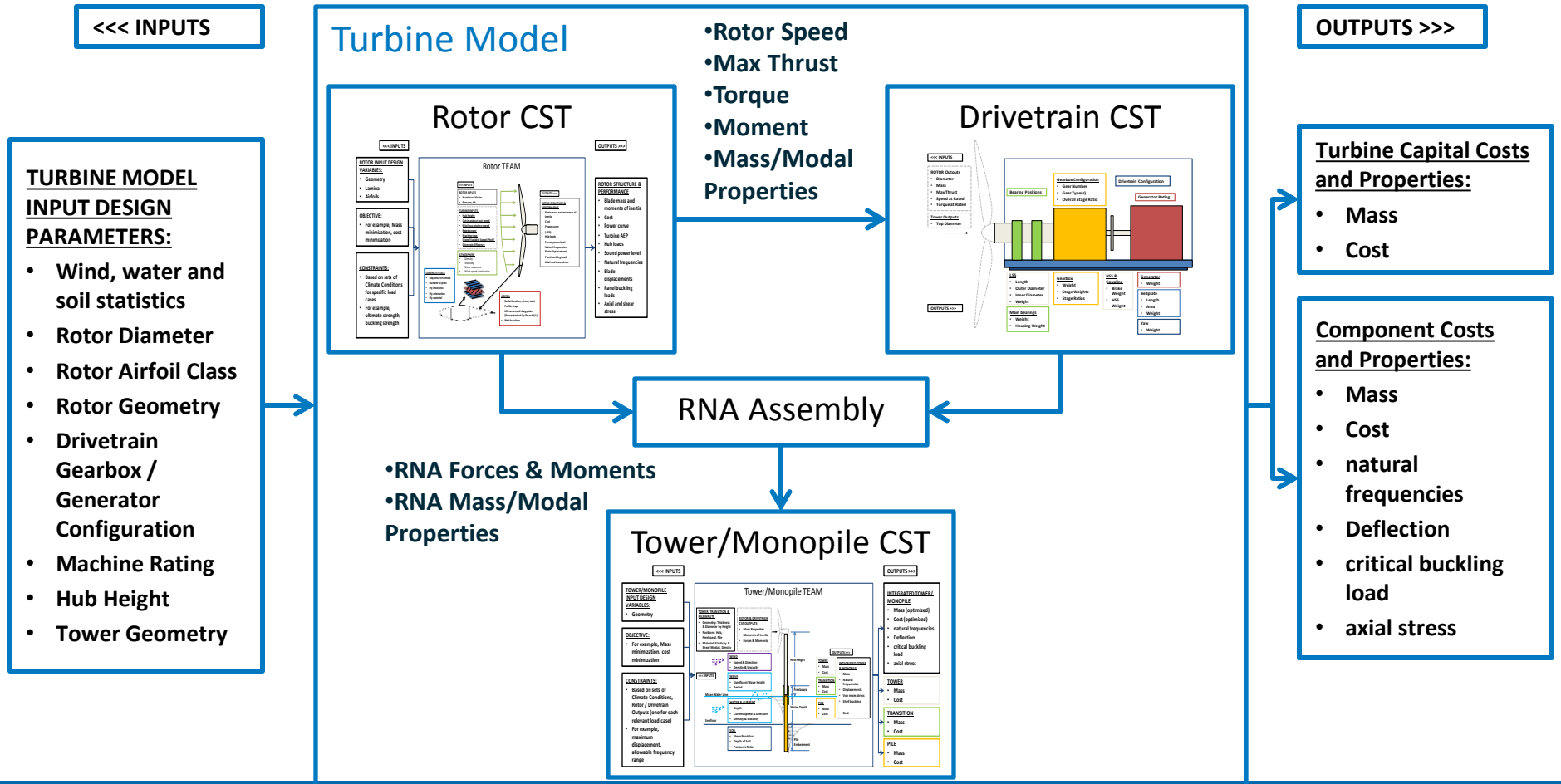
TowerSE (with pBEAM)

- **Strengths:**
  - Flexible in allowing arbitrary wind/wave loading for different boundary conditions & fast beam FEM appropriate for steel towers
- **Limitations:**
  - Only applies at present to cylindrical steel towers



Turbine Assembly and Turbine_CostsSE

- Model integrates components and passes loads from rotor to drivetrain to tower
- System level optimization of turbine possible for a number of different configurations
- Costs calculated based on component mass-to-cost relationships



AeroelasticSE wrapper for FAST

- **Two approaches for wrapping FAST:**
  - Template-based (update using key word search)
  - Full "Variable Tree" Representation of FAST turbine
- **Both interface to case analyzer capability developed in FUSED-Wind**
  - Run standard IEC cases
  - Run loads analysis with various statistical distributions for inputs using uncertainty analysis methods

Plant Level Models

- **Plant models aggregate all system aspects to find overall cost of energy**
  - Turbine Capital Costs: Turbine_CostsSE
  - Annual Energy Production: Plant_EnergySE
  - Balance of Station: Plant_CostsSE
  - Operations & Maintenance: Plant_CostsSE
  - Finance: Plant_FinanceSE

Plant_EnergySE (with openWind)

- **Basic energy production model based on wind resource statistics and loss inputs**
- **Wrapper for AWS Truepower openWind allows for flow model with wake effects**
  - Updated wrapper for current openWind Enterprise version to be released in 2014

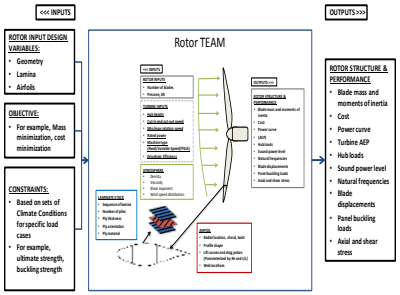
<<< INPUTS

ROTOR MODEL INPUT DESIGN PARAMETERS

- **Wind Statistics**
- **Rotor Diameter**
- **Rotor Airfoil Class**
- **Rotor Geometry**
- **Drivetrain Gearbox / Generator Configuration**
- **Machine Rating**
- **Hub Height**
- **Drivetrain Efficiency**

Annual Energy Production Model

Rotor CST

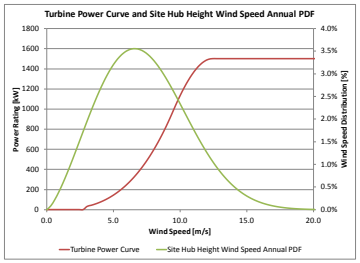


•Power Curve

O&M Model

•Availability

Energy Production Model



x Availability

x Plant Losses

OUTPUTS >>>

Energy Production:

- **AEP**
- **Plant Capacity Factor**

Plant_CostsSE BOS (with new NREL Models)

- Basic balance of station models for land-based and offshore wind plants available from NREL Cost and Scaling Model
- New land-based model based on larger set of design parameters and current wind plant cost data expected for release in the fall of 2014
- New offshore model based on larger set of design parameters and current wind plant cost data expected for release in 2015

<<< INPUTS

BOS MODEL INPUTS:

- Wind, water, soil characteristics
- Transportation modes and costs
- Grid interconnection and cabling inputs

TURBINE MODEL OUTPUTS:

- Component Dimensions & Weights

Balance of Station Model

OUTPUTS >>>

BOS MODEL OUTPUTS:

- Permits & Engineering Costs
- Transportation & Staging Costs
- Assembly & Installation Costs
- Grid Interconnection Costs

Plant_CostsSE OPEX (with ECN OPEX model)

- Basic operational expenditure models for land-based and offshore wind plants available from NREL Cost and Scaling Model
- New land-based model based on larger set of design parameters and updated wind plant cost data expected for release in the fall of 2014
- Wrapper available for ECN offshore operational expenditures model

<<< INPUTS

O&M MODEL INPUTS:

- Wind, water, soil characteristics
- Transportation modes and costs
- Grid interconnection and cabling inputs
- Component Failure Rates

TURBINE MODEL OUTPUTS:

- Component Dimensions, Weights & Costs

Operations & Maintenance Model

OUTPUTS >>>

O&M MODEL OUTPUTS:

- Land lease costs
- Annual Maintenance & Repair Costs
- Annual Replacement Costs

Plant_FinanceSE (with SAM finance module)

- **Basic financial models for land-based and offshore wind plants available from NREL Cost and Scaling Model**
- **Detailed wind plant cash flow model available via interface to System Advisor Model (SAM) cash flow model expected for release 2014/2015**

<<< INPUTS

CASH FLOW MODEL INPUTS:

- Electricity Price
- Debt / equity ratio
- Debt Interest Rate
- Equity Rate
- Tax Rate
- Incentives
- Project Timeline

OTHER MODEL OUTPUTS:

- Turbine Capital Costs
- Balance of Station Costs
- Annual Energy Production
- Operations & Maintenance Costs

Cash Flow Finance Model

OUTPUTS >>>

CASH FLOW MODEL OUTPUTS:

- Project Net Present Value (NPV)
- Project Internal Rate of Return
- Project Pay Back Period
- Project (Levelized) Cost of Energy

Software Distribution and Maintenance

Software access via new website:

http://nwtc.nrel.gov

Ongoing/Future WISDEM Model Development

- **Planned model fidelity build-out over time with coordinated efforts through FUSED-Wind activities**
- **Current model development**
  - Support Structure Design
    - JacketSE
    - Floating platform design
  - Plant Energy Production
    - FLORIS_SE
    - WindSE
  - Plant Costs
    - NREL BOS models
    - NREL OPEX models
  - Plant Finance
    - SAM wrapper

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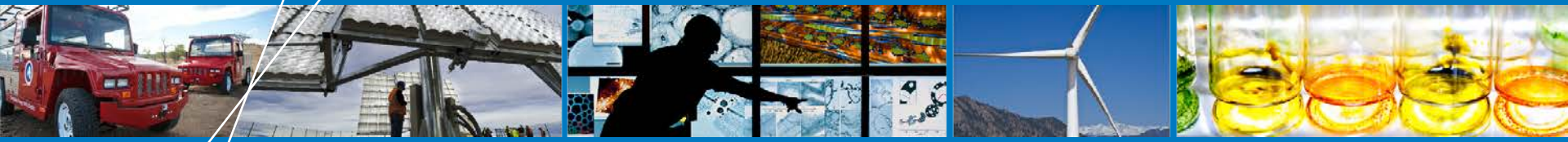

Initial Analysis Work

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Initial Analysis Work

1. **Comparison across multi-fidelity modeling of wind plant cost of energy**

2. **Investigation of impacts of tip speed on turbine design and plant cost of energy**

3. **Uncertainty analysis of wind turbine loads**

4. **Investigation of joint turbine-plant design**

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

Reference Project

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

NREL 5 MW Reference Turbine Parameter Value	
Rotor:	
Rotor Diameter	126 m
Rated Wind Speed	12.1 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 Length / Monopile Length	60 m / 30 m
Tower Top / Base Diameters	3.87 m / 6.0 m
Tower	
Drivetrain Configuration	3-stage Geared (EEP)
Rated Power	5 MW
Gearbox Ratio	97:1
Drivetrain Efficiency at Rated Power	94.4%

Offshore Site Conditions	
Distance to Shore	30 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 s

Model Comparisons

- **Reference turbine and plant analyzed via three different model configurations**
  - Uses full set of version 1.0 WISDEM models
- **Global sensitivity performed on key turbine design parameters (also key NREL CSM inputs):**
  - rotor diameter
  - hub height
  - rated power
  - maximum allowable tip speed
- **In all cases, no internal optimization permitted – beyond study scope**

Model Comparison via Reference Project

- **Baseline COE analysis**

	NREL CSM	NREL w/ TurbineSE & Plant_CostsSE Models	NREL w/ TurbineSE, Plant_CostsSE Models & OpenWind
LCOE ($/kWh)	$0.11	$0.20	$0.20
AEP (kWh/turbine/year)	18,113,563	18,079,737	18,667,378
Turbine Cost ($/kW)	$1,190	$1,848	$1,848
BOS Costs ($/kW)	$1,533	$3,505	$3,505
OPEX ($/kW/year)	$100	$121	$121

  - Overall cost of energy higher using new model set:
    - Turbine costs are significantly higher – calibrated to data for current turbine technology
    - Balance of Station costs of NREL CSM were known to be very low – new model (based on empirical data) estimates BOS costs as much higher
  - COE for new models are closer to industry-reported offshore wind costs for European projects

Sensitivity Analysis: Comparison

- **Sobol indices show generally more interaction between variables in case 2 and 3 (using new WISDEM models) as compared to case 1 (using NREL CSM)**

	COE		AEP		BOS		OPEX		TCC		Turbine Mass	
	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect
rotor diameter	**0.30**	**0.55**	**0.66**	**0.70**	0.00	0.00	**0.56**	**0.60**	0.20	**0.62**	**0.85**	**0.86**
rated power	**0.24**	**0.36**	0.17	**0.27**	**1.00**	**1.00**	**0.30**	**0.39**	0.15	**0.24**	0.00	0.01
hub height	0.02	0.05	0.05	0.05	0.00	0.00	0.04	0.04	0.07	**0.29**	0.14	0.14
maximum tip speed	0.12	0.22	0.04	0.05	0.00	0.00	0.03	0.04	0.07	**0.45**	0.00	0.01

Sobol Indices Case 1

	COE		AEP		BOS		OPEX		TCC		Turbine Mass	
	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect
rotor diameter	**0.54**	**0.66**	**0.65**	**0.76**	**0.09**	**0.22**	**0.09**	**0.39**	**0.20**	**0.62**	**0.13**	**0.65**
rated power	**0.06**	**0.08**	**0.03**	**0.13**	**0.75**	**0.92**	**0.49**	**0.62**	**0.15**	**0.24**	**0.02**	**0.09**
hub height	**0.01**	**0.04**	**0.00**	**0.09**	**0.01**	**0.13**	**0.05**	**0.23**	**0.07**	**0.29**	**0.19**	**0.47**
maximum tip speed	**0.26**	**0.35**	**0.13**	**0.16**	**0.00**	**0.02**	**0.03**	**0.25**	**0.07**	**0.45**	**0.06**	**0.41**

Sobol Indices Case 2

http://arc.aiaa.org/doi/abs/10.2514/6.2014-1087

Initial Analysis Work

1. Comparison across multi-fidelity modeling of wind plant cost of energy

2. Investigation of impacts of tip speed on turbine design and plant cost of energy

3. Uncertainty analysis of wind turbine loads

4. Investigation of joint turbine-plant design

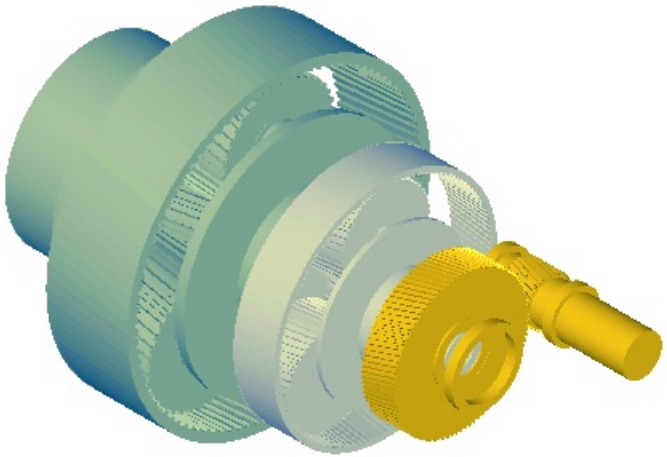
Tip Speed Investigations

- **Increasing tip speed benefits expected largely in reduction of drivetrain**

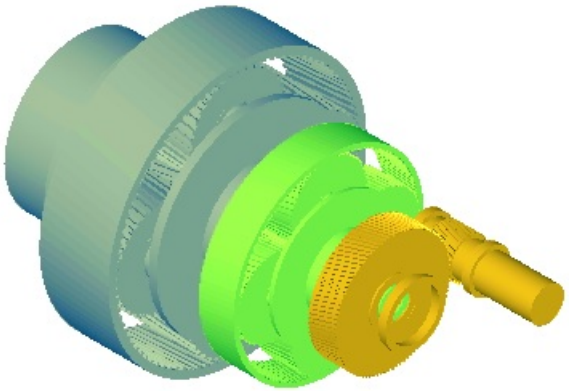
- **Two studies performed:**
  - Sequential optimization of the wind turbine followed by plant level cost of energy analysis
    - Higher fidelity rotor optimization
  - Integrated system level optimization with overall cost of energy objective

Study 1: Sequential Optimization

- **Collaborative effort with Sandia National Laboratories**
  - High fidelity rotor modeling by Sandia for rotor followed by WISDEM based drivetrain and tower design and system cost analysis by NREL
- **Cost of energy reduction of ~1.5% mainly due to reduction in gearbox size**
- **Significant trade-offs in blade dimensioning and weight compared to energy production and drivetrain dimensioning**



Baseline gearbox at 80 m/s tip speed



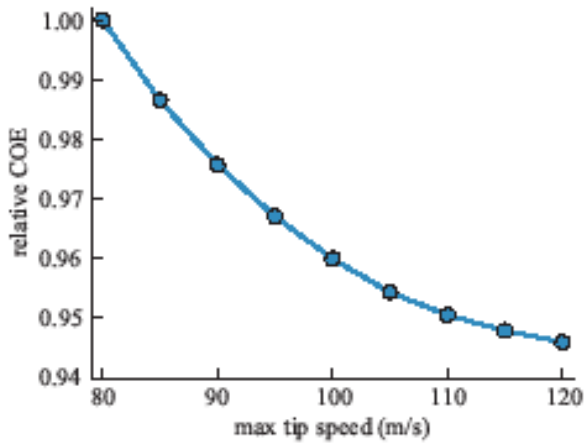
Reduced size gearbox at 100 m/s tip speed

Study 2: Integrated System Optimization

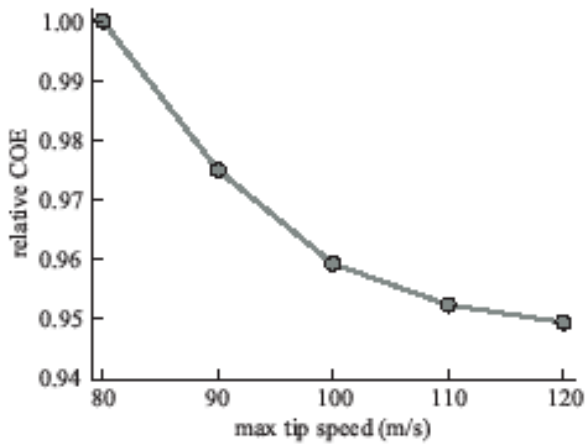
- **Rotor, drivetrain, and tower designed in simultaneous process using cost of energy as overall system objective**
  - Uses full set of models for WISDEM version 1.0

- **Analysis uses lower fidelity tool but explores design space over a range of tip speeds, turbine class and site conditions, and variations in rotor diameter and hub height**

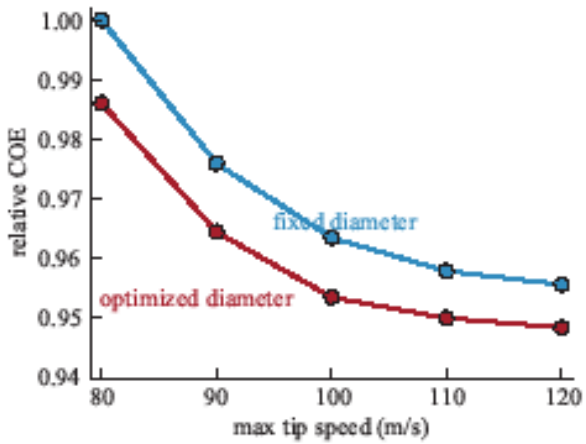
- **Cost reductions of ~5% seen for a variety of turbine/site configurations**



a) Class IB turbine



b) Class IIIB turbine



c) Class 1B variable rotor size

5% cost of energy reduction possible moving to very high tip speeds of 120 m/s

http://iopscience.iop.org/1742-6596/524/1/012087/

Initial Analysis Work

1. Comparison across multi-fidelity modeling of wind plant cost of energy

2. Investigation of impacts of tip speed on turbine design and plant cost of energy

3. Uncertainty analysis of wind turbine loads

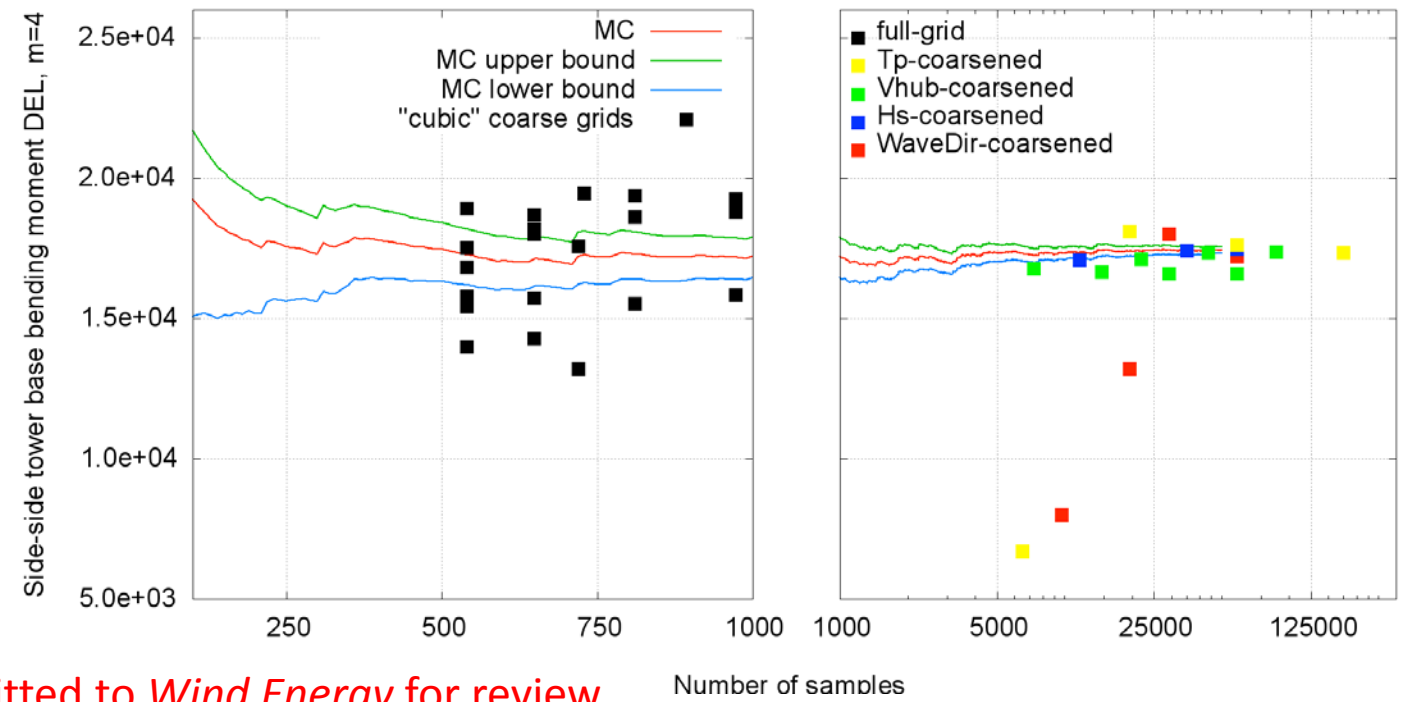
4. Investigation of joint turbine-plant design

Study 3: Loads Uncertainty Analysis

- **Investigation of Monte Carlo integration to fatigue load estimation of floating offshore wind turbine with spar-buoy support and comparison to normal grid-based simulation:**
  - Uses AeroelasticSE and FUSED-Wind case analyzer
  - 5 dimensions of environmental conditions:
    - Wind speed: Weibull
    - Wave direction: von Mises conditioned on wind speed
    - Wave height: gamma conditioned on wind speed and wave direction
    - wave period: gamma conditioned on wind speed and wave height
    - Wind-platform direction: von Mises conditioned on wind speed

Study 3: Loads Uncertainty Analysis

- **Monte Carlo demonstrated improved convergence over grid method**
  - Additional work exploring more sophisticated uncertainty analysis methods and



Paper submitted to *Wind Energy* for review

Initial Analysis Work

1. Comparison across multi-fidelity modeling of wind plant cost of energy

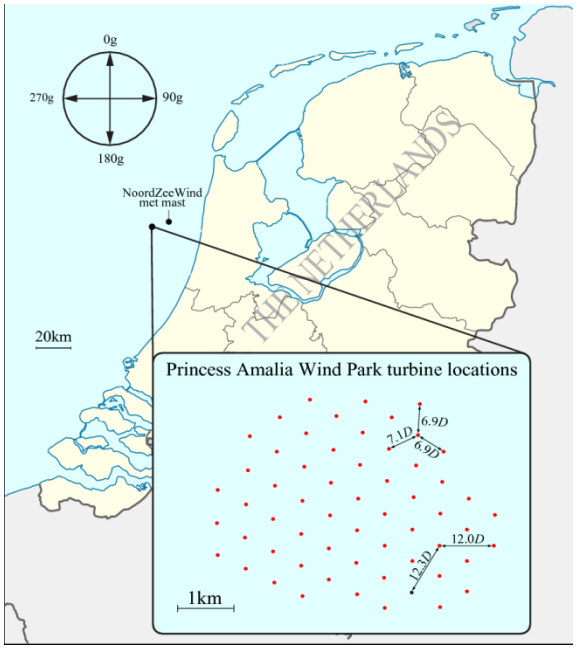
2. Investigation of impacts of tip speed on turbine design and plant cost of energy

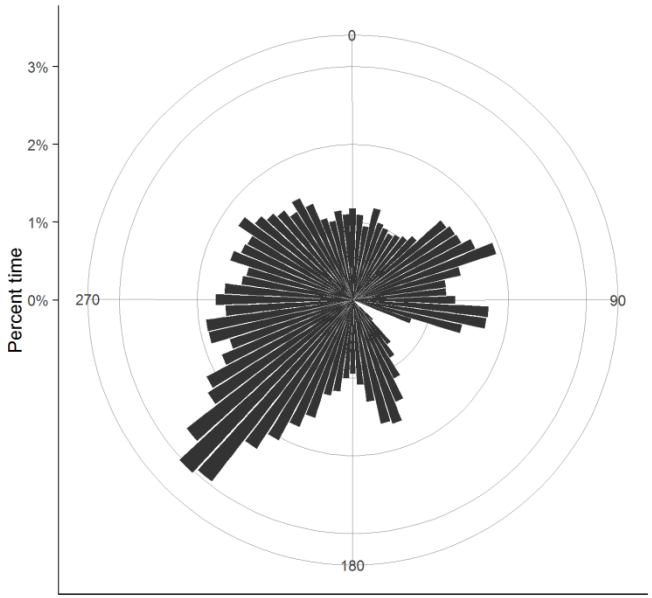
3. Uncertainty analysis of wind turbine loads

4. Investigation of joint turbine-plant design

Study 4: Integrated Turbine-Plant Design

- **Integrated design of wind plant turbine controls for yaw with wind plant layout for wake mitigation and increased power output**
  - Uses FLORIS-SE (not yet released)
  - Optimization performed using real wind farm data inputs for wind resource





Study 4: Integrated Turbine-Plant Design

- **Study involved 4 analysis cases:**
  - 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 yaw optimized for each wind direction and position optimized simultaneously

Study 4: Integrated Turbine-Plant Design

- **Different objective functions consider for maximizing mean power**
  - Joint optimization of wind turbines and plants
  - Future work will consider overall energy production

Table IV. Comparison of Baseline, YawOpt, PosOpt, and YP key metrics.

	$Baseline$	$YawOpt$	$PosOpt_{Density}$	$PosOpt_{Cable}$	$PosOpt_{Boundary}$	$YP_{Density}$	YP_{Cable}	$YP_{Boundary}$
Mean Power (MW)	78.86	84.91	78.86	90.67	80.68	78.84	92.33	85.61
Area (km^2)	14.53	14.53	12.45	33.28	14.47	8.96	32.53	14.48
Cable Length (km)	32.74	32.74	27.50	32.74	28.45	23.88	32.74	27.80
Power Density (W/m^2)	5.43	5.84	6.33	2.72	5.58	8.80	2.84	5.91

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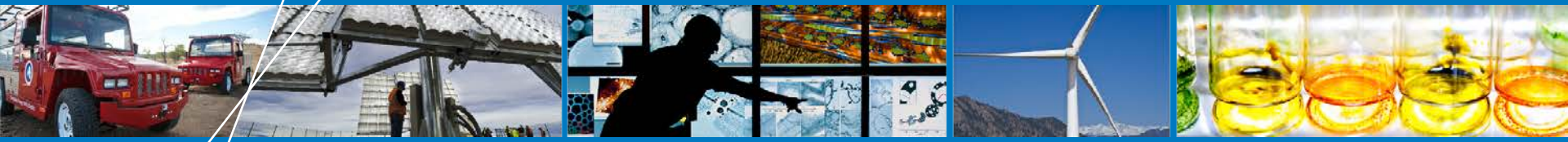


Summary and Future Work

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.

Summary

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

2. Initial work shows improved ability to capture system interactions moving to new SE model set and perform a large number of different types of analysis

3. Tool provides ability to investigate system changes and innovations for overall cost of energy

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

Future Activities

- Continued development of underlying wind plant system modeling framework with DTU Wind Energy and Sandia National Laboratories

- Bi-annual workshop brings together wind plant systems engineering researchers and practitioners (next workshop in January 2014)

  http://www.nrel.gov/wind/systems_engineering/se_workshop_2015.html

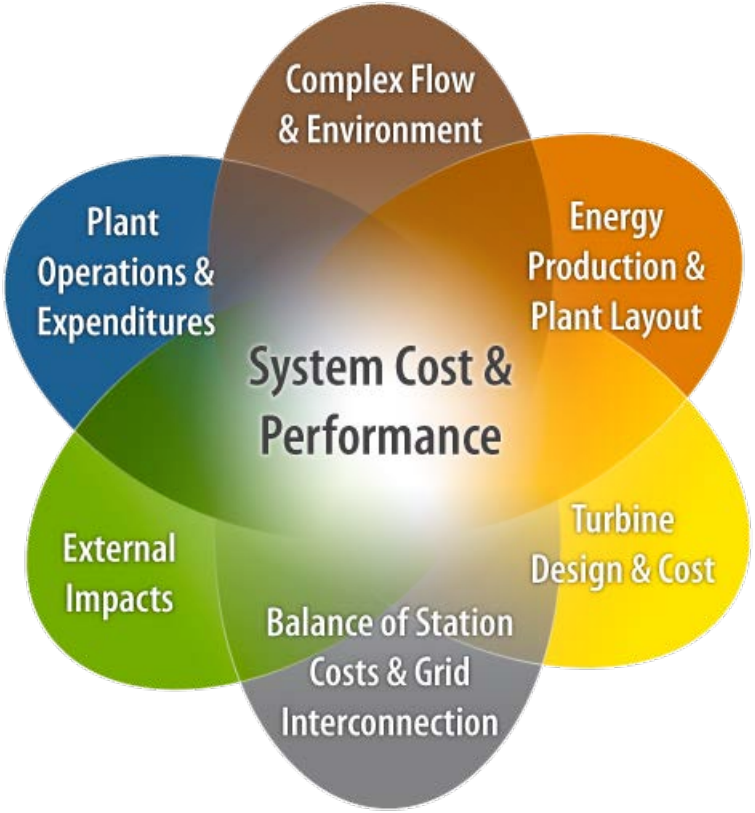
- Quarterly newsletter highlights new industry and academic research and design activity in WPO&SE

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

- Outreach and training for systems engineering software (contact systems.engineering@nrel.gov for assistance)

Discussion / Q&A

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



http://nwtc.nrel.gov/WISDEM