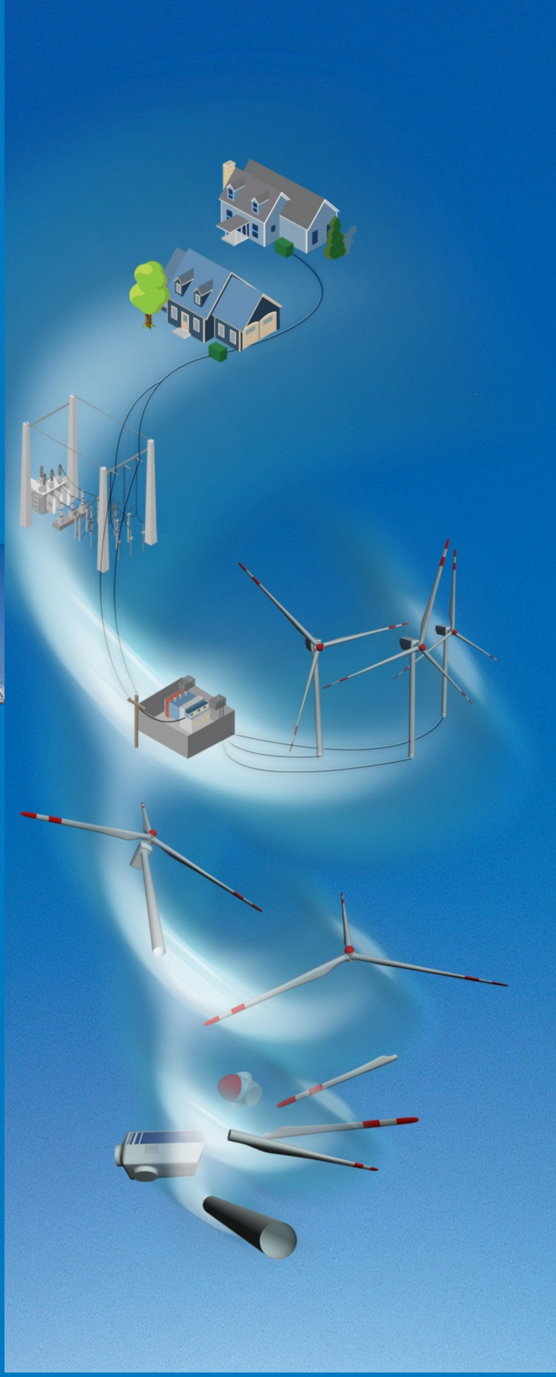
NREL Wind Energy Systems Engineering Program Overview

and Introduction to TWISTER



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National Renewable Energy Laboratory

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Agenda: TWISTER Tutorial

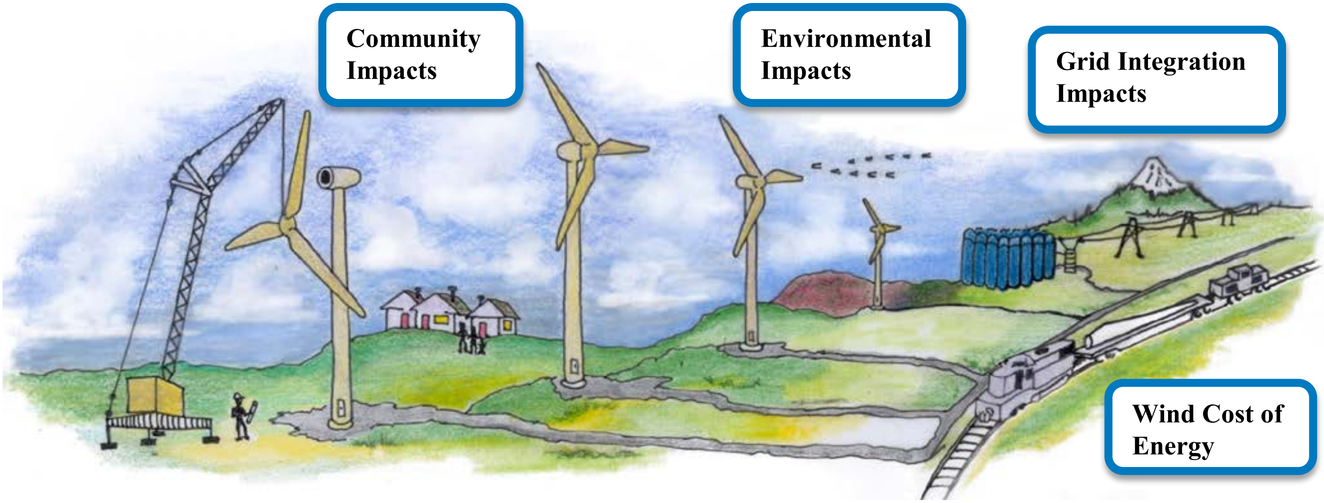
- Systems Engineering Program Overview
- Model Development
- Integrated System Analysis

Agenda: TWISTER Tutorial

- **Systems Engineering Program Overview**
- Model Development
- Integrated System Analysis

Motivation

- **Wind power systems are complex –**
  - Many disciplines – aerodynamics, structures, and electrical, etc.
  - Many stakeholders – supply chain, developers, financiers, environmentalists, and communities.
  - Long time scales – nominal operation over several decades.
  - Large scope – activity within a single component to interaction of turbines within the plant to interaction of plant with the grid.



Wind Energy System Cost of Energy

- **Often use simplified cost of energy (COE) representation as a global system objective:**

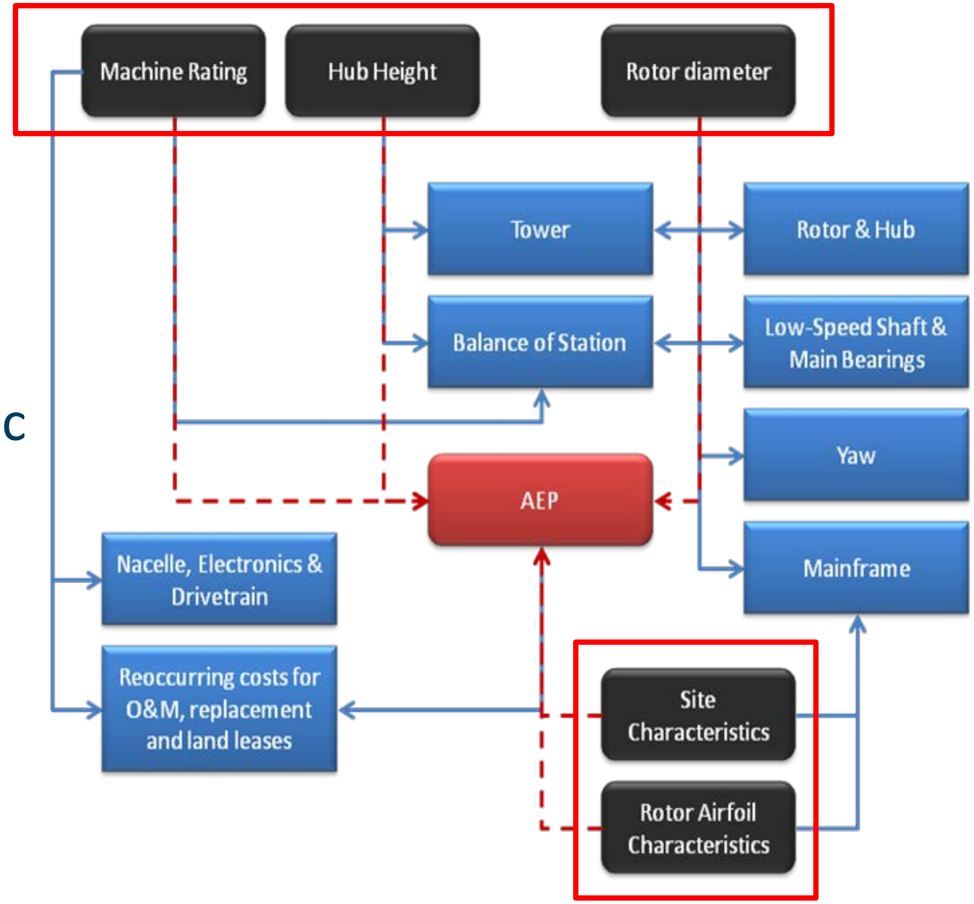
$$COE = \frac{FCR(BOS + TCC) + AOE}{AEP}$$

  - Where COE is cost of energy, BOS is balance of station cost, TCC is turbine capital cost (for full project), FCR is the fixed charge rate to annualize investment costs, AOE is the annual operating expense, and AEP is the annual energy production.

Determining Cost of Wind 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

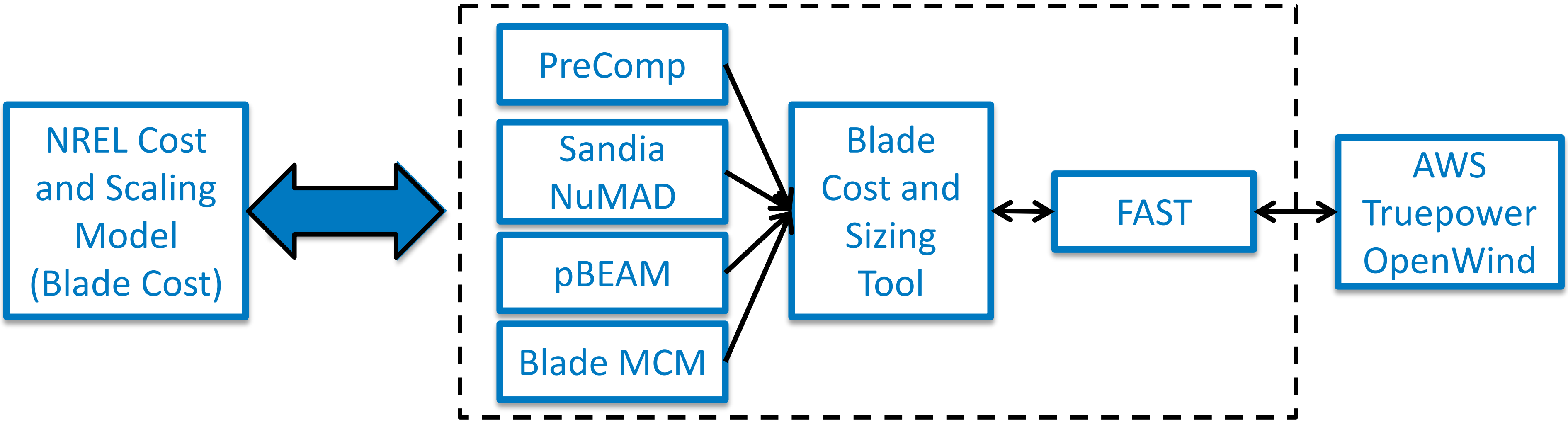


NREL Wind Energy System Engineering

- **NREL Initiative in Systems Engineering for Wind Energy seeks to:**
  - **Develop a software platform to integrate physics-based modeling efforts with cost-modeling efforts;**
  - **In order to:**
    - **Support program efforts for characterization of potential impacts of innovation / system changes on overall wind plant COE,**
    - **Provide a capability that can be flexibly adapted for a variety of analysis needs, and**
    - **Enable easier collaboration among stakeholders (labs, academia, and industry).**

NREL System Engineering Program Objectives

- **Integration of models into framework includes several areas:**
  1. **Turbine component structure and cost models,**
  2. **Structural models with dynamic models of turbine performance, and**
  3. **Integration of turbine models with physical plant models for turbine interactions affecting loads and energy production.**
- **At each level, a range of model fidelity is possible/needed for analysis flexibility (highly modular).**

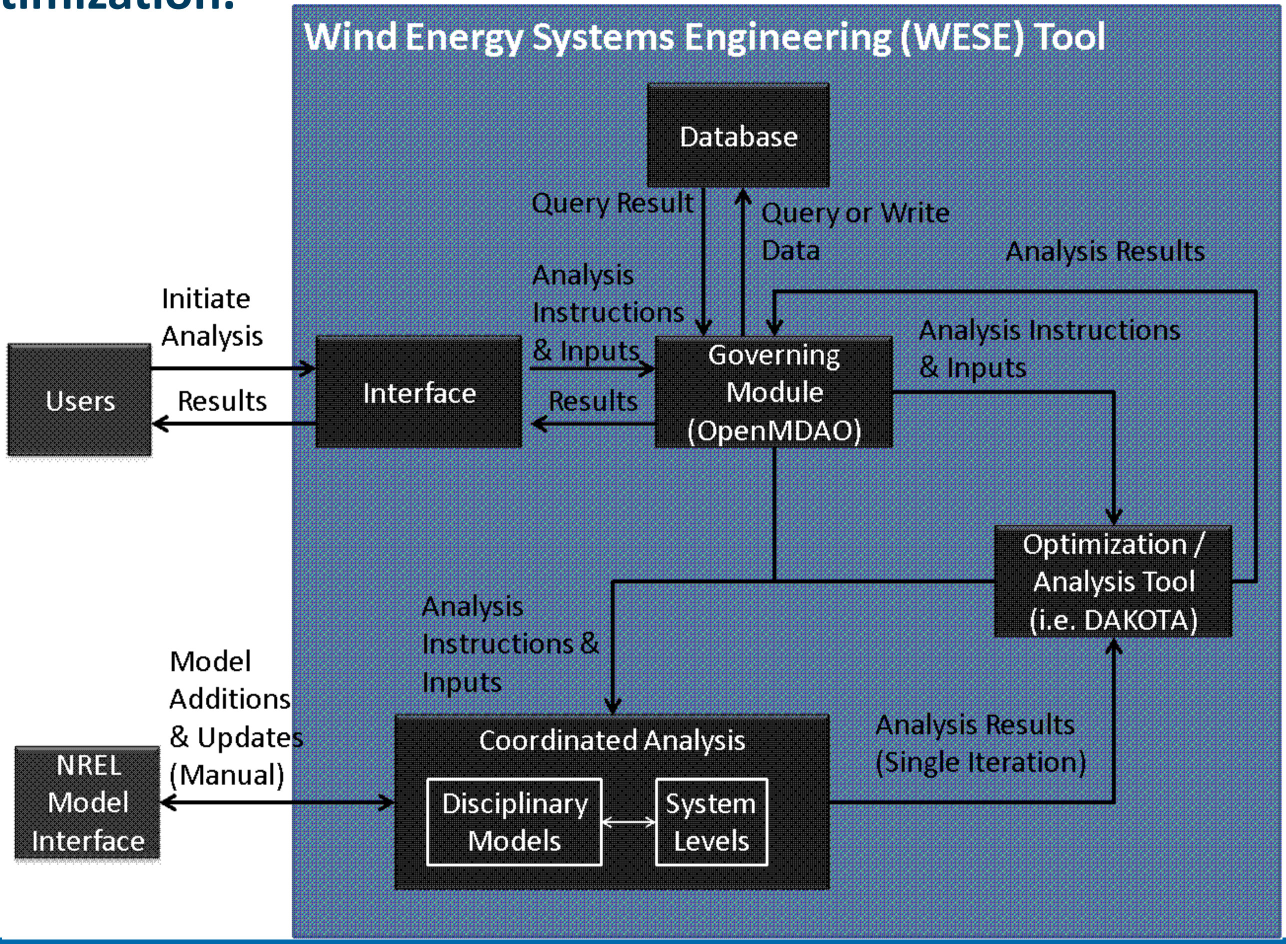


Example transition from Cost and Scaling Model to Systems Engineering Framework

NREL Systems Engineering Software Framework

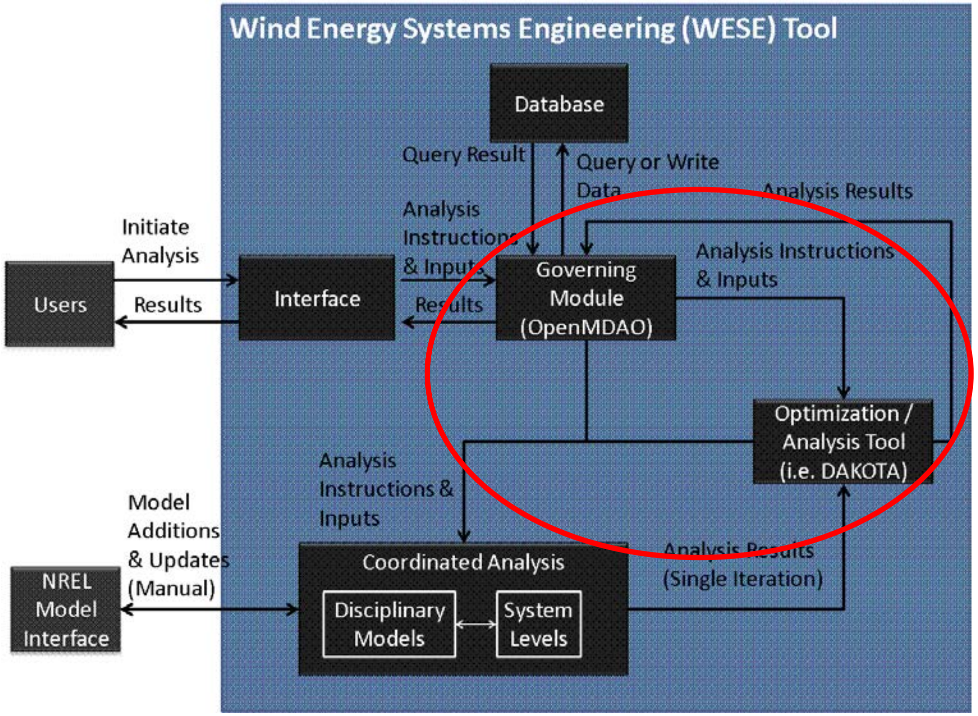
Integrated analysis tool using:

1. **models of varying levels of fidelity across . . .**
2. **different levels of a wind energy system, and**
3. **performing a variety of multi-disciplinary analyses from sampling to optimization.**



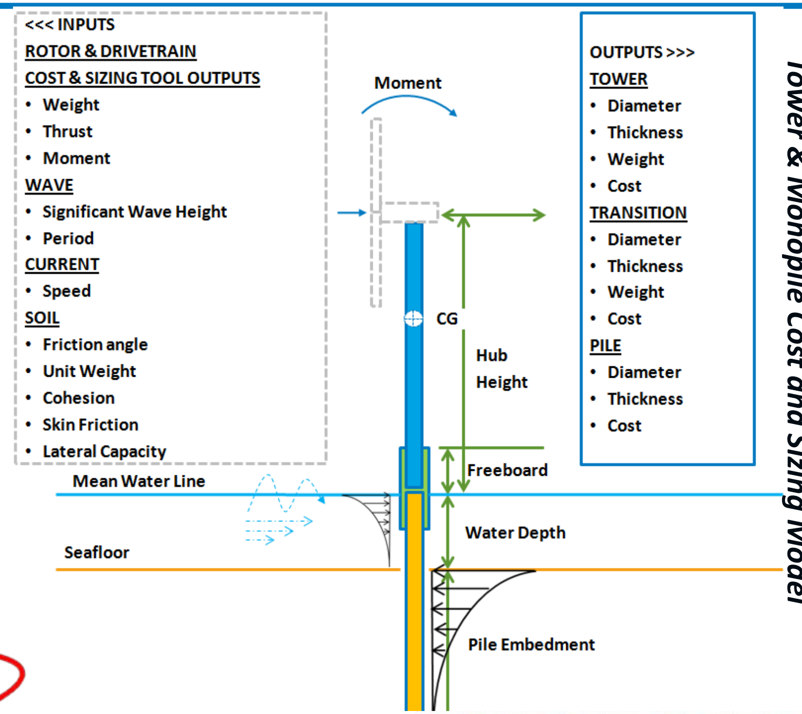
NREL Systems Engineering Software Framework

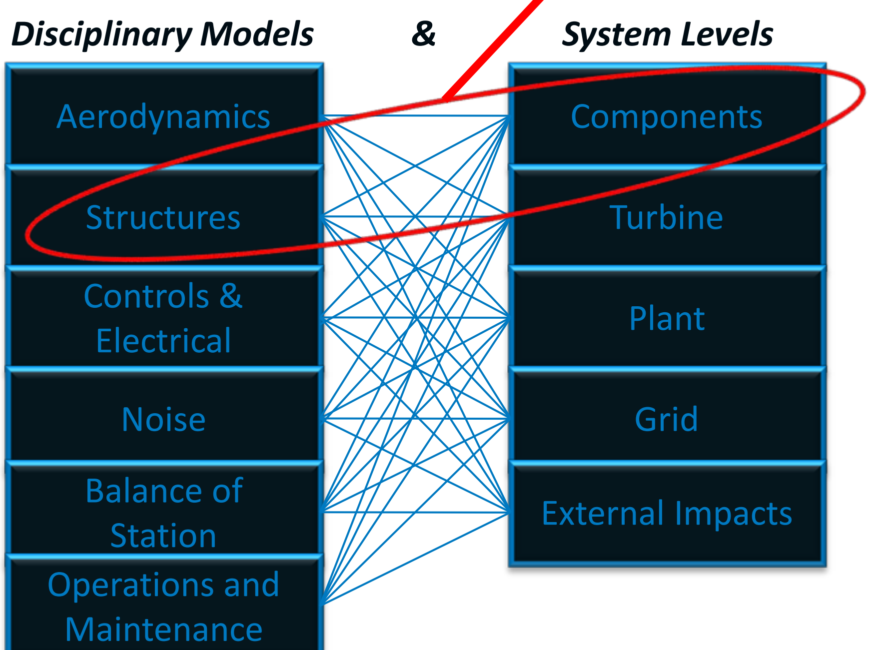
- **Governing model:**
  - Work flows integrate models together in structured ways (use of NASA's OpenMDAO software), and
  - Easily reconfigured (model selection and analysis structure).
- **Optimization / Analysis tool**
  - Different algorithms drive model analysis (internal to OpenMDAO via Sandia's DAKOTA software).

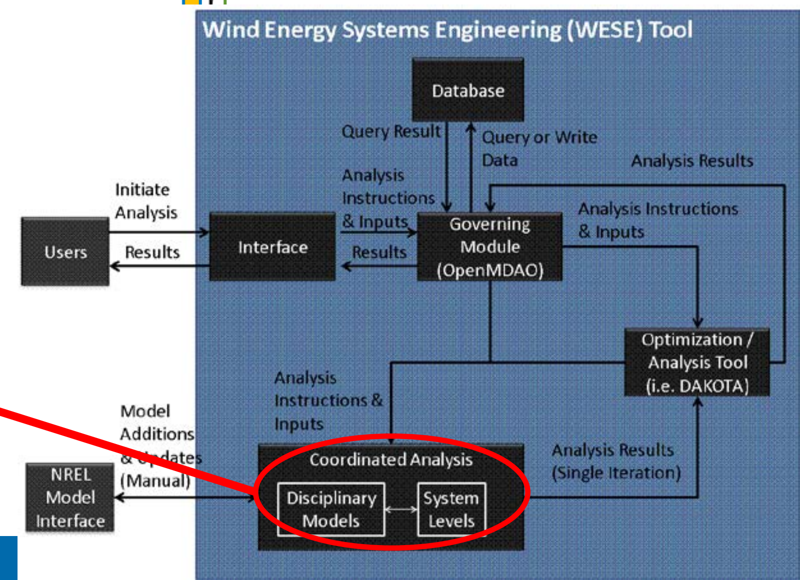


NREL Systems Engineering Software Framework

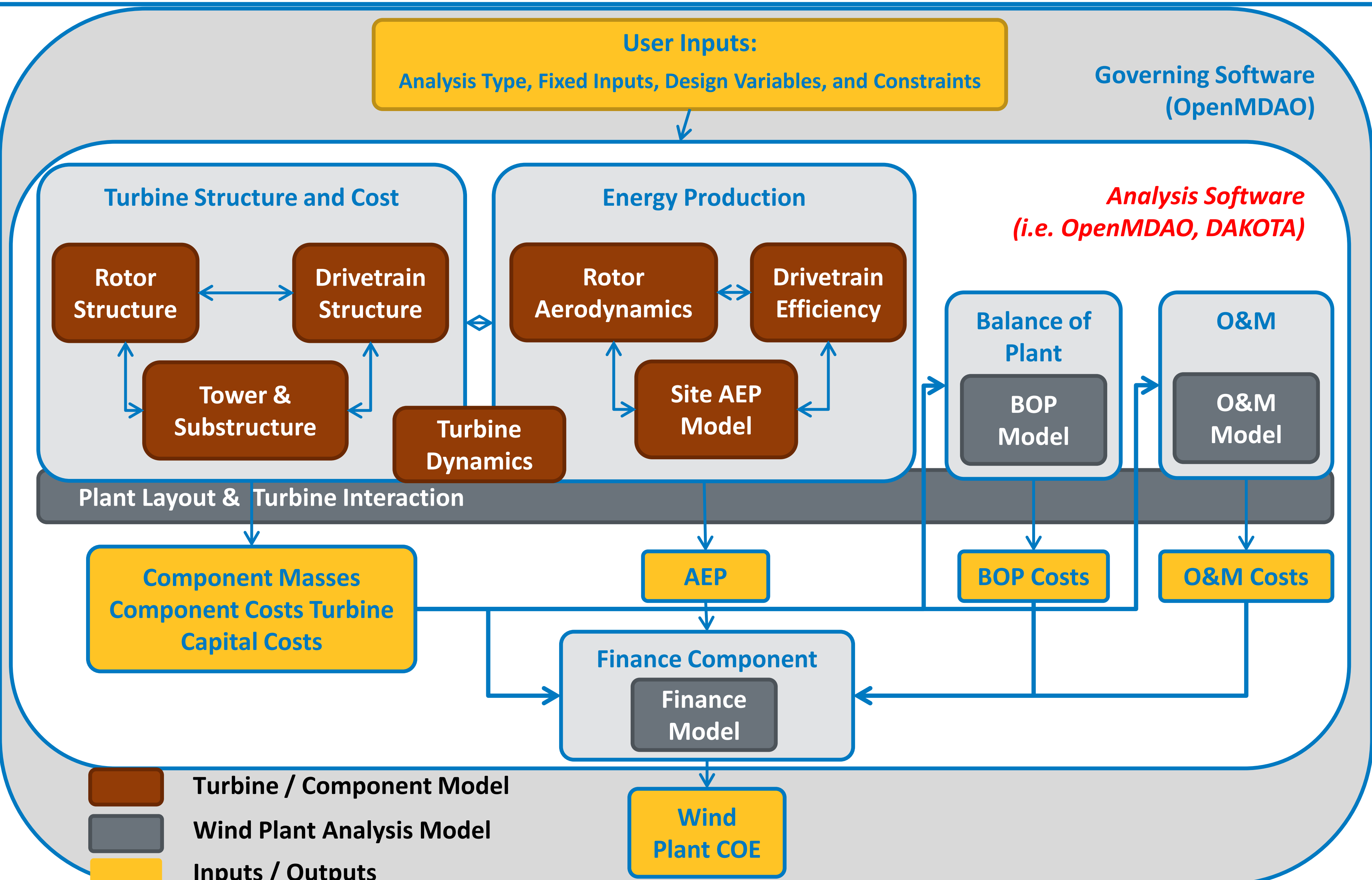
Coordinated analysis: integration of various models across disciplines and wind plant.







Systems Engineering Software Framework



Agenda: TWISTER Tutorial

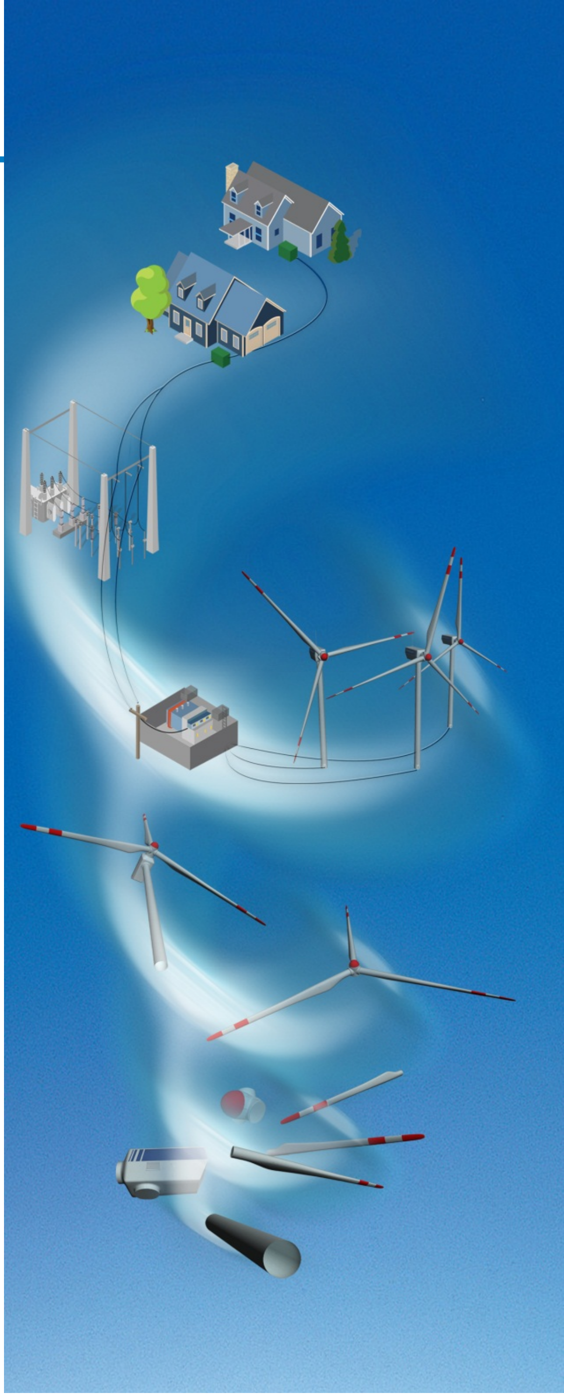
- Systems Engineering Program Overview
- **Model Development**
- Integrated System Analysis

Systems Engineering:

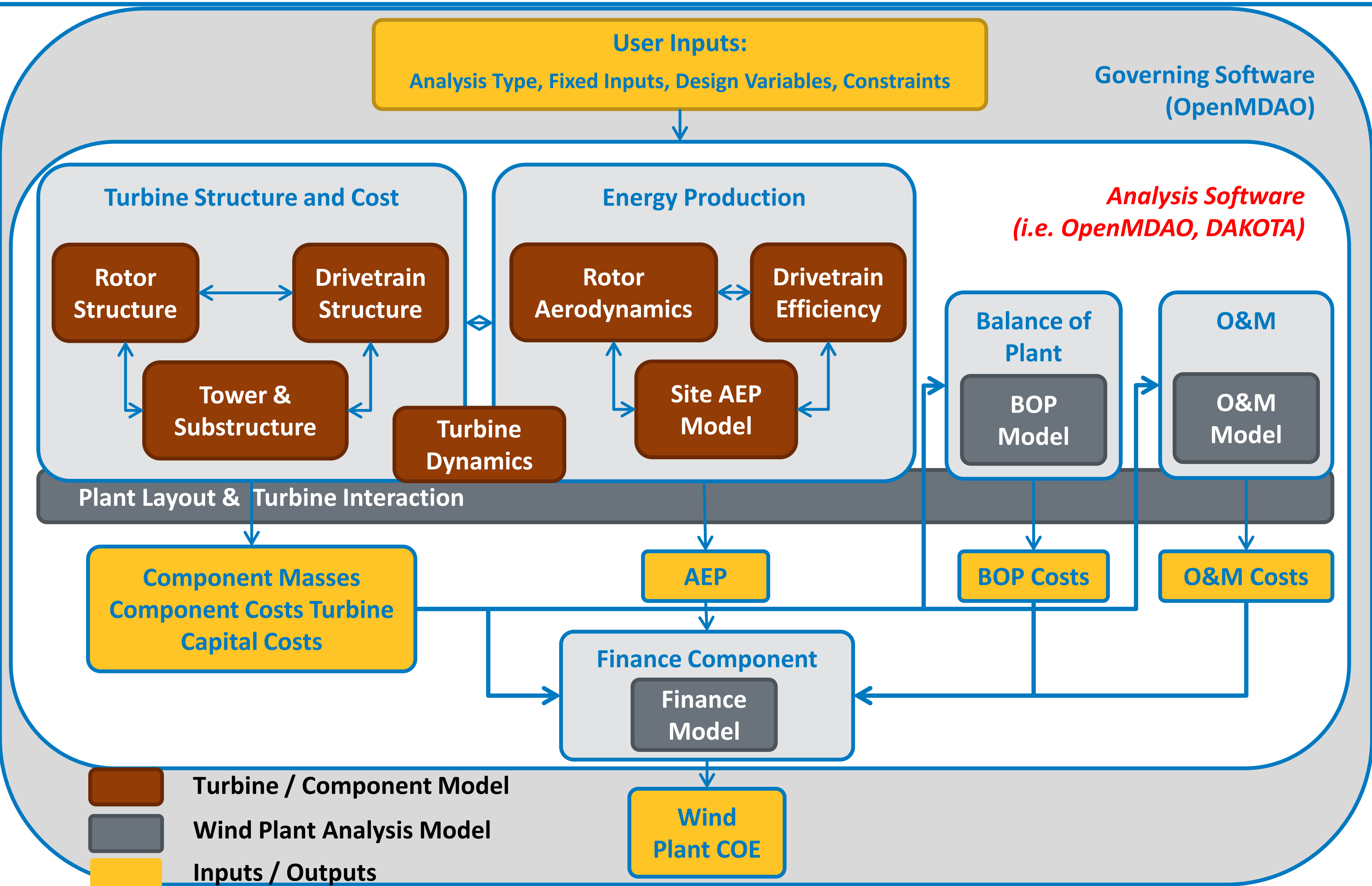
Model Development

- Near-term goal:
  - Replace NREL Cost and Scaling Model at each model level (TCC, AEP, BOS, Operations & Maintenance (O&M), and Finance):
    - Develop initial turbine physical model set that properly couples turbine component structural models (follows the load-path),
    - Reconfigure component cost models to depend on component properties (masses and dimensions) versus abstract turbine properties (i.e., rotor diameter), and
    - Leverage updates to plant models for land-based and offshore systems underway.
  - Implement basic software architecture and tool that can be adapted.

- Long-term goal:
  - Continually improve model fidelity of different models, and
  - Allow flexible interchange of models for various analyses.

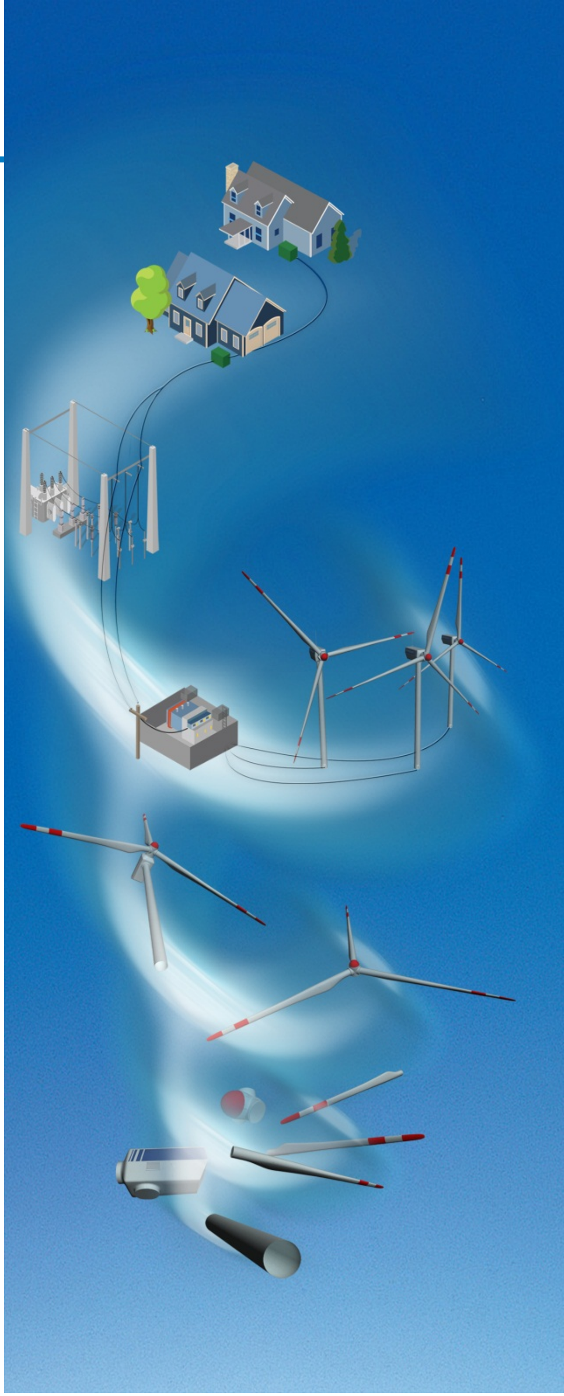


Systems Engineering Software Framework



Systems Engineering:
Model Development

- **Model Development and Updates are Being Made for Each Major Wind Plant Modeling Area:**
  - **Turbine Engineering and Analysis Models (TEAMs) –**
    - » **Physics-based modeling of main turbine components.**
  - **Turbine Cost and Sizing Tools (CSTs) –**
    - » **Integration of component and physical cost models.**
  - **Plant Level Models –**
    - » **BOS, Energy Production, O&M, and Finance.**



Turbine Engineering Analysis Model: Rotor

- **Geometry and Materials are pre-defined.**
- **Outputs include blade mass properties and rotor performance.**

<<< INPUTS

ROTOR INPUTS

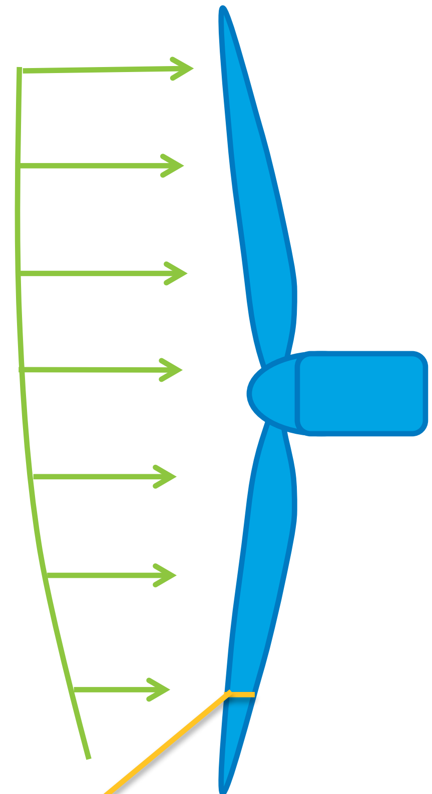
- **Number of blades**
- **Precone, tilt**

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



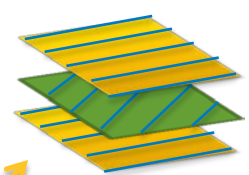
OUTPUTS >>>

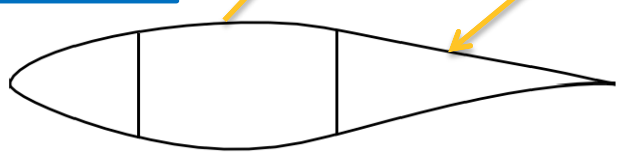
ROTOR STRUCTURE & PERFORMANCE

- **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**

LAMINATE STACK

- **Sequence of lamina**
- **Number of plies**
- **Ply thickness**
- **Ply orientation**
- **Ply material**





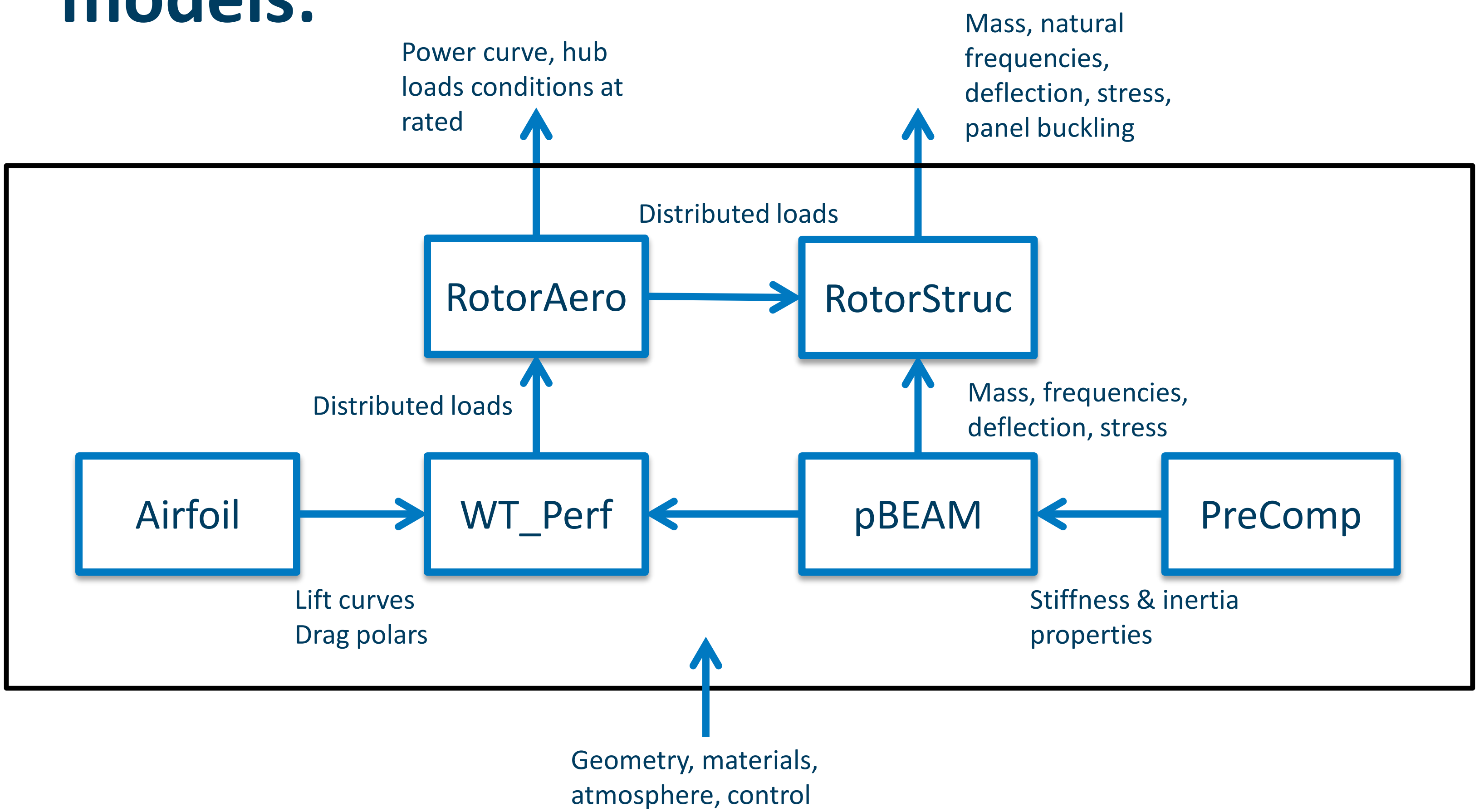
AIRFOIL

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

TEAM must be wrapped by optimizer and connected to cost model to create CST.

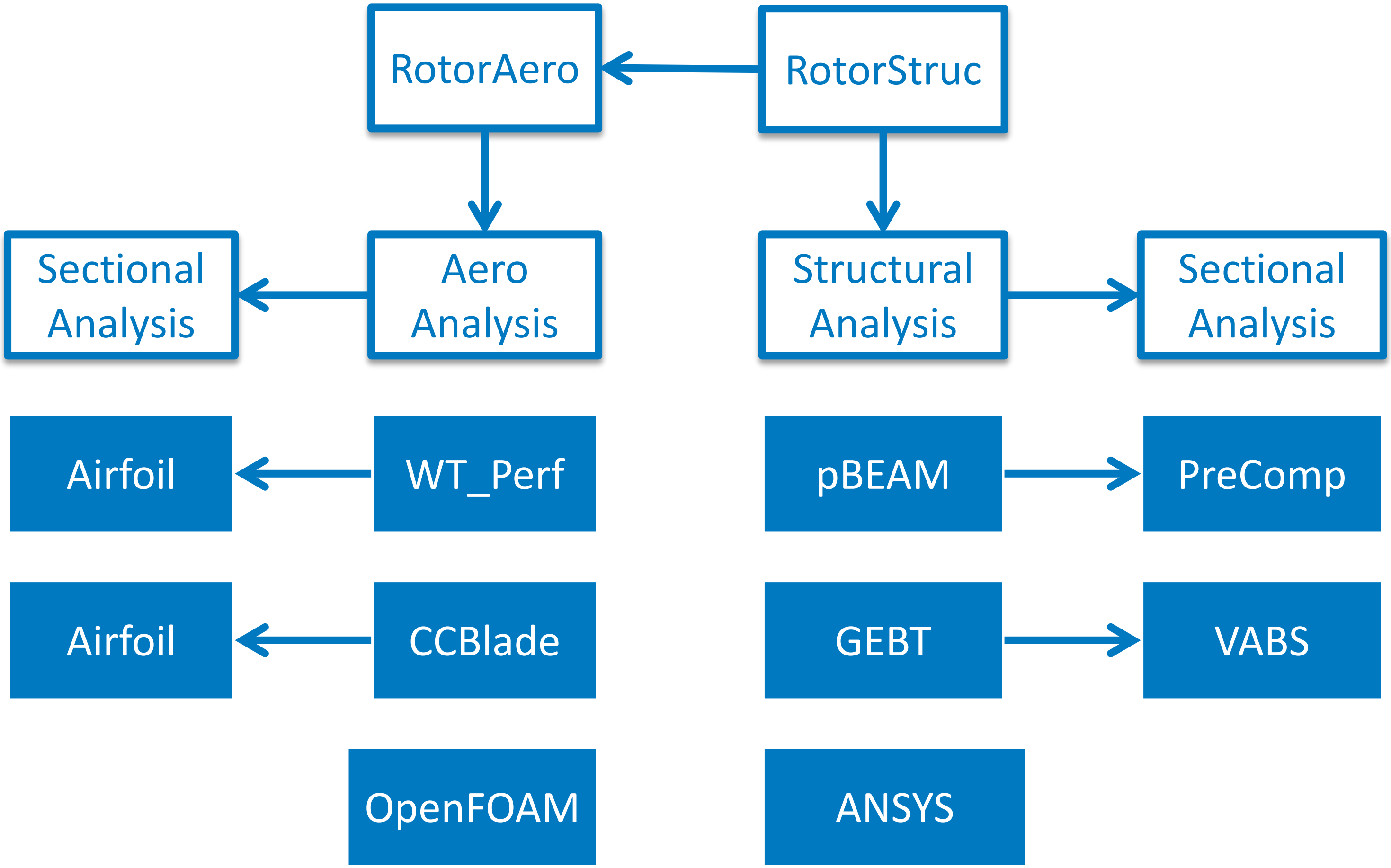
Turbine Engineering Analysis Model: Rotor

- **Rotor analysis model involves several sub-models:**



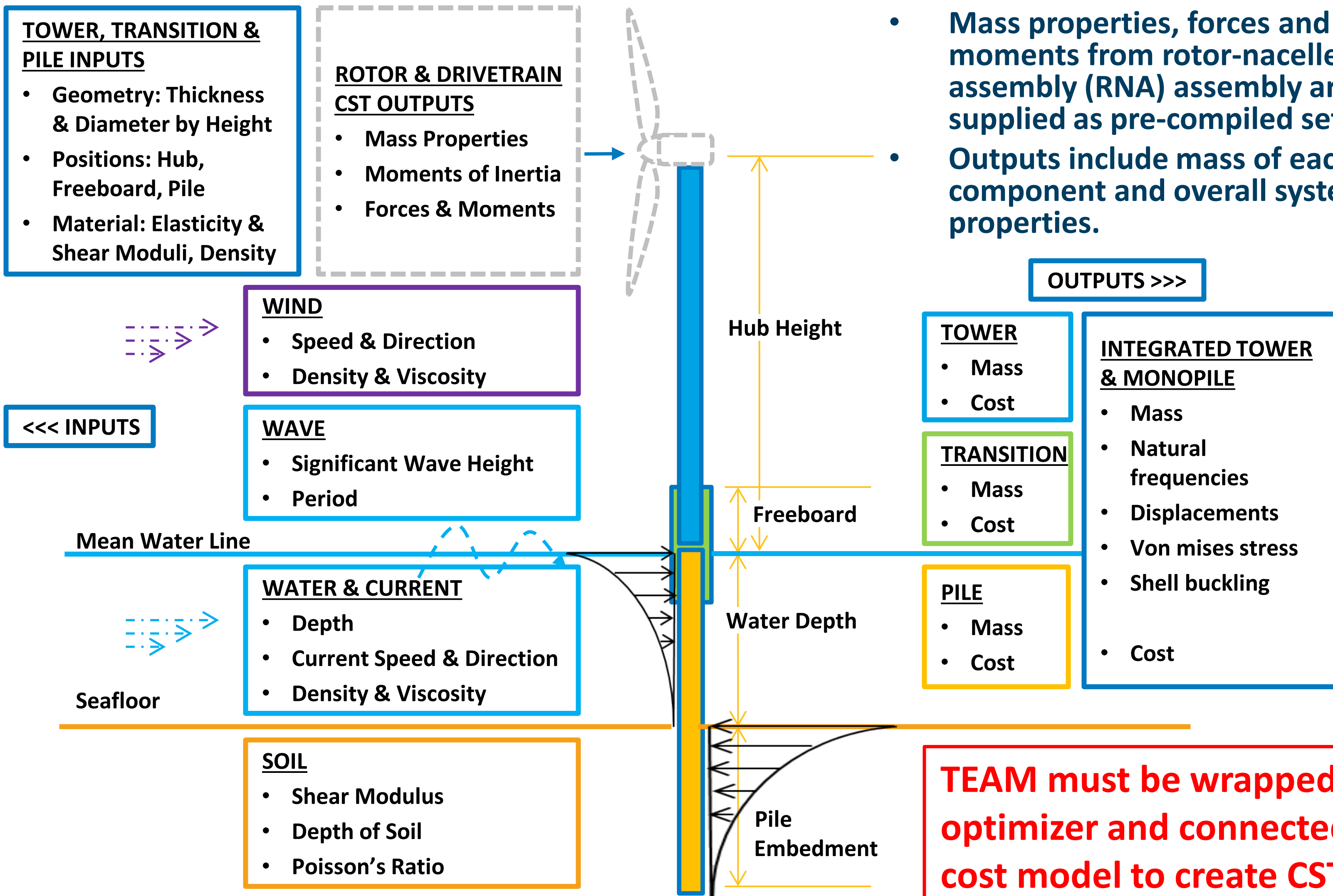
Turbine Engineering Analysis Model: Rotor

- **Rotor Model – Adaptable Models:**



Turbine Engineering Analysis Model: Tower/Monopile

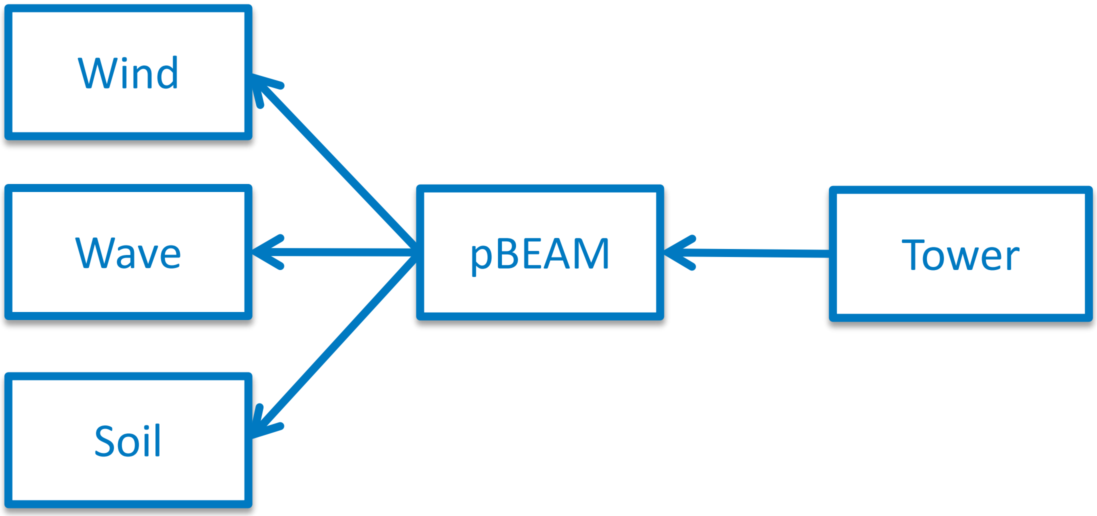
- Geometry and materials are pre-defined,
- Mass properties, forces and moments from rotor-nacelle assembly (RNA) assembly are supplied as pre-compiled set, and
- Outputs include mass of each sub-component and overall system properties.



TEAM must be wrapped by optimizer and connected to cost model to create CST.

Turbine Engineering Analysis Model: Tower/Monopile

- **Tower model involves combination of environmental and tower/monopile structural models:**
  - These are adaptable just as with rotor model



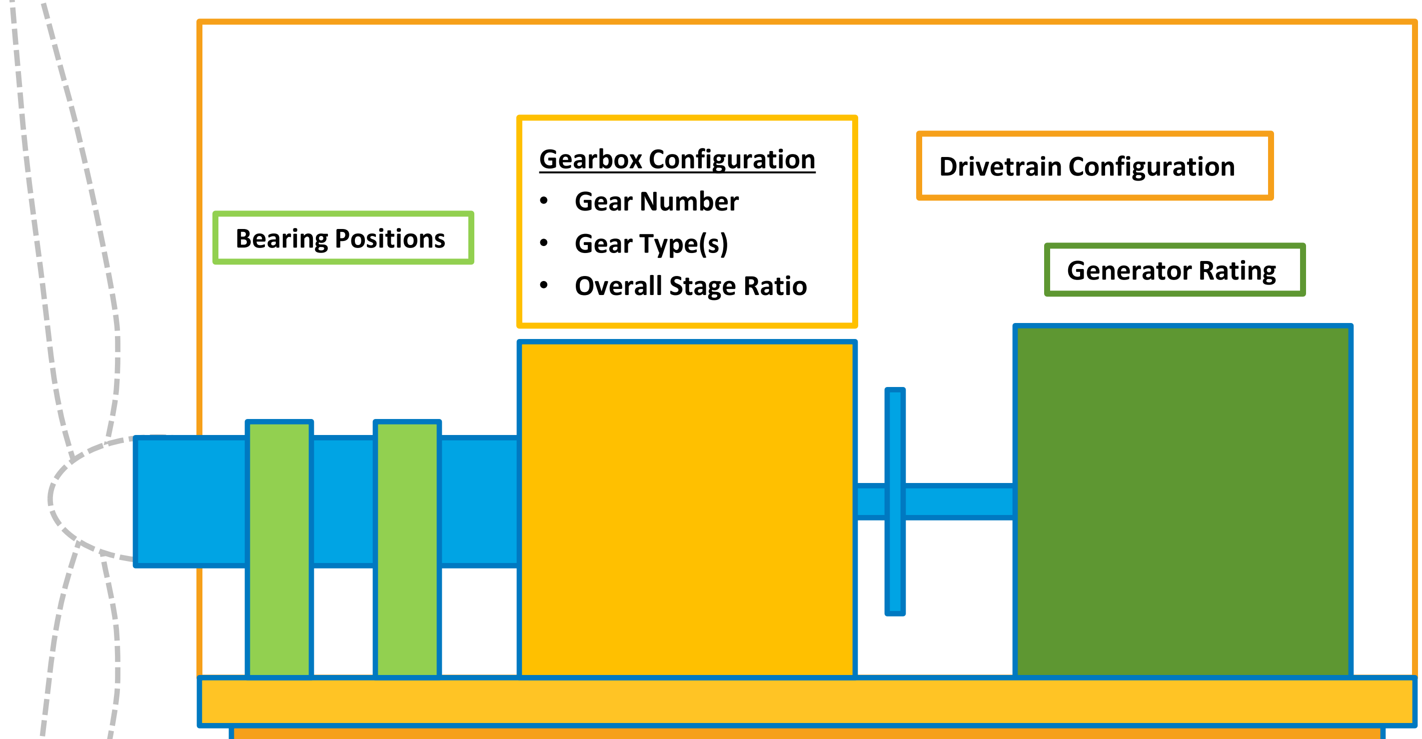
Drivetrain Cost and Sizing Tool

- Semi-empirical model relating input loads directly to component masses & costs, and
- NOTE: 3-stage gearbox configuration is shown but direct-drive configuration will also be implemented.

<<< INPUTS

ROTOR Outputs
- Diameter
- Mass
- Max Thrust
- Speed at Rated
- Torque at Rated

Tower Outputs
- Top Diameter



OUTPUTS >>>

LSS
- Length
- Outer Diameter
- Inner Diameter
- Weight

Main bearings
- Weight
- Housing Weight

Gearbox
- Weight
- Stage Weights
- Stage Ratios

HSS & Coupling
- Brake Weight
- HSS Weight

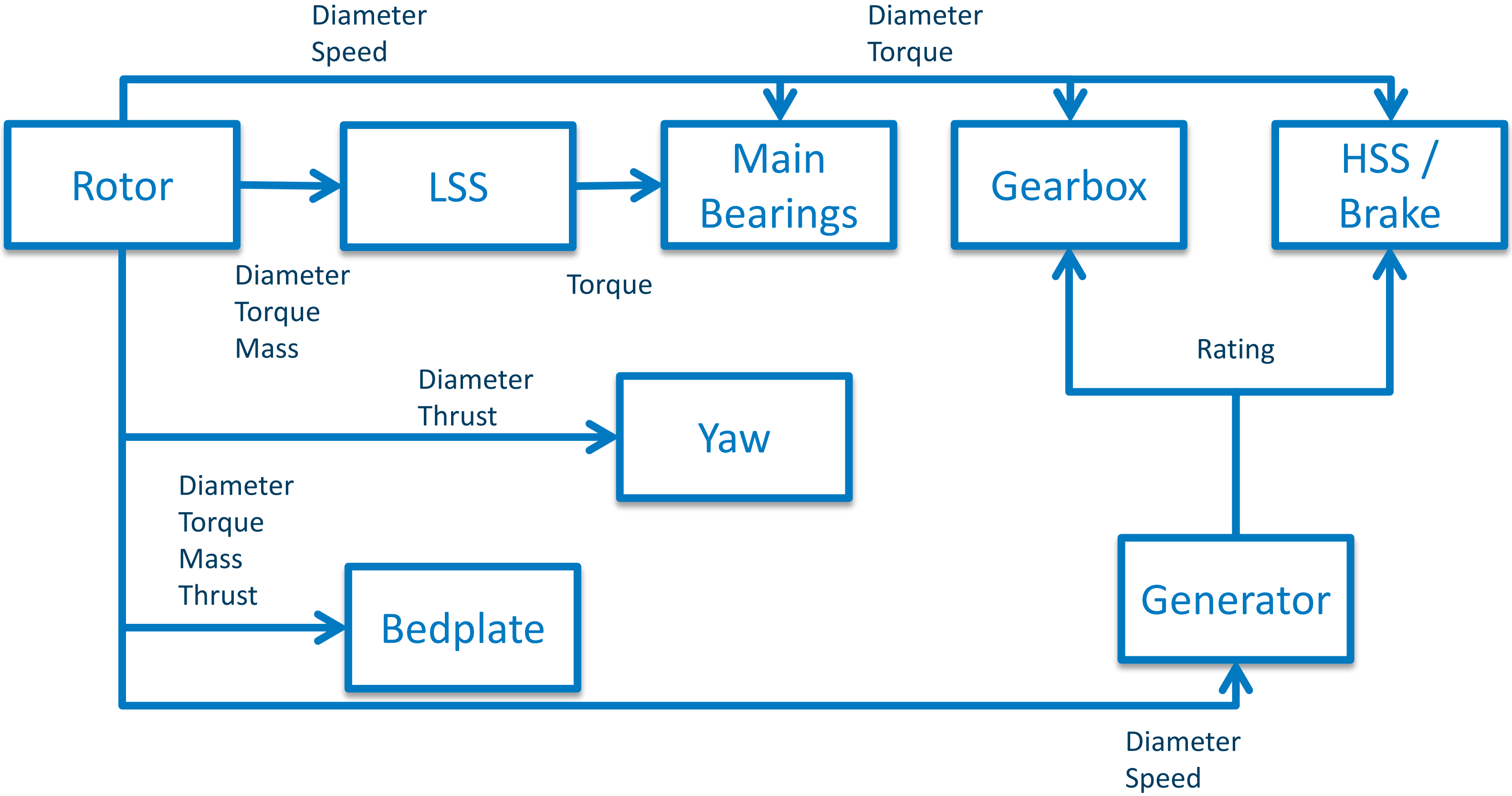
Generator
- Weight

Bedplate
- Length
- Area
- Weight

Yaw
- Weight

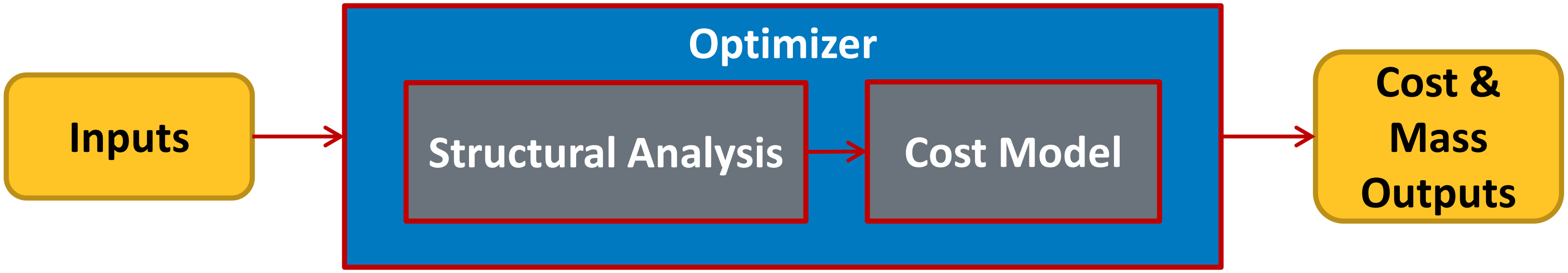
Drivetrain Cost and Sizing Tool

- **Drivetrain uses semi-empirical methods to size components based on loads (updated Sunderland Model)**



Wind Turbine Models:
Cost Determination

- **Efforts exist to create design based models for each component:**
  - Mass-cost models developed for individual components in rotor, tower and drivetrain based on determination of underlying data of NREL CSM –
    - – Scaling of input factor costs over time is possible.
  - Development of more detailed materials and manufacturing cost models for various components is underway.



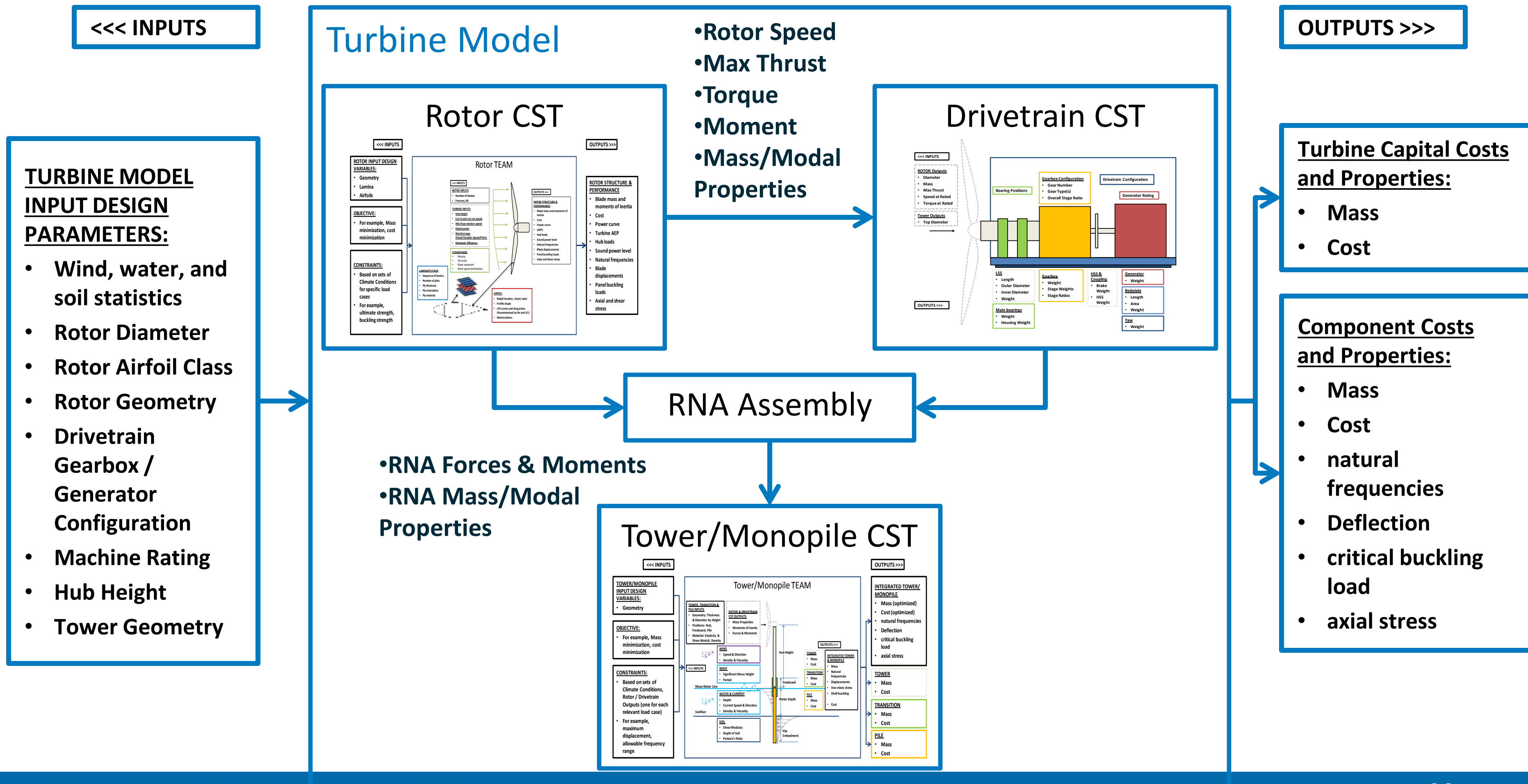
Plant Level Models:

TCC, AEP, BOS, O&M, and Finance

- **Plant models aggregate all system aspects to find the overall COE:**
  - TCCs,
  - AEP,
  - BOS,
  - O&M, and
  - Finance.

Plant Level Models: Turbine Capital Costs

- Model aggregates component costs and masses together.
- Optimization may be done using various Multi-Disciplinary Optimization methods.
- Meta-models may be used in place of sub-optimizations for sensitivity analysis.



Plant Level Models: AEP

- Model takes power curve provided or determined by rotor CST.
- Energy production based on site Weibull statistics and turbine availability along with any losses (or may be determined by a energy production model that accounts for turbine wake interactions).

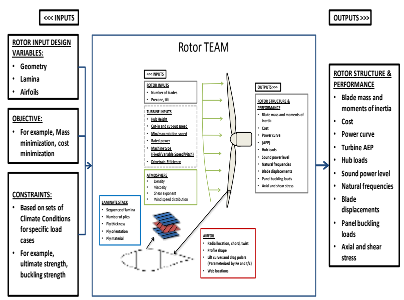
<<< INPUTS

ROTOR MODEL INPUT DESIGN PARAMETERS

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

AEP Model

Rotor CST

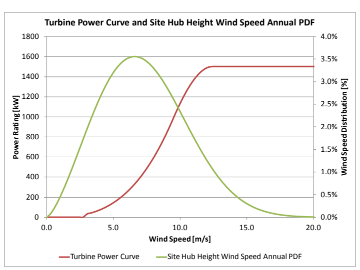


•Power Curve

O&M Model

•Availability

Energy Production Model



x Availability

x Plant Losses

Future Developments

Plant layout model with wake interactions.

OUTPUTS >>>

Energy Production:

- AEP
- Plant Capacity Factor

Plant Level Models: Balance of Station

- **New NREL Wind Plant Balance of Station Models under development in collaboration with DNV (land-based) and GLGH (offshore)**
- **Model takes input from turbine model regarding component dimensions and weights (or may use machine rating, rotor diameter)**
- **Models for onshore and offshore balance of station calculate all capital costs excluding turbines**

<<< INPUTS

BOS MODEL INPUTS:
- **Wind, water, soil characteristics**
- **Transportation modes and costs**
- **Grid interconnection and cabling inputs**

TURBINE MODEL OUTPUTS:
- **Component Dimensions & Weights**

BOS Model

OUTPUTS >>>

BOS MODEL OUTPUTS:
- **Permits & Engineering Costs**
- **Transportation & Staging Costs**
- **Assembly & Installation Costs**
- **Grid Interconnection Costs**

Plant Level Models: Operations & Maintenance

- **New O&M models available for land-based (sub-contract with DNV) and offshore (licensed from ECN).**
- **Model takes input from turbine model regarding component dimensions, weights, and costs (and failure rates if available).**
- **Models for onshore and offshore O&M calculate all annual operating expenses for plant.**

<<< 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

Project Level Models: Finance / Cash Flow

- Detailed wind plant cash flow model available via interface to System Advisor Model (SAM) cash flow model.
- Model takes inputs from all other plant models on costs and energy production.
- Model determines values of a variety of financial indicators of interest.

<<< 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:

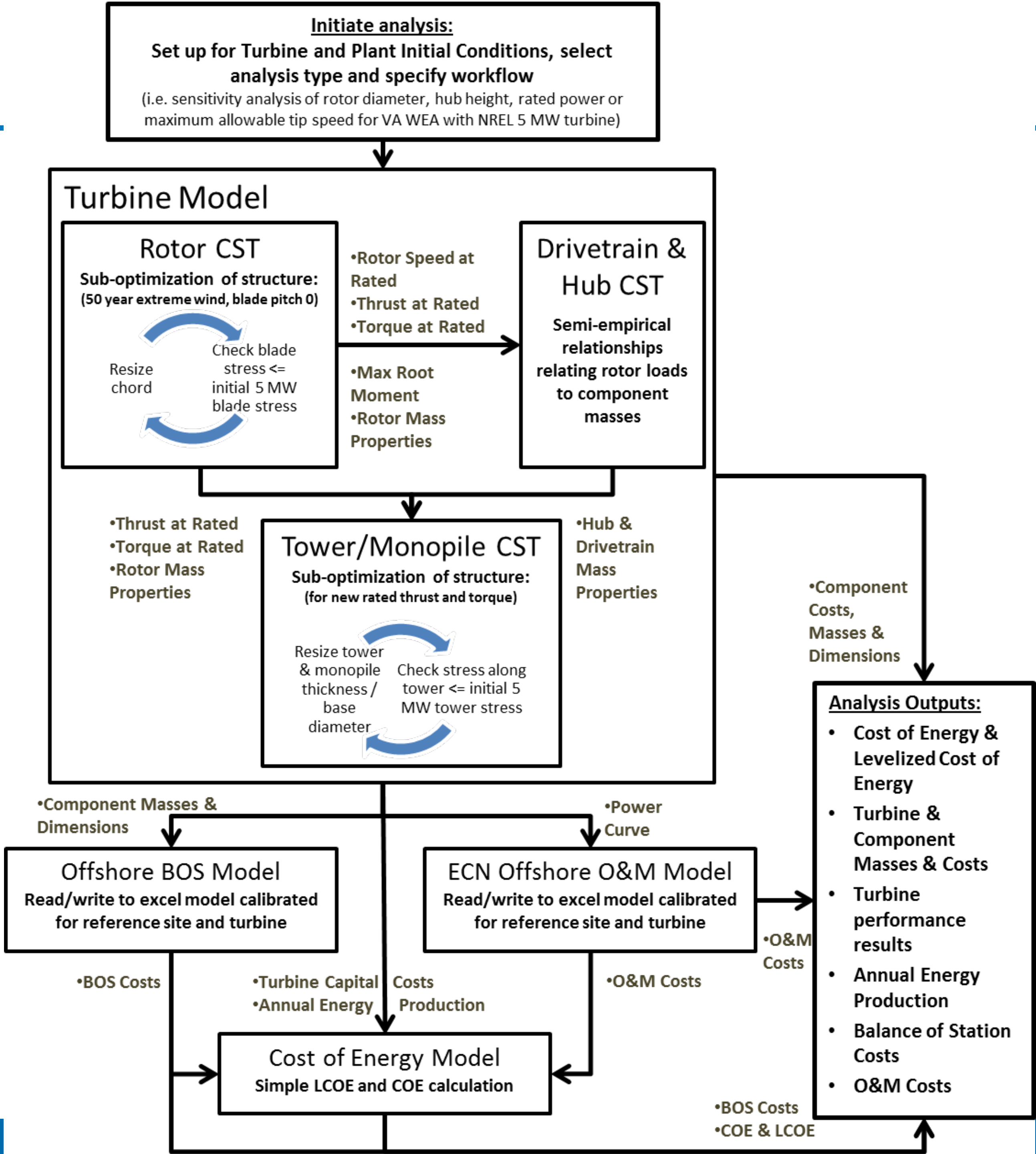
- Project Net Present Value (NPV)
- Project Internal Rate of Return
- Project Pay Back Period
- Project LCOE

Agenda: TWISTER Tutorial

- Systems Engineering Program Overview
- Model Development
- **Integrated System Analysis**

Initial Analysis: Sensitivity Study

- Parameter scans on basic turbine design parameters: rotor diameter, hub height, rated power, and maximum allowable tip speed.



Initial Analysis: Sensitivity Study

- **Any analysis requires both turbine *and* plant design inputs:**
  - Study uses NREL 5-MW reference turbine model and Virginia Wind Energy Area as 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%

Virginia Wind Energy Area Site Conditions	
Distance to Shore	46 m
Sea Depths	<5% at ~20 m, 25%+ at ~30 m
Wind Speed at 90 m	Mean = 9.78 m/s Weibull shape = 2.15, scale = 10.5
Significant Wave Height	10-year Extreme = 7.5 m 50-year extreme = 8 to 8.5 m/s
Significant Wave Period	10-year Extreme = 19.6 s

Initial Analysis: Sensitivity Study

- **Baseline COE analysis CSM versus CSTs**

	NREL CSM	NREL SE w/ CSTs
COE	$0.11	$0.18
AEP (MWh / turbine-yr)	18,800	19,900
Turbine Capital Costs ($ / kW)	$1,200	$1,000
BOS Costs ($ / kW)	$1,700	$3,600
O&M Costs ($ / kWh)	$0.027	$0.026

  – Overall cost of energy higher using new model set:
    - Energy production of higher fidelity physics-based model slightly higher than that of NREL CSM.
    - Turbine capital costs are similar between two models (slightly higher for the NREL CSM due to the inclusion of a 10% “marine-ization” factor).
    - O&M costs roughly consistent from old to new model.
    - Balance of Station costs of older CSM were known to be low – essentially doubled in updated model.

  – COE for new model closer to industry-reported offshore wind costs for European projects.

Initial Analysis: Sensitivity Study

- **Sensitivity of system cost to changes in key parameters (rotor diameter, rated power, hub height, and maximum tip speed) performed – change of +/- 10% for each.**
- **Example analysis: rotor diameter.**

Percent Changes in Parameters	NREL CSM		NREL SE w/ CSTs	
Rotor Diameter (m)	-10.0%	+10.0%	-10.0%	+10.0%
COE	↑	↓	↑	↓
AEP (kWh / turbine-yr)	↓	↑	↓↓	↑↑
TCCs ($ / kW)	↓↓	↑↑	↓	↑
BOS Costs ($ / kW)	--	--	↓	↑
O&M Costs ($ / kWh)	↓	↑	↓	↑

– Changes in COE was more pronounced using new set of models that capture more system coupling:
  - Rotor diameter influences balance of station model in latter case; overall BOS impact on costs of energy higher for new model set.
  - Operations & Maintenance model shows less influence since causal relationship of energy production is removed (surrogate for loads).

– Consistent with expectation for "growing the rotor."

Initial Analysis: Sensitivity Study

- **Sensitivity of system cost to changes in key parameters (rotor diameter, rated power, hub height, and maximum tip speed) performed – change of +/- 10% for each**
- **General analysis show:**
  - Directional influence of sensitivities are consistent with expected results
  - Improvement on ability of cost and scaling model to capture system effects of design changes

Parameter	Direction of Change	CSM COE Impact (rounded)	SE Model COE Impact (rounded)
Rotor Diameter	Increase	--	↓
	Decrease	↑	↑
Rated Power	Increase	↑	--
	Decrease	↑	↓
Hub Height	Increase	--	↓
	Decrease	--	↑
Max Tip Speed	Increase	--	--
	Decrease	--	↑

Conclusions and Summary

1. A systems perspective to wind energy cost and performance analysis is essential – extensive coupling exists between physical assets over long periods of time.

2. NREL has developed initial capability for modeling integrated wind plant systems for performance and cost.

3. Initial work shows improved representation of coupling in analysis results; however, model improvement is needed across all system models.

Next Steps

1. Continued development of individual models to upgrade fidelity of various areas (plant energy production, drivetrain component structural and cost modeling, etc)

2. Application and validation of initial model set in a variety of analyses

3. Increased focus on collaboration through the establishment of a "unified framework" for wind energy system modeling based on OpenMDAO