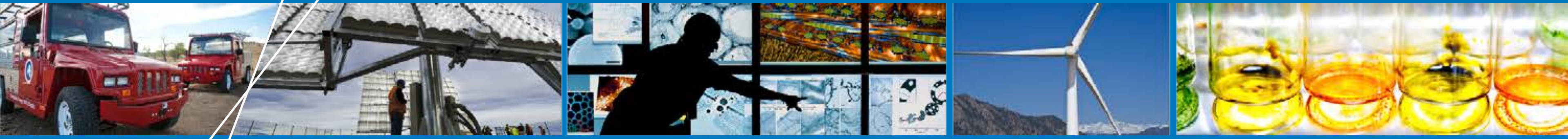
NATIONAL RENEWABLE ENERGY LABORATORY

WISDEM Modeling Capability



June 2017

Wind Energy Systems Engineering

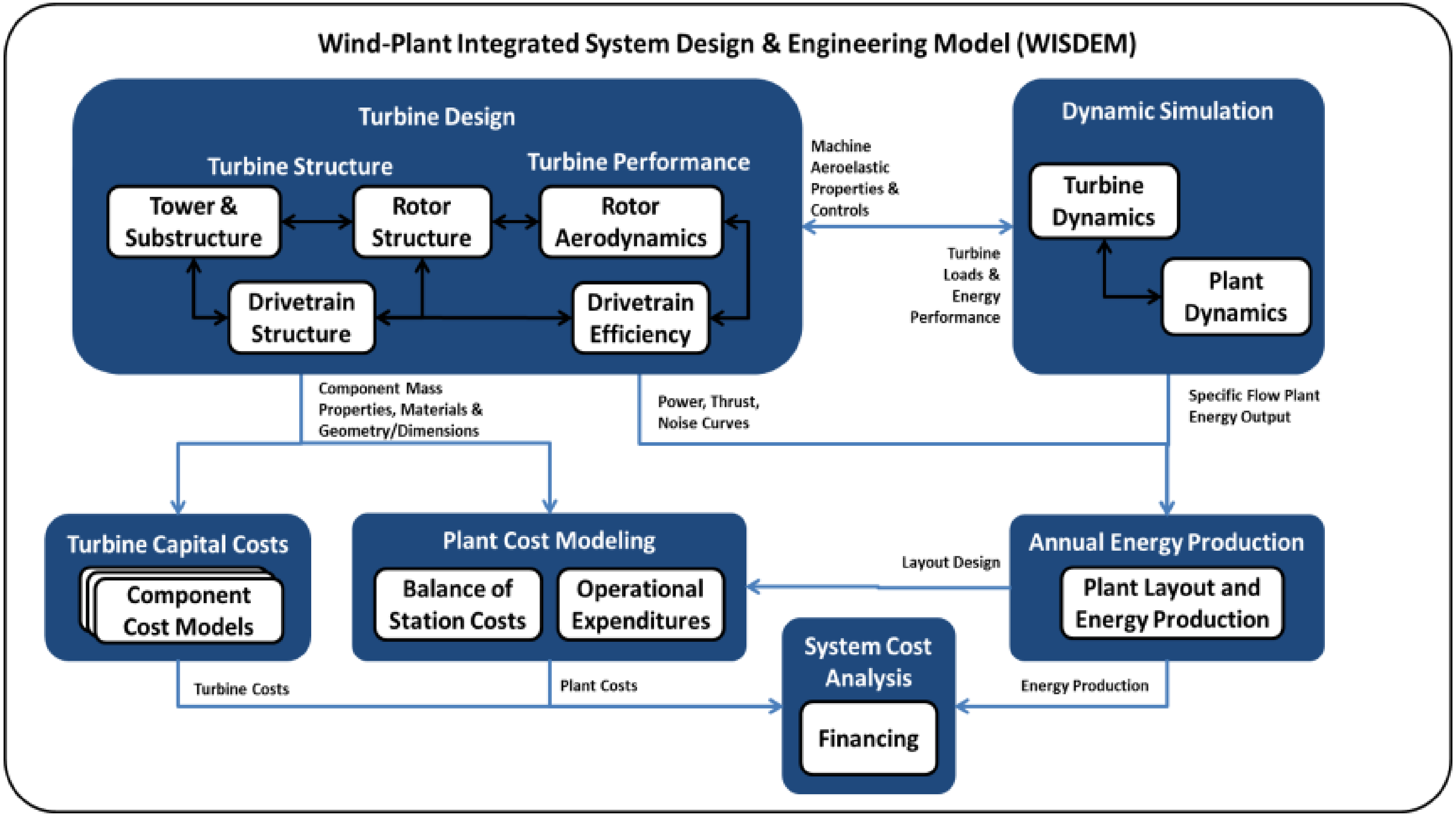
To address these challenges, the NREL wind energy systems engineering initiative has developed an analysis platform and research capability to capture important system interactions to achieve a better understanding of how to improve *system-level* performance and achieve *system-level* cost reductions.

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

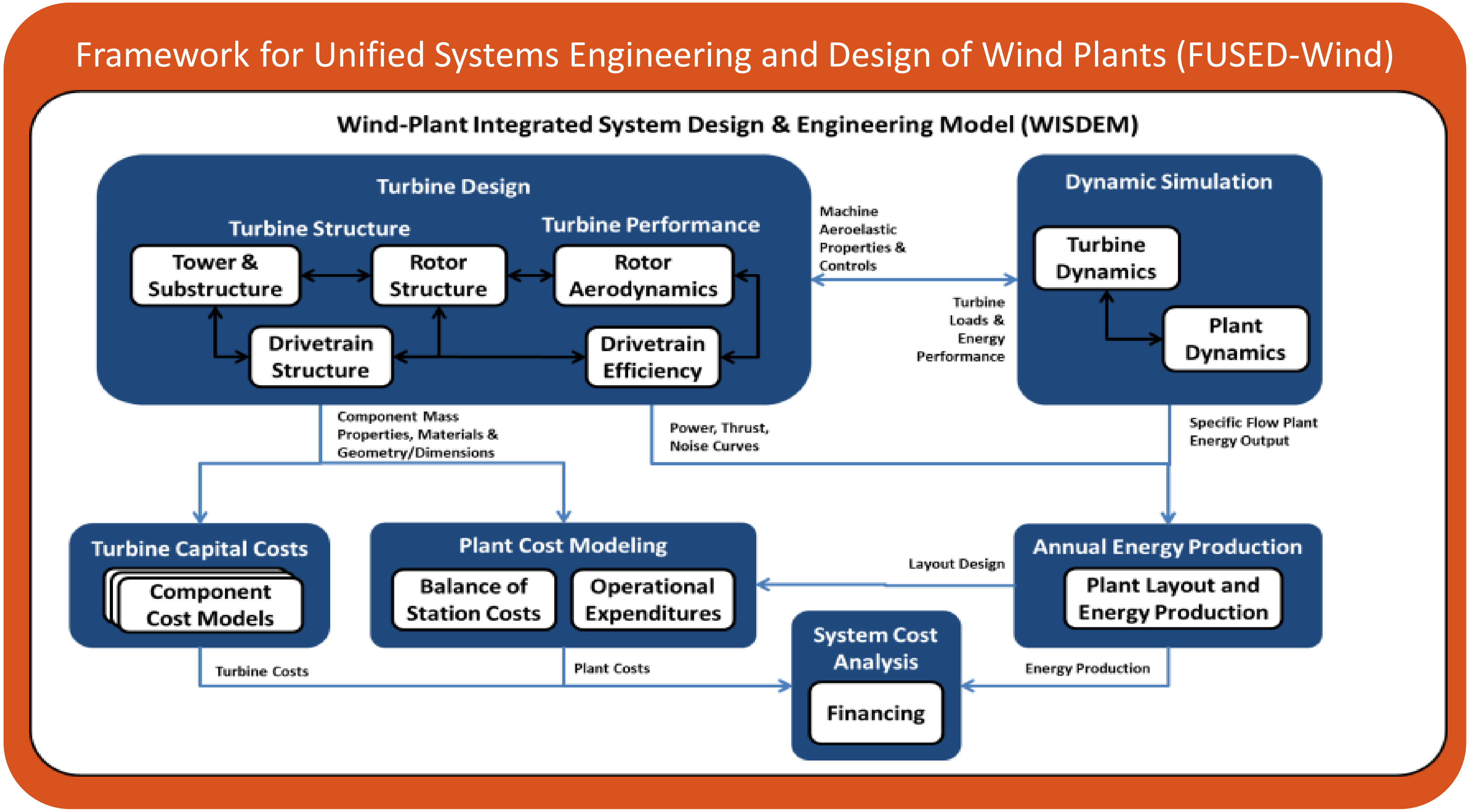
WISDEM™ creates a virtual, vertically integrated wind plant from components to operations.



http://nwtc.nrel.gov/WISDEM

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

NREL WISDEM Current Status

- **Initial Release of Version 2.0:**
  - Physics-based design and sizing tools for a wind turbine (RotorSE, DriveSE, GeneratorSE, TowerSE)
  - Phyics-based design and sizing tools for offshore support structure (TowerSE, JacketSE, FloatingSE – spar only)
  - 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
  - Controls-based energy production model (FLORISSE)
  - CFD based energy production model (WindSE)
  - Wrapper for FAST (AeroelasticSE)

Turbine / Support Structure Models

Turbine and Support Structure Models

- **Turbine models for design and sizing of major wind turbine components:**
  - RotorSE
  - DriveSE/DriveWPACT
  - GeneratorSE
  - 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
  - Only cursory assessment of fatigue (currently working on FAST coupling)
  - Ability to map detailed layup description to cross-sectional properties

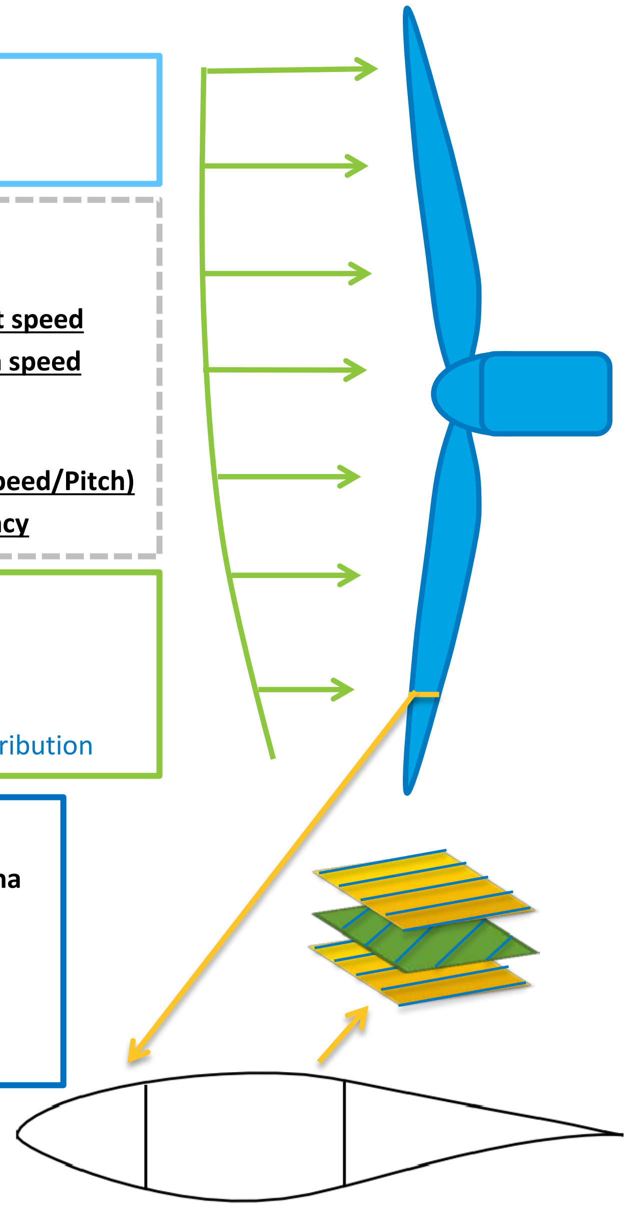
<<< INPUTS

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 >>>

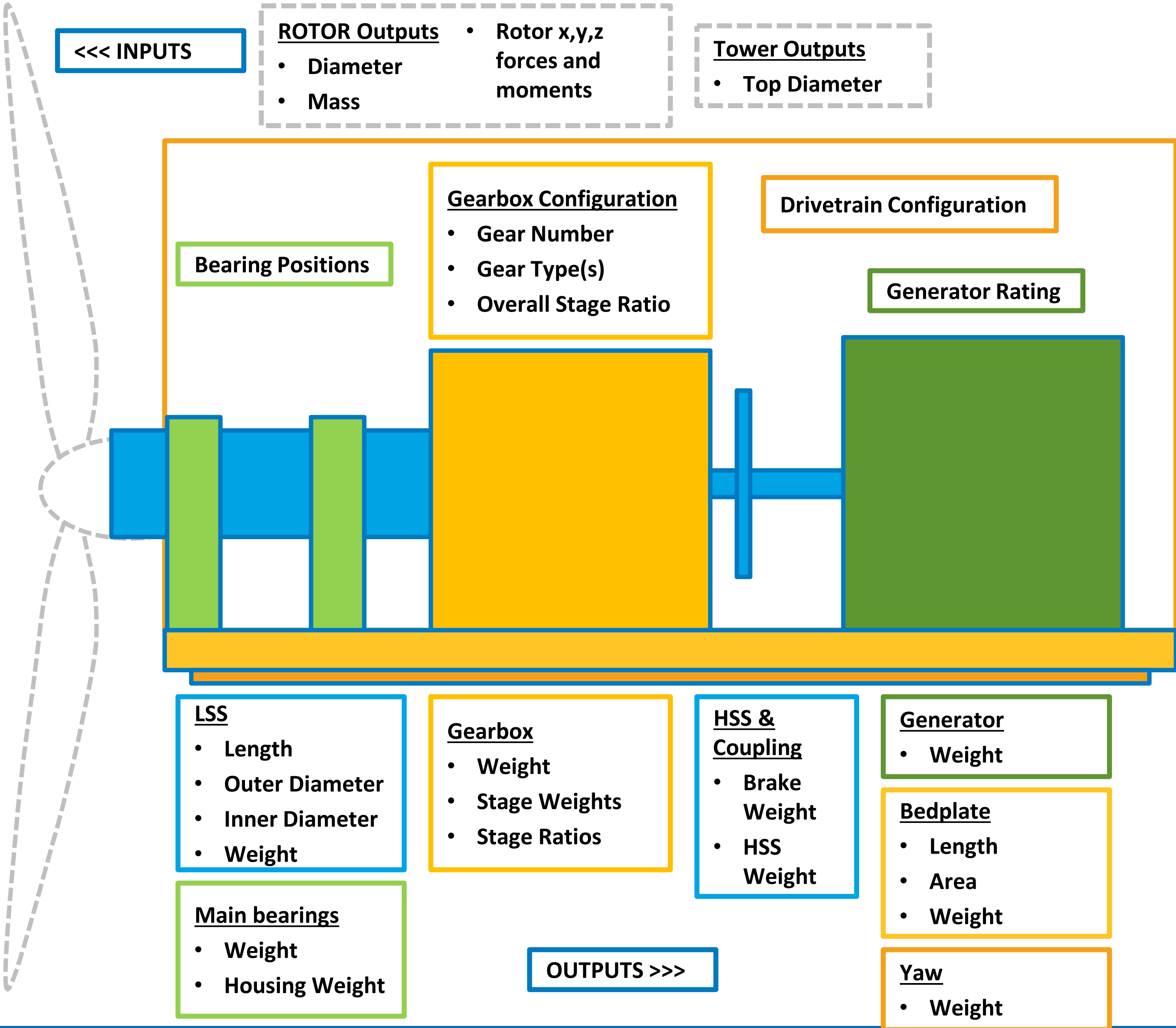
ROTOR STRUCTURE & PERFORMANCE
- **Blade mass and moments of inertia**
- **Cost**
- **Power curve**
- **Turbine AEP**
- **Hub loads**
- **Sound power level**
- **Natural frequencies**
- **Blade displacements**
- **Panel buckling loads**
- **Axial and shear stress**

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:**
  - Only geared systems currently modeled; need to develop models for direct-drive

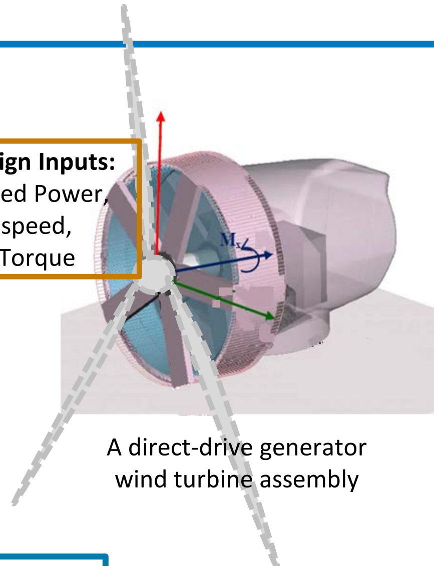


GeneratorSE

Strengths:

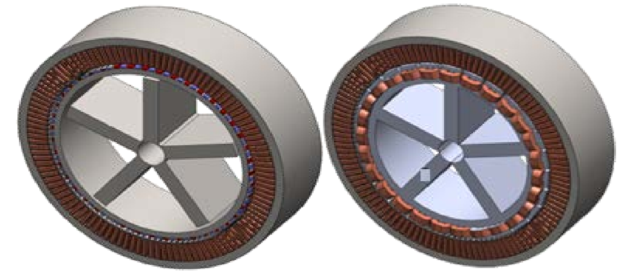
- **Torque-based design for four types of Generator configurations**
- **Can design for low speed-direct drive, medium and high speed drivetrains**
- **Provides for an Integrated detailed structural and Electromagnetic design**
- **Can be tuned for Motor applications**
- **Can be integrated with DriveSE for integrated drivetrain design Optimization**

Design Inputs:
Rated Power,
speed,
Torque



A direct-drive generator wind turbine assembly

Generators for low speed (direct drive) , medium speed and high speed drivetrains



Permanent magnet excited(PM) **Electrically excited(SG)**

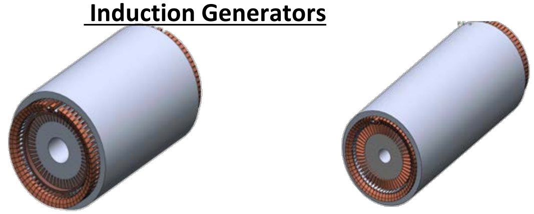
Synchronous Generators

Electromagnetic design	Structural design
• Air gap diameter, Length • Magnet dimensions(PM) , Pole pairs, Excitation current (EESG)	• Number of Spokes • Spoke dimensions to satisfy deflection constraints
Performance parameters Resistance, Reactance • Magnetic loading • Current densities • Terminal Voltage • Efficiency	Performance parameters/Deflection constraints • Tangential stress criteria • Moments of Inertia
Masses and Material costs for magnet, Copper, iron and structural support	

Generators for medium speed and High speed drivetrains

Doubly-Fed Type (DFIG) **Squirrel Cage Type (SCIG)**

Induction Generators



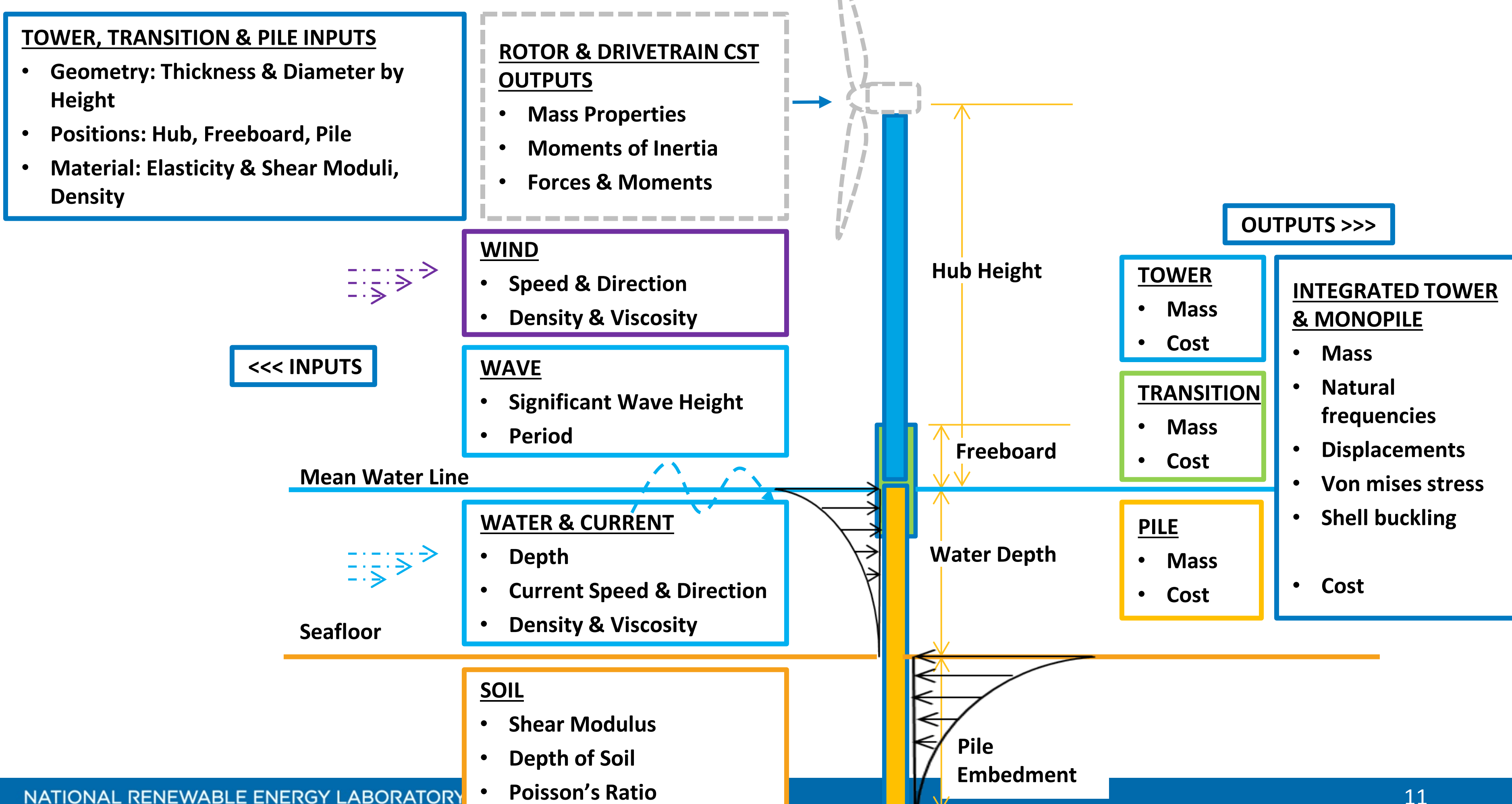
Electromagnetic design	Structural design (In progress as part of SULI project)
• Air gap diameter, Length Pole pairs, Excitation current , Rated Slip	• Generator Stator Casing • Generator Shaft
Performance parameters Resistance, Reactance • Magnetic loading • Current densities • Terminal Voltage • Efficiency	Performance parameters • Tangential stress • Moments of Inertia • Resonance properties
Masses and Material costs for Copper, iron and structural support	

Current limitations:

- **Does not include for detailed thermal modelling (hot spots and winding temperature rise estimation)**
- **Does not include main shaft design and generator bearing support design not included.**
- **PMSG topologies only model radial flux configuration. Insights into more advanced generator topologies such as transverse flux , axial flux permanent magnet generators and superconducting machines are expected to be more valuable in the coming future.**

TowerSE (with pyFrame3DD)

- **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 (tapered) cylindrical steel towers – plan to address concrete in WTT SBV project



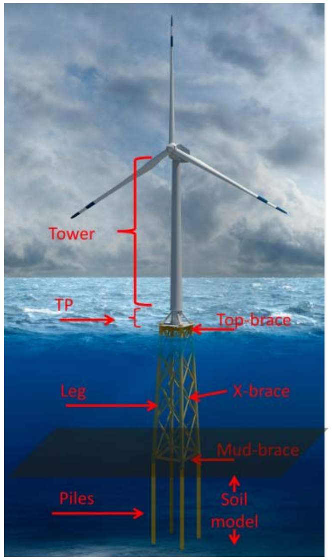
JacketSE (with pyFrame3DD)

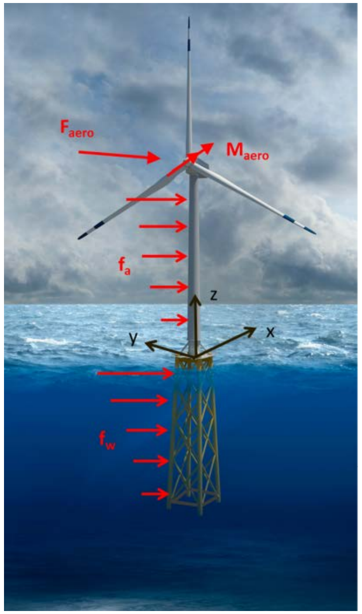
- **Strengths:**
  - Possibility of optimization of each subcomponent (tower, substructure members, piles)
  - API code checks
  - Flexible geometry configuration
  - Soil-Pile interaction via linearized stiffness
  - Can generate SubDyn input deck

- **Current limitations**
  - Simplified (quasi-steady) hydrodynamics; wave loads only on main legs
  - Fatigue analysis: missing (important for joints)
  - Pile lateral capacity: missing
  - Analytical gradients: missing

Inputs

- Water depth
- Wave and Wind conditions (Hmax, wind speed, densities…)
- Deck and Hub heights
- Number of legs(3-4)
- TP lumped mass
- RNA mass tensor
- Hub
- Material mechanical properties
- Soil parameters
- Variables' acceptable ranges (constraints)
- RNA loads
- Drag and added mass coefficients
- Load/material PSFs

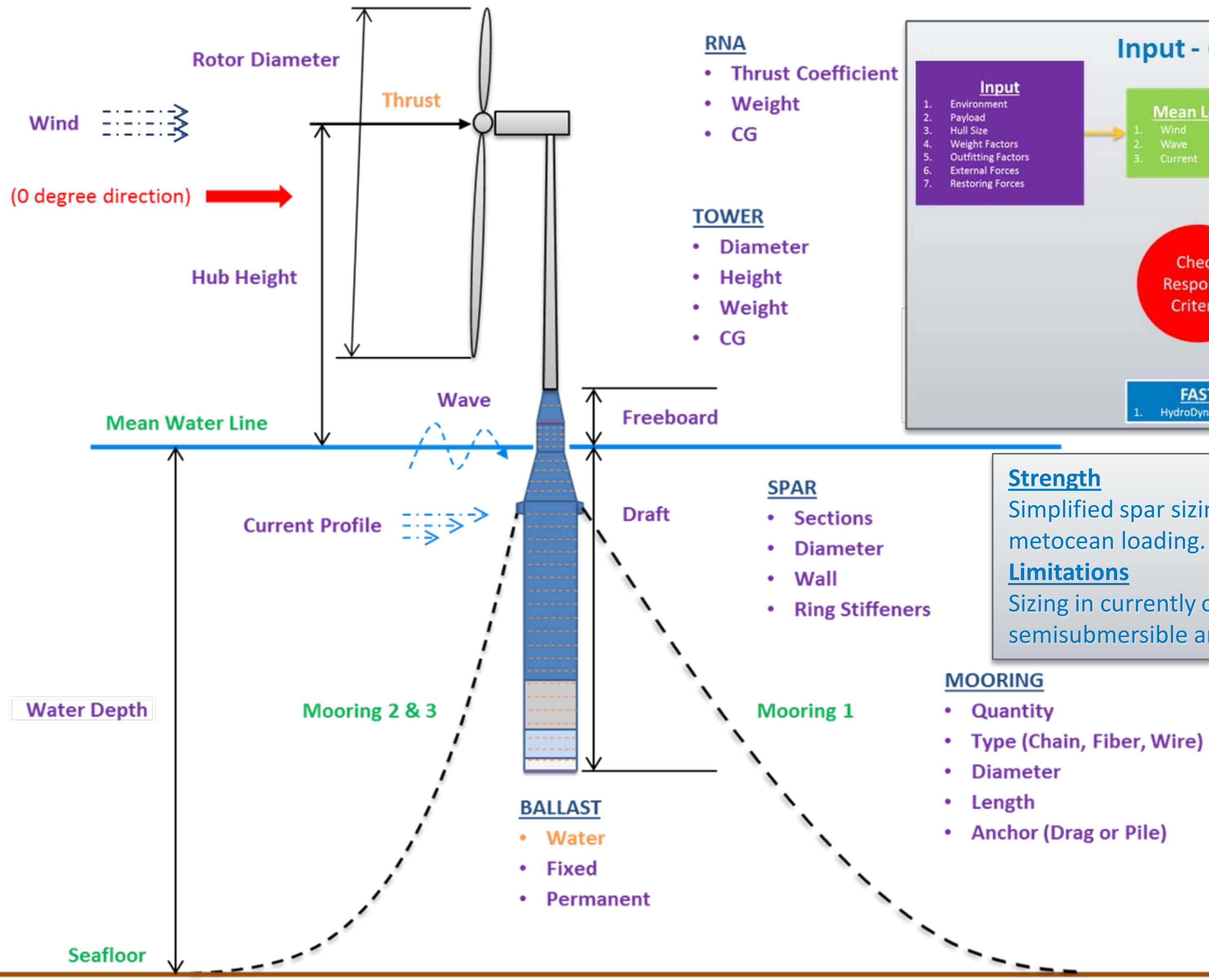


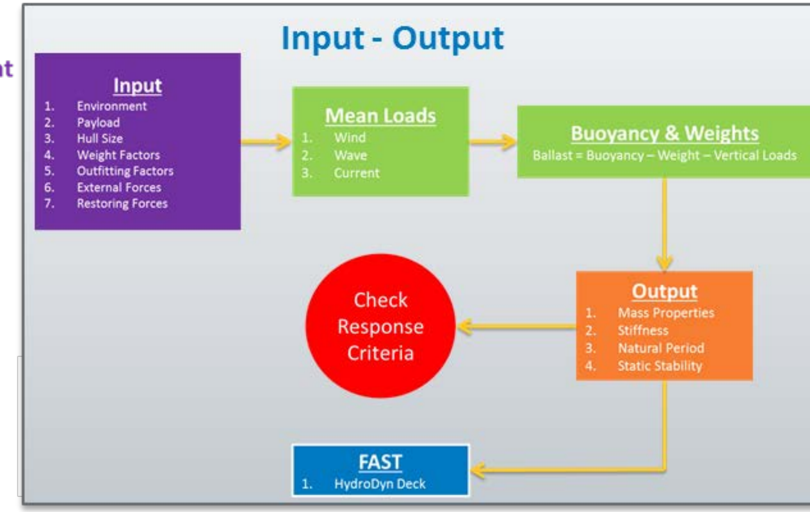


Outputs

- Batter
- Piles' OD,t
- Legs' OD,t
- Braces' OD, t
- TP girder OD,t
- Tower base OD,t
- Tower top OD, t

FloatingSE





Strength

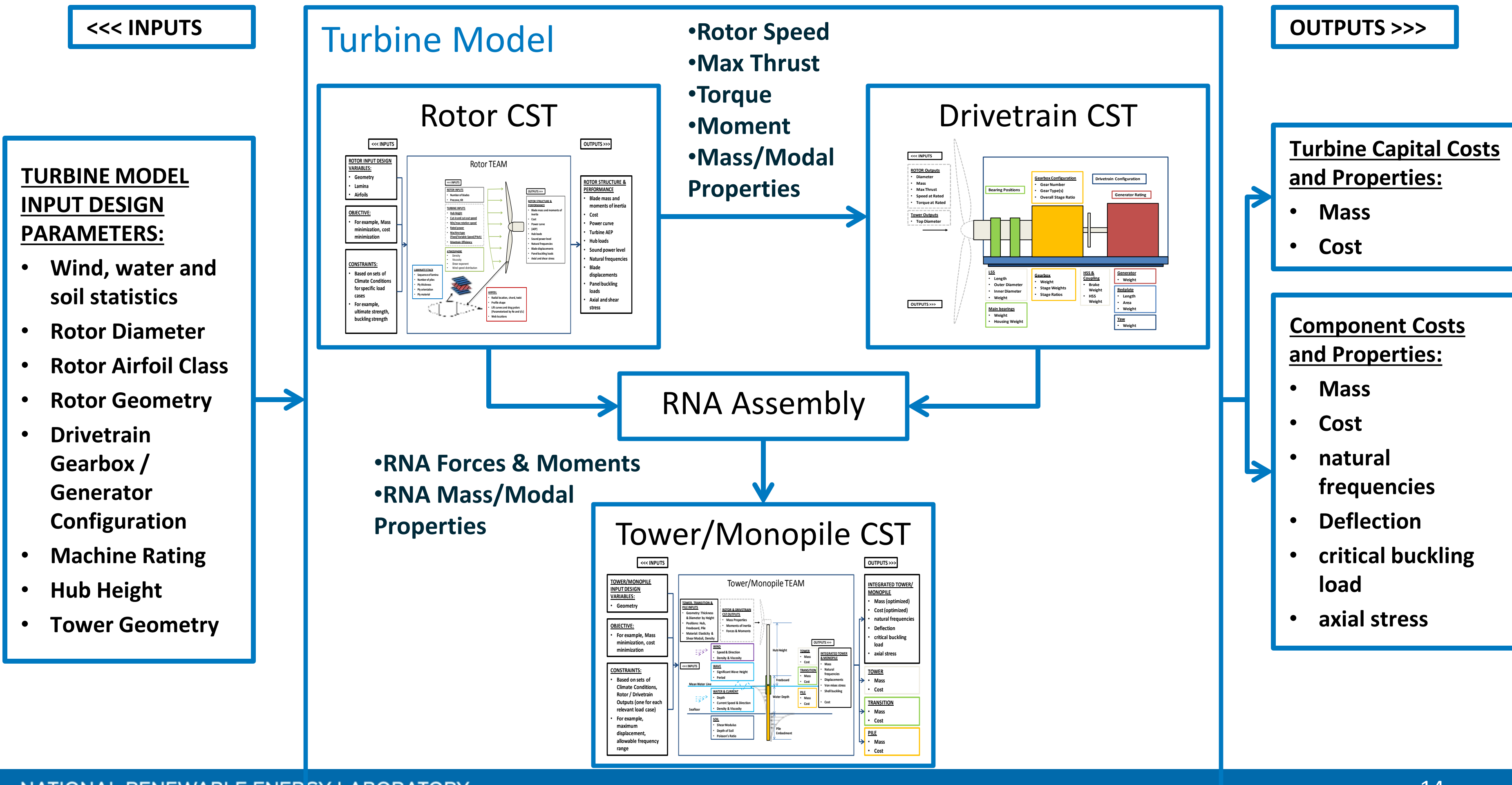
Simplified spar sizing and response based on metocean loading.

Limitations

Sizing in currently only available for spars and not semisubmersible and tension leg platform (TLP).

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

- **Wrapper allows for use of FAST v 7 or 8 (wrapper for OpenFAST under development)**
- **Ability to run many load cases is possible**
  - Run standard IEC cases
  - Run loads analysis with various statistical distributions for inputs using uncertainty analysis methods
- **Ability to adapt turbine design within an optimization and analyze loads with FAST is possible (coupled to Turbine SE models)**

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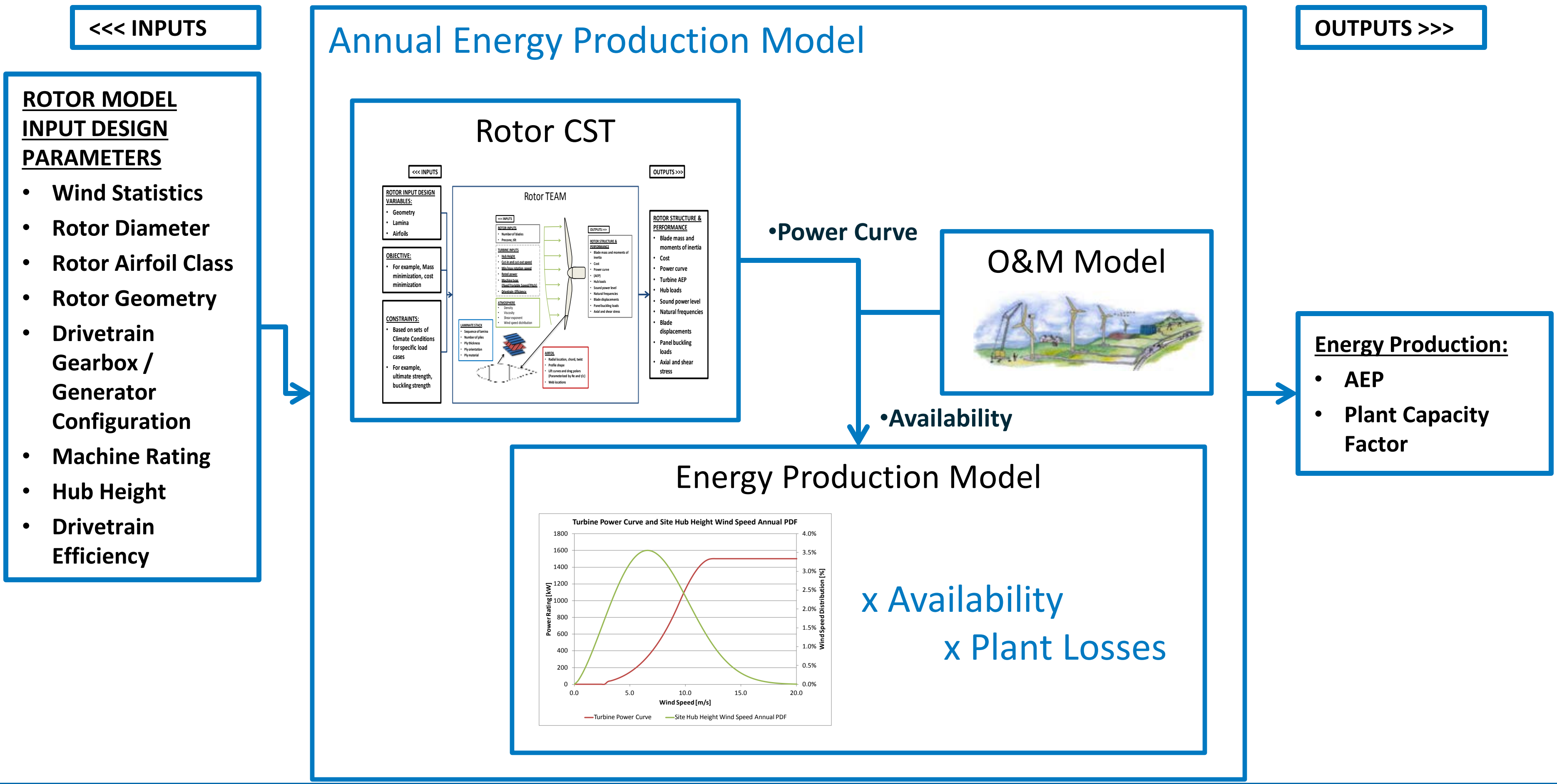
Plant Models

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, FLORISSE, WindSE
  - Balance of Station: Plant_CostsSE
  - Operations & Maintenance: Plant_CostsSE
  - Finance: Plant_FinanceSE

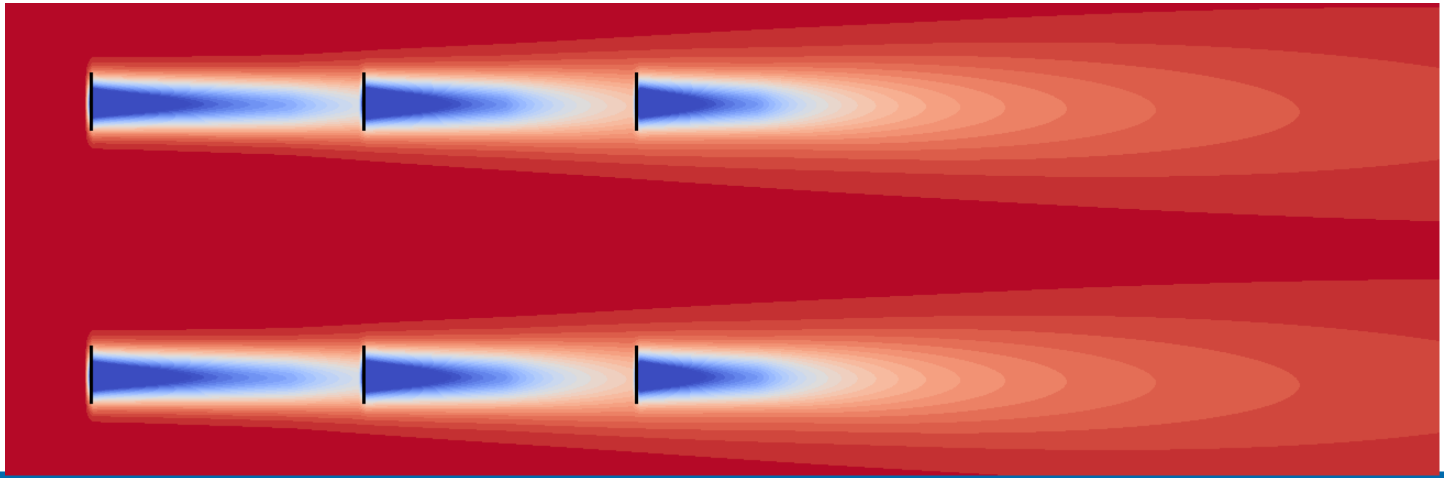
Plant_EnergySE (with openWind)

- **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



FLORISSE

- **Inputs:** turbine model (rotor diameter, hub height, Cp/Ct), control settings (yaw position) and atmospheric conditions (wind resource statistics, stability)
- **Outputs:** power output of each turbine and overall annual energy production
- **Strengths:**
  - Accounts for changes in atmospheric conditions
  - Runs in fractions of a second
  - Can be used for large-scale optimizations
- **Weaknesses:**
  - Static, steady-state, linear wake model
  - 6 tuning parameters
  - Takes into account power, but not loads



WindSE

Strengths:

- Medium fidelity **nonlinear 3D RANS CFD**
- Solves **adjoint equations** for high dimensional gradients
- Enables gradient-based optimization of layout, yaw, hub height, and axial induction factor
- Includes effects of **atmospheric stability**
- Dimension reduction for **UQ** through active subspaces

Current limitations

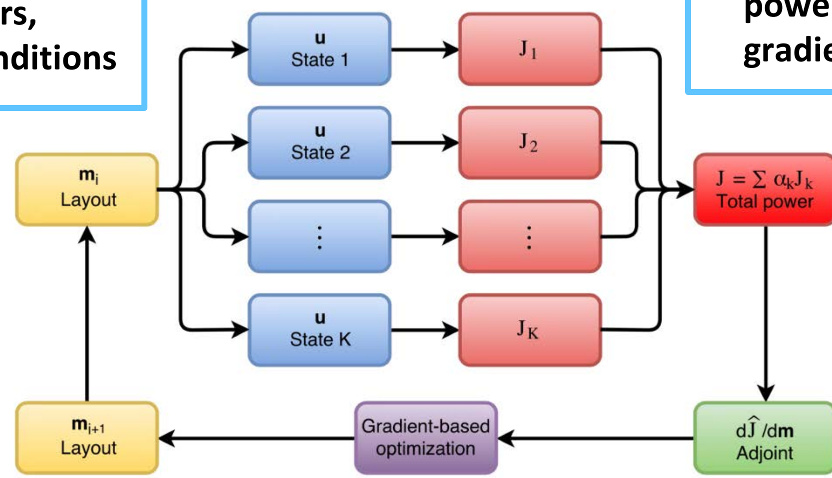
- Computational cost: FlORISSE<<WindSE<<SOWFA
- Steady state

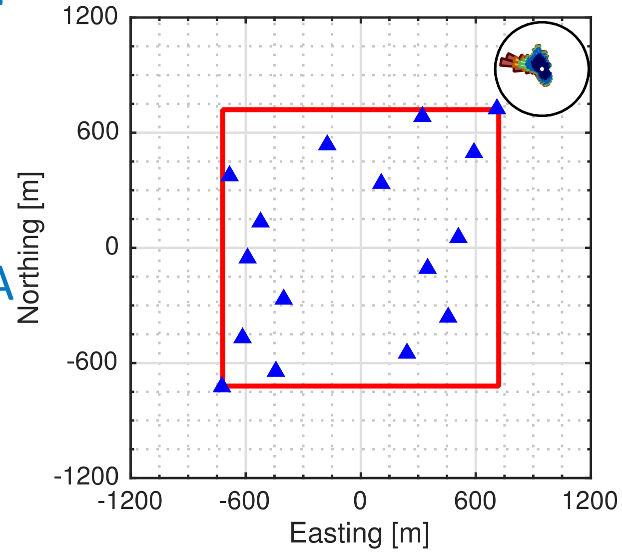
<<< INPUTS

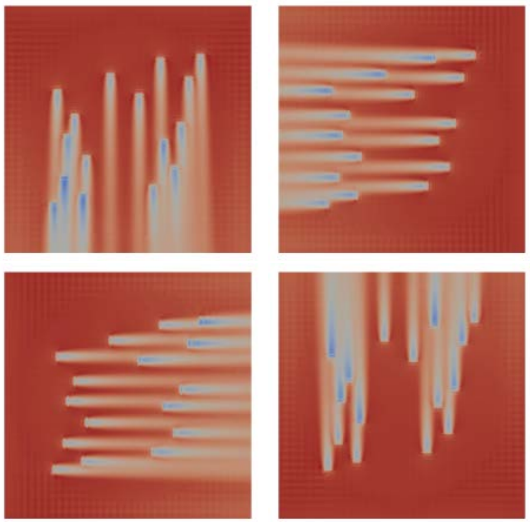
- **Turbine parameters, inflow conditions**

OUTPUTS >>>

- **3D flow field, power, gradients**







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
- New offshore model based on larger set of design parameters and current wind plant cost data

<<< 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 BOS (with new NREL Models)

- **Land-based BOS model:**
  - Empirical model based on subcontract with RES Americas for data from a few years ago; significant work is still needed to develop the model and ensure it works for current technology and has flexibility to adapt for future technology analysis
  - Current version was coded into C++ and wrapped in python and is used in some SE work
- **Offshore BOS model:**
  - Empirical model with significant design input consideration based on subcontract with DNV; this model has been vetted extensively in FOA projects, additional offshore analysis work, IEC Wind Task 26 on cost of energy, collaborations with ECN etc; a report on the model is currently in the publication process; this model is ready-to-go though there are opportunities (as with all models) for extensions of capability
  - Current version was coded into C++ and wrapped in python and is used in some SE work

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**
- **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_CostsSE OPEX (with new NREL Models)

- **Land-based OPEX model:**
  - An old model from GEC now DNV was developed a long time ago; newer data was collected on O&M failure rates and costs a few years ago with DNV; this data needs to be incorporated into the old model and significant work to vet the model is needed
  - Current version of GE model was coded directly into python but has not yet been fully integrated to SE tool; we currently use the cost and scaling model opex module for land-based opex
- **Offshore OPEX model:**
  - Currently we use the ECN offshore model; there are limitations with this: 1) it requires a license, 2) it is in excel which means its very difficult to interface with in more complex analysis, 3) it is in excel so modifying it in more sophisticated ways and adapting it for new technology is very difficult; there are other offshore opex models out there that we will investigate as well.
  - Current excel version is wrapped in python and is used in some SE work

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 will be available through interface to System Advisor Model (SAM) cash flow model which is currently going through open source release process**

<<< 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

Ongoing/Future WISDEM Model Development

- **Planned model fidelity build-out over time with coordinated efforts through FUSED-Wind activities**
- **Near-term known model development**
  - Support Structure Design
    - Concrete tower model under development
    - Other floating platforms
    - Coupling with modeling capability from floating platform LDRD
  - Cost models
    - Improved design-based BOS and OPEX models for land-based and fixed-bottom offshore
    - Integration of floating wind plant cost models
  - Plant Finance
    - SAM wrapper once released
  - Integration of FAST.Farm dynamic wind plant model

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

http://nwtc.nrel.gov/WISDEM