Wind Project Design and Optimization: Introduction, Validation, and Applications of openWind

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Background

- Commercial-scale wind plant design and optimization require the successful synthesis of quality site information with potentially competing layout, technology, and construction requirements.
- Seeking a platform that would more intuitively integrate GIS-based site information and provide more transparency in project optimization, AWS Truepower developed the openWind software package. The founding premise of this effort, and openWind, is to foster industry collaboration and research with a flexible wind project design platform.
- This discussion will present an overview of wind project design with openWind, including key project inputs, an introduction to openWind's development and validation, and discussion of some of the software's specific tools, applications, and collaboration opportunities.

Presentation Outline

- About AWS Truepower
- Defining Inputs: Site Selection and Characterization
- openWind Development and Validation
- openWind Tools and Applications
- Plans and Collaborative Opportunities

Who We Are

- Independent assessments on 60,000+ MW
- Project roles in over 80 countries
- Established in 1983; nearly 30 years of industry experience
- Over 100 professional staff
- Experts in meteorology, spatial analysis, environment, and engineering

What We Do

AWS Truepower works with developers and investors to advance renewable energy worldwide.

Our services cover the lifecycle of solar and wind projects, from initial site qualification through due diligence, performance assessment, and real-time forecasting.

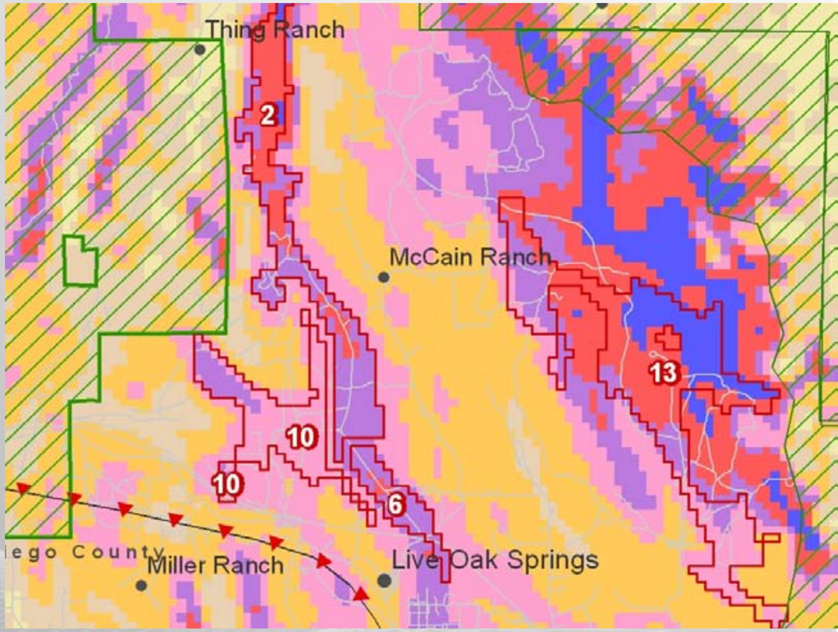
Defining Inputs

- Wind project design is a complex, multi-faceted optimization challenge, balancing among other things:
    - Site Selection and Land Constraints
    - Wind resource and Energy production potential
    - Turbine and Operation characteristics
    - Balance of plant costs (access roads, cables, other infrastructure)
- Effectively defining these parameters is a key first step in project optimization.

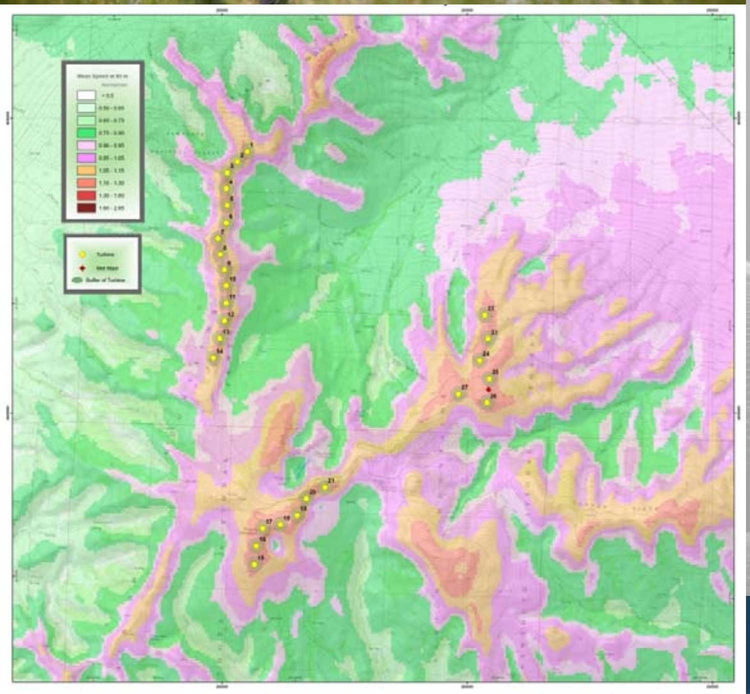
Defining Inputs: Site Selection

During prospecting, identify site(s) and define respective project boundaries and characteristics based on primary development priorities and goals:

- Attractive wind resource
- Transmission access and available capacity
- Site constructability (slopes, road access)
- Compatible land uses and constraints (noise, shadow)
- Local support
- Few or no environmental and cultural obstacles
- Defining these within Geographical information systems (GIS) framework is essential



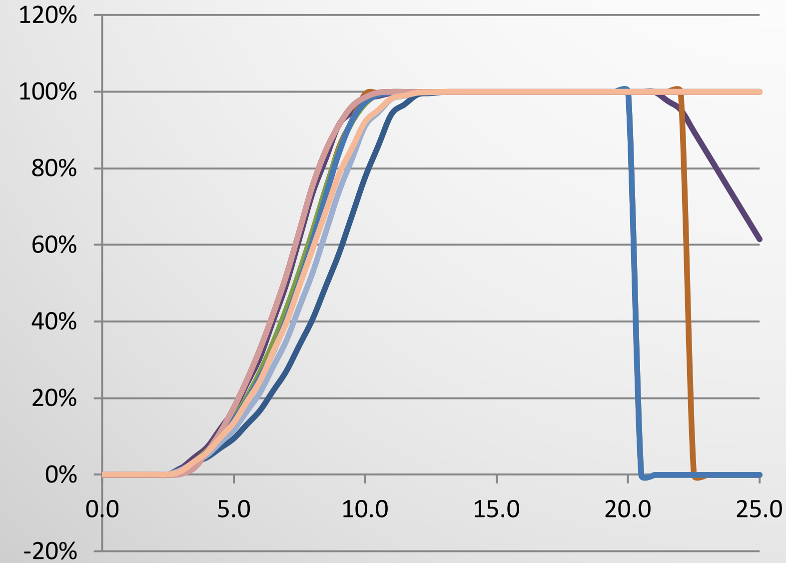
Defining Inputs: Resource

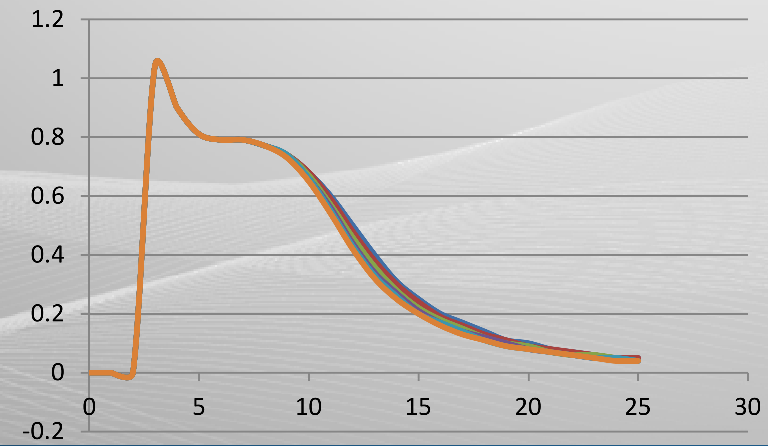


- Accurate calculation of energy production potential, including related parameters such as suitability and wake losses, requires thorough examination of site wind resources.
- Defined through integration of measurements, historical analysis and windflow modeling.
- Typical outputs from this work (and inputs to optimization):
  - –Hub Height Wind speed map
  - –Hub Height Wind resource grid
  - –Site temperature, TI, and shear characteristics
  - –Speed/direction distributions
  - –Time series of key parameters

Defining Inputs: Turbine

- Key physical, operational and cost details about the project's turbine(s) are necessary for production, wake, and cost of energy calculations.
  - –Hub height, rotor diameter, rotor tilt
  - –Power and thrust curves by density, TI, shear and noise
  - –Operational temperature envelope
  - –Installation requirements and costs
- Turbine- and project-related parameters that affect curtailment and loss calculations, such as turbine suitability definitions, grid-related operational rules, and any permit-related requirements





Defining Inputs: Costs

- To move beyond energy production optimization, project costs and finance structures should be characterized as best as possible to help optimize for cost of energy.
- Even reasonable preliminary estimates on BOP parameters – road construction costs, inter-array cabling sizes – can help generate a layout that is closer to buildable and a lower cost of energy than one optimized on production alone.

openWind: Development

- openWind is a software program developed by AWS Truepower, LLC, as an aid for the design, optimization, and assessment of wind power projects.
- It is built around an open-source platform for maximum transparency and to encourage stakeholder collaboration and the growth of a community of users and developers.
- In its user interface, data types, and architecture, the software is patterned from Geographical Information Systems (GIS).
- Its core energy computations are designed to be functionally identical to those of other leading wind farm design programs.

openWind: *Community Edition*

- Validated Energy Capture
- Standard Wake Models:
  - Park
  - Modified Park
  - Eddy Viscosity
- Layout Optimization
- ISO 9613 Noise Model
- Zones of Visual Impact (ZVI) Model
- Optimization Respecting Noise and ZVI Limits
- Mass-Conservation Wind Flow Model (WindMap)
- *openWind* Query System
- Layer Logic and Layer Validity (including buffer setting)
- GPS Integration
- Cross-Platform (runs on Windows/Linux/Unix, 32bit and 64bit)
- Pervasive multi-threading

It's free! awsopenwind.org

Active community forum (2000+ users)

openWind: Architecture

- A project consists of multiple layers – similar to GIS overlays
- openWind is "aware" of the meanings of layers and their relationships to one another
- A key relationship is Parent – Child: the "parent" layer is able to use information contained in the child and may be constrained by the child in some way, and vice-versa
- Each layer may also be given an interpretation – e.g., road, electric cable, water, wind resource grid, turbine, etc.
- In this way very complex optimization problems can be described naturally and easily

openWind: Interface

- **GIS-style interface** accepts most formats:
  - ESRI Shape (*.SHP), ASCII grid (*.ASC), floating point binary grid (*.ADF)
  - WAsP Map files (*.MAP)
  - IDRISI grid (*.RST & *.RDC)
  - GeoTiff (*.TIF) and image files (*.PNG, *.BMP, *.JPG, *.TIF, *.GIF)
  - Binary Interleaved grid (*.BIL)
  - Surfer binary and ASCII grids (*.GRD)
  - Canadian CDED (*.DEM)
  - ASCII XYZ grids (*.XYZ)
  - WindFarmer ASCII DTM (*.DTM)
  - AWS Truepower WRB format (*.WRB)
- Works in Universal Transverse Mercator and automatically converts from geographic to UTM coordinates

openWind: Validation

Model-to-Model

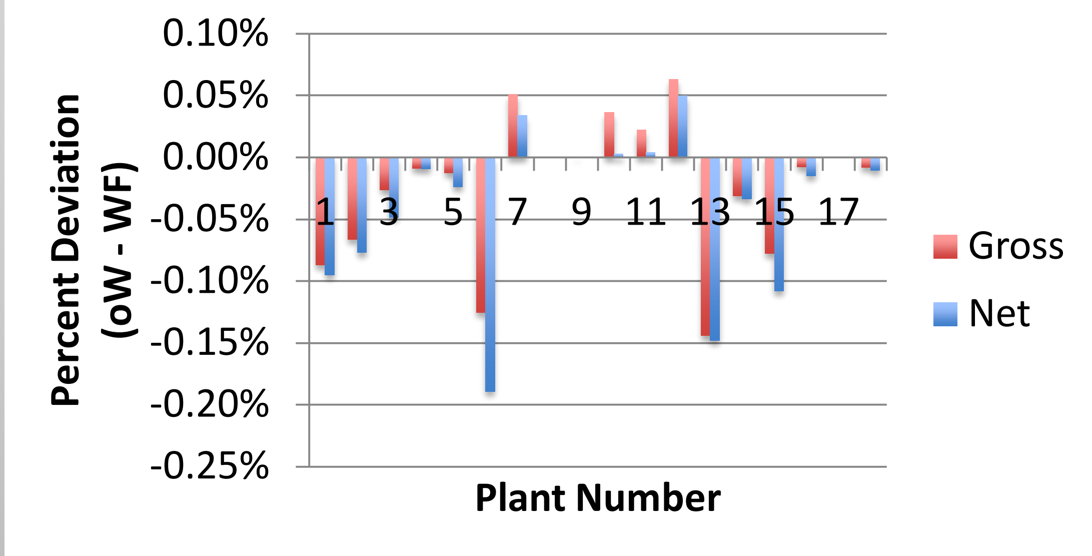
- A comprehensive validation with 20 wind projects
- *openWind* output compared to a leading commercial program
- Gross production matched **within 0.1%**

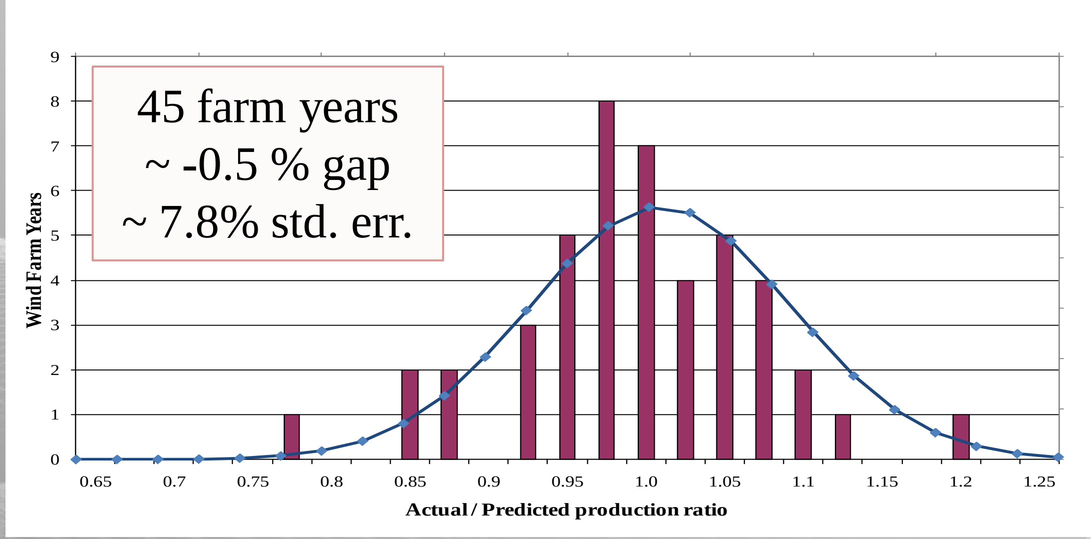
Model-to-Observed

- Estimated production for 45 plant years at 11 plants
- Compared results with actual output
- **Mean error 2.7%** - within uncertainty of the data

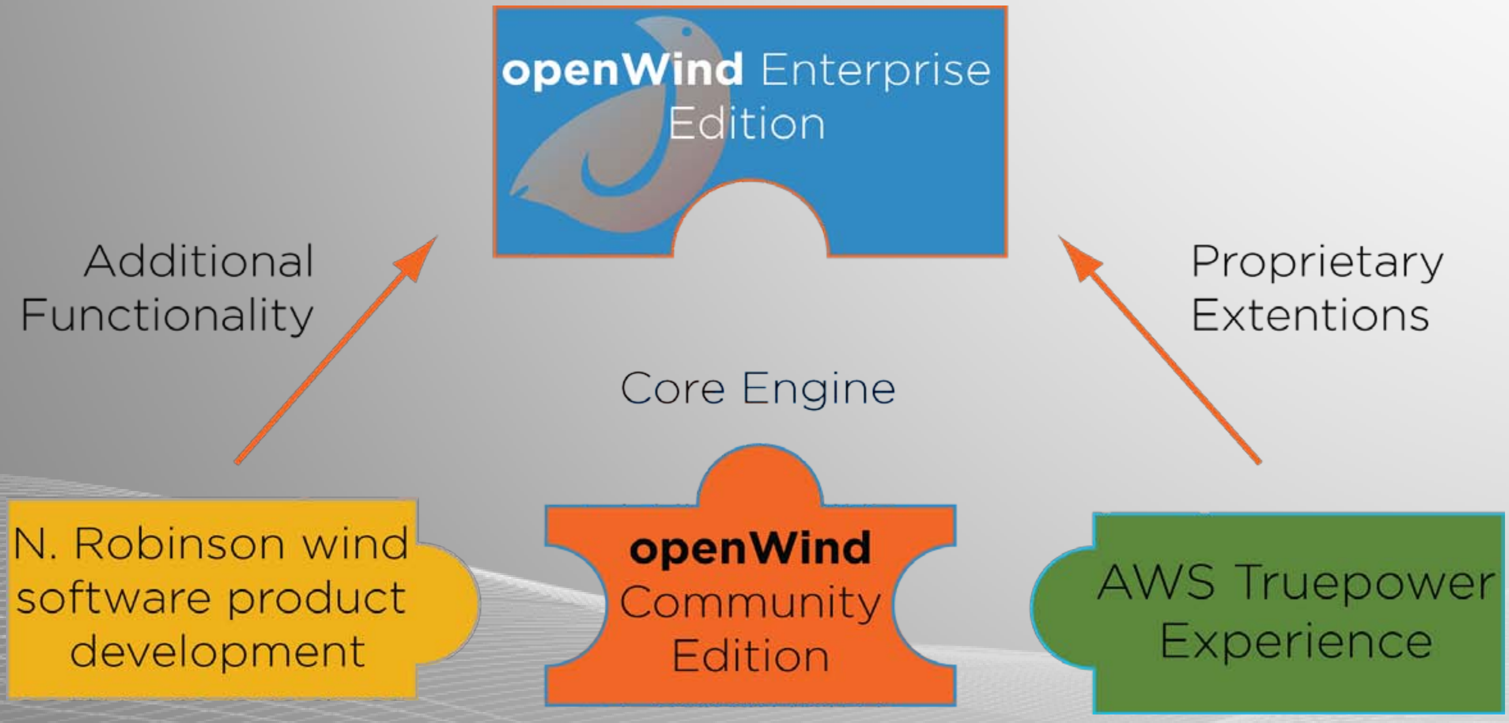
openWind: Validation

- Deviation in percent between openWind and GH WindFarmer, gross and net (with Modified Park) model
- Frequency distribution of predicted and observed production ratios for 45 years of data at 11 plants
- Additional validation details are available in the Theoretical Basis and Validation Document





openWind: *Enterprise Edition*

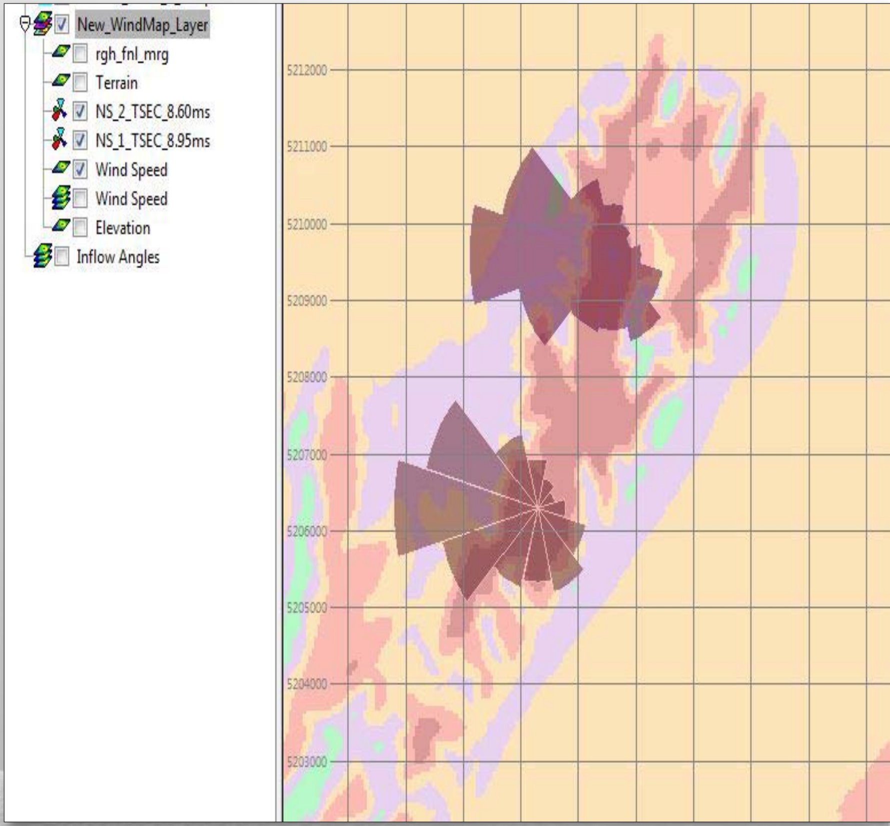


openWind: *Enterprise*

- Cost of energy optimization
- Deep Array Wake Model (DAWM)
- Uncertainty module
- Non-ideal performance losses
  - Directional curtailment, inflow angle, turbulence
- Authentication of Reports
- Gridded turbine layouts
- Siting and Optimization for Large Constrained Sites
- Shadow Flicker
- Project- and Client-specific customization available

Tools: Wind Flow Model

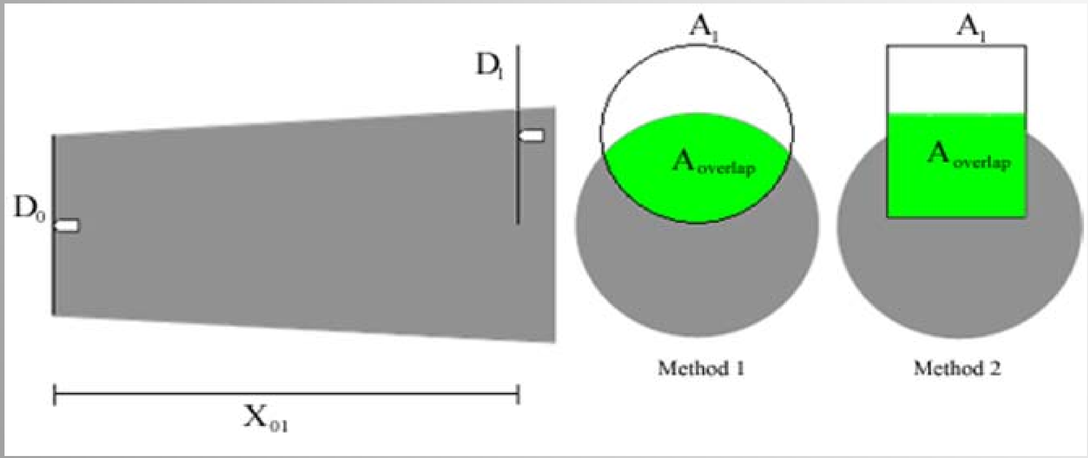
- WindMap within openWind
  - Mass-consistent model
  - Does well in simple and moderate terrain
- Inputs required:
  - Met mast data
  - Elevation data
  - Roughness information
- Recommend a more advanced model(s) for final wind flow assessment, e.g.:
  - AWS SiteWind system – coupled mesoscale NWP-mass-consistent model
  - Other wind flow models (CFD, etc.) can also be used



Tools: Wake Modeling

- Park & Modified Park
- Eddy Viscosity
- Deep Array Wake Model (DAWM)
- Others may be developed and added

Tools: Park and Modified Park



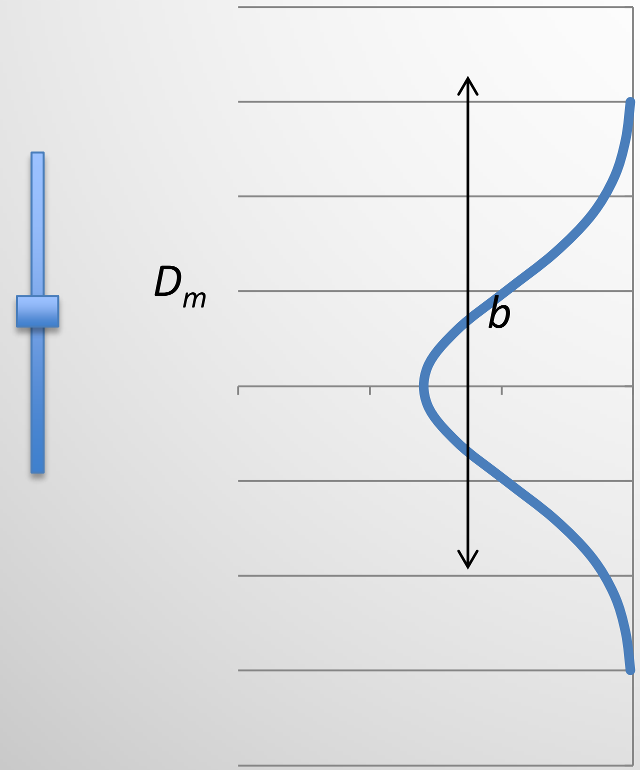
$$\delta V_{01} = U_0 \left(1 - \sqrt{1 - C_t}\right) \left(\frac{D_0}{D_0 + 2kX_{01}} \right)^2 \frac{A_{overlap}}{A_1}$$

- Initial centerline deficit defined by actuator disk theory
- Wake width grows according to empirical wake decay constant *k*
- Wakes combine according to the degree of overlap between wake and downstream rotor

Tools: Eddy Viscosity

$$U\frac{\delta U}{\delta x}+V\frac{\delta U}{\delta r}=\frac{\varepsilon}{r}\frac{\delta(r\,\delta U/\delta r)}{\delta r}$$

$$U=U_i\left(1-D_m e^{-3.56\frac{r^2}{b^2}}\right)$$



- Initial wake defined by a Gaussian curve
- Wake expands by turbulent mixing with the ambient flow according to the thin-shear-layer approximation of Navier-Stokes equations
- Wake persistence depends on turbulence

Tools: Deep Array Wake Model (DAWM)

- Standard wake models assume turbines do not modify ambient flow: it's a one-way process
- Evidence suggests large arrays *can* reduce the available energy in the boundary layer: it's a two-way process
- Can be used during the optimization to accurately model the wake losses
  - Optimizer will work to reduce wake losses as it is optimizing

Tools: DAWM

- Standard wake models assume turbines do not modify the ambient wind flow: it's a one-way process
- Evidence suggests large arrays *can* reduce the available energy in the boundary layer: it's a two-way process
- Frandsen (2007) modeled an infinite array as a change in surface drag, parameterized by a surface roughness length:

$$z_{00} = h_H \exp\left(-\frac{\kappa}{\sqrt{c_t + \left(\kappa / \ln\left(h_H / z_0 \right) \right)^2}} \right)$$

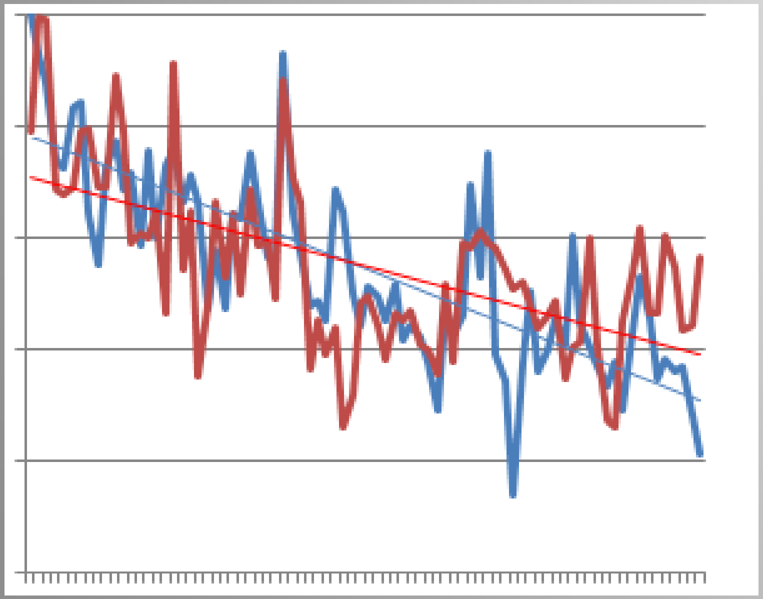
- The effect of the roughness change grows with distance downstream until it reaches the top of the boundary layer

Tools: DAWM

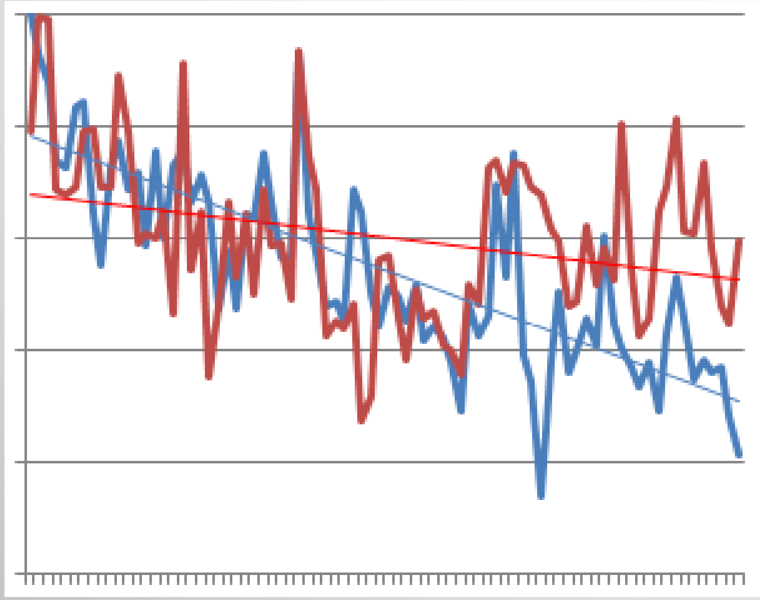
- AWS Truepower adapted Frandsen's theory by modeling individual turbines as a localized roughness change
- DAWM includes both a standard wake model (e.g., Modified Park or EV) and the roughness-change model
- Whichever model produces the greater wake loss is the one that is used
- This effectively divides the array into "shallow" and "deep" zones
- Typically the shallow zone is the first 4-5 rows

Tools: DAWM Validation

Onshore Project 1



DAWM/EV

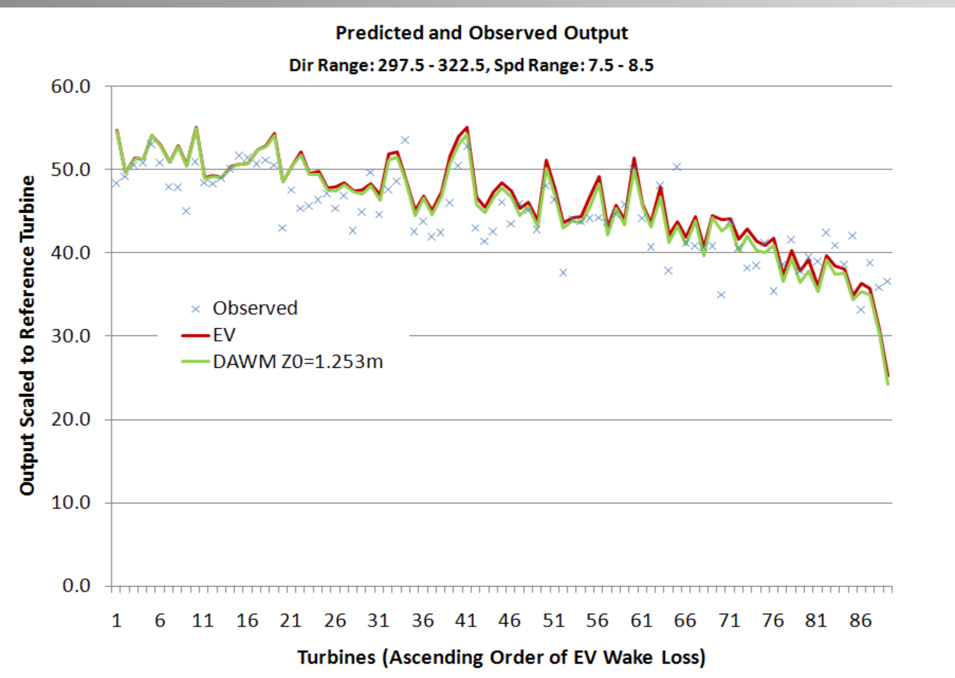


EV

- DAWM tested at two offshore projects and three onshore projects
- Both offshore projects demonstrate a deep array effect
- Two of three onshore projects demonstrate deep array effect

Tools: DAWM Validation

Onshore Project 3



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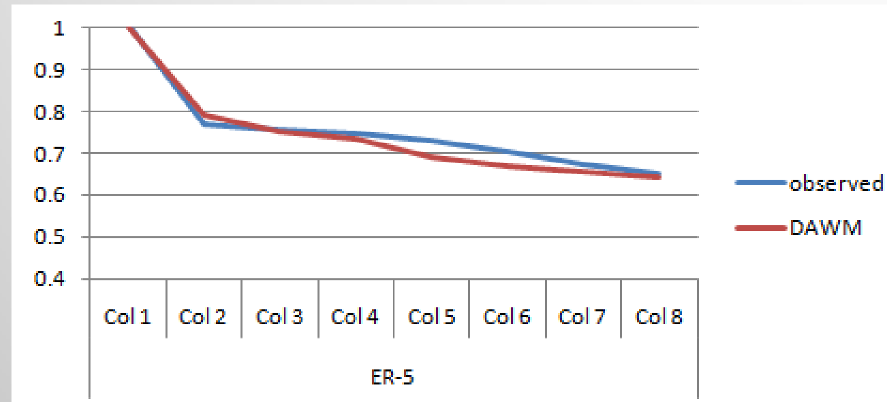
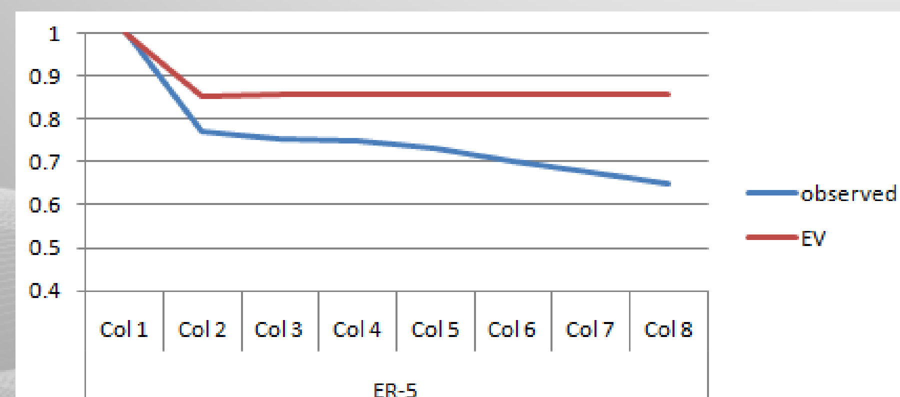


DAWM/EV

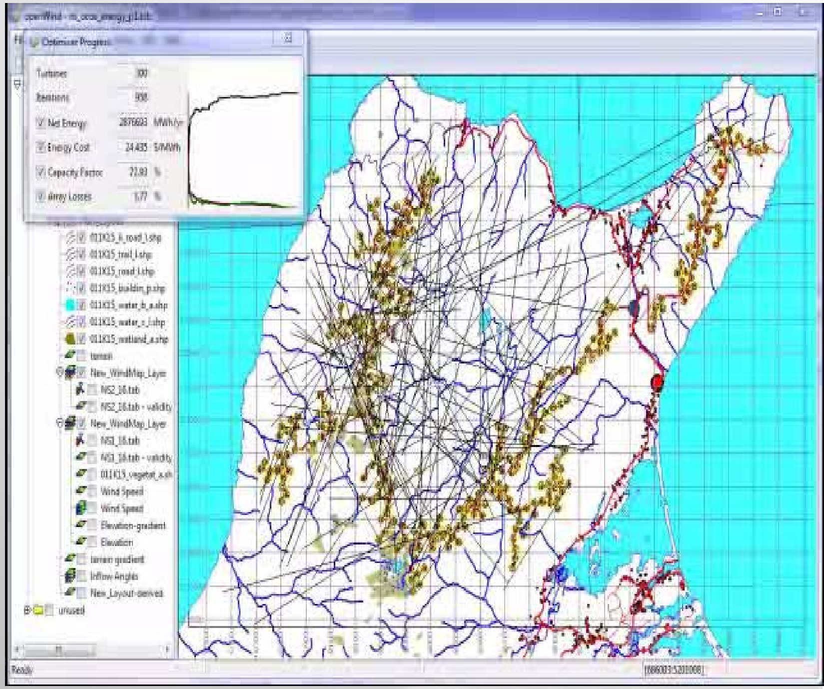


EV only

Additional validation details available in the DAWM whitepaper.

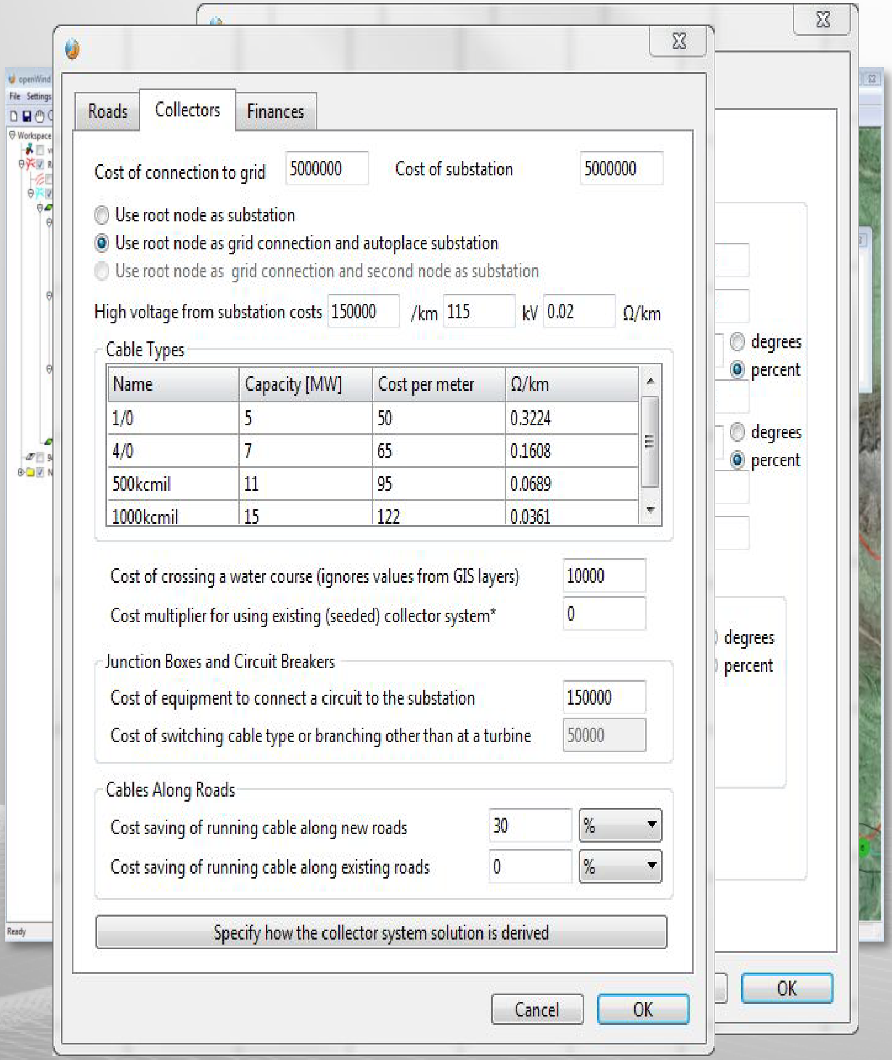
Tools: Cost of Energy Optimizer

- Create realistic, buildable layouts – roads and wiring are not free
- Minimize the cost of energy – not just maximize production
- Develop a custom plant cost model
    - Basic financing assumptions
    - Periodic and one-time costs
- Find optimal plant size
- Identify and eliminate high-cost (stranded) turbines
- Create more compact, lower cost layouts



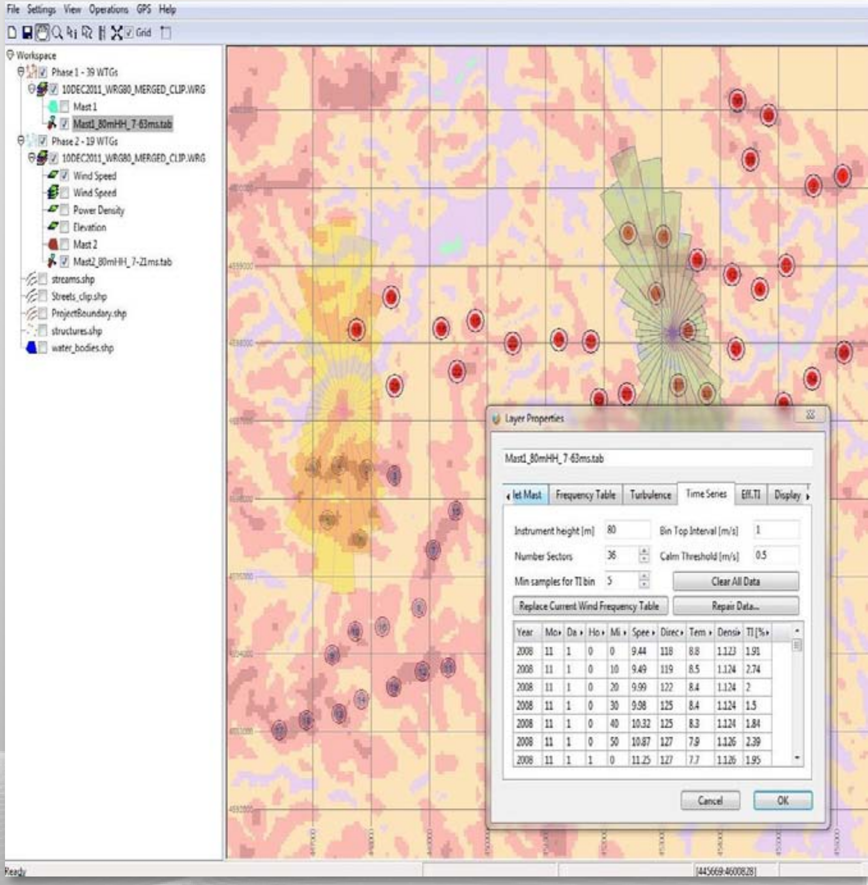
Tools: Cost of Energy Optimizer

- Design and cost access roads and cabling networks
  - Define maximum gradient, minimum turn radius
  - Upgrade existing roads where cost-effective
  - Barriers and costs to cross water and protected areas
  - Define cable types and automatically divide layout into circuits



Tools: Time-Series Energy Capture

- Time-series energy capture models plant output from moment to moment rather than using standard frequency table
- Model effects of seasonal and diurnal variation in
  - Wake losses
  - Turbulence intensity
  - Air density
  - Temperature (high-low temperature shutdown)
- Produce time series of net energy over any period
- Customisable reporting of values per turbine and/or per site



Tools: Turbine Scheduling

- Uses time-series energy capture
- Multiple uses
  - Assess effects of environmental curtailments
  - Calculate energy loss due to a noise curtailment
  - Model effects of turbines turned off during specific times

Plans & Opportunities

- AWS Truepower is open to collaborative opportunities with openWind. Some examples include:
  - Integration with other wind flow, wake, design, and/or optimization models
  - Enhanced computing and/or optimization approaches
- A number of openWind tools are planned for near-term development or refinement:
  - Offshore wind production and cost of energy optimization
  - Enhanced loss calculation, e.g. electrical losses, stability-driven losses
  - Uncertainty Assessment

THANK YOU!

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http://www.awsopenwind.org