Application of Systems Engineering to Wind Farm Design
A Focus on Meteorology & Tools

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December 14, 2010
Wind goes in, money comes out!

Don’t forget the other externals

Other Weather
Snow & Ice
Electricity
Data
Overview

Systems Engineering

- Analyzing Customer Needs/Requirements
- Design Synthesis

Meteorology

- Geography – where’s the windiest spot near a given market opportunity?
  - Define a project boundary
  - Estimate NCF
- Design preliminary turbine array and observation campaign
  - Internal Constraints Analysis
  - Site suitability
  - Near-site surface data
Overview (Continued)

Systems Engineering

• Design Validation & Iteration

Meteorology

• Meteorological Observation & Modeling
  – Observations: MET towers, Sodar, Lidar
  – Long Term Data
  – Spatial Models: WAsP / WindFarmer / WRF/OpenFOAM
  – Internal Control Documents (ICDs) provide consistency as well as dictate project advancements & milestones
Overview (Continued)

Systems Engineering

- Iteration & Tradeoff analysis
- Construction
- Operations

Meteorology

- Evaluate production & maximize
  - Rough crosswind / downwind spacing
  - Individual turbine placement
  - Analysis of complex turbine / terrain interactions
  - Implementation of lessons from operations
- Identify root cause of excessive faulting or failures
  - Due to meteorological conditions
  - Due to complex interactions
Tools (Early Stage)

- Nearby Observations
- Wind Map
- Slope
- Deviation From Fitted Plane
Tools (Mid-Stage)

- NCAR / NCEP Global Reanalysis
  - WRF (dynamic downscaling)
  - Multivariate regression

- On-site Observations
  - MET towers (lots and lots of MET towers!)
  - Sodar & Lidar
    - Captures scales relevant to terrain and turbines
Tools (Mid-Stage)

• Spatial Modeling
  – WAsP (Jackson & Hunt Flow Model, 1975)
    – 2D Navier–Stokes equations
    – Assumes log velocity profile
    – Polar grid
    – Quick
    – Validated for numerous types of terrain
      – Including terrain where it shouldn’t be applied
    – Black box
  – Windfarmer
    – Used to calculate turbine wake impacts & energy yield
    – Includes eddy viscosity wake model
    – Can be initialized from many flow models
Tools (Late Stage)

- OpenFOAM (CFD)
  - FOAM (F)ield (O)perations (A)nd (M)anipulation library
  - OpenFOAM is an Open Source C++ library and collection of solvers (executables)
  - OpenFOAM is particularly well suited for interface tracking problems (i.e. two or more fluids).
  - OpenFOAM is not specifically designed for atmospheric flows like WRF but is easily modified by comparison.
Tools (Late Stage)

- **OpenFOAM Solver**
  - **buoyantPimpleFoam** - Transient solver for buoyant, turbulent flow of compressible fluids
    - Includes the gravitational body force
  - **buoyantBoussinesqPimpleFoam** - Transient solver for buoyant, turbulent flow of incompressible fluids
    - Includes the gravitational body force
    - Uses Boussinesq approximation
  - **simpleWindFoam** – Steady-state solver for incompressible, turbulent flow
    - Does not include the gravitational body force
    - Includes external source in the momentum equation to approximate wind turbines
Tools (Late Stage)

- Wakes due to terrain are visible
- Complex flows can be visualized
Tools (Beginning to End)

- Application of tools to real example
  - Layout Revision
    - Setback analysis
    - Input from observational campaign
- As-Builts
Tools (Operational)

• Retrospective Study (Monthly / Quarterly)
  – Permanent on-site meteorological facility
  – Past climate (Global reanalysis)
  – Helpful to have overlapping observation periods with development METs
Tools (Operational)

- Performance
  - Analysis of faulting
    - Is it based on turbine placement or something else?

- Does faulting display a directional dependence?
  - Placement?
Summary

• Systems engineering enables one to optimally managing a technically complex system such as wind farm development and operations
• Numerous wind farm design tools are available to help the meteorologist with most tasks
• When wind farm development through operations is viewed as a whole, successive wind farms will have higher performance
• Application of these tools, plus continuous updating tools and methodology, will ultimately yield higher performing wind farms