Site selection, optimisation and energy production

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Wind turbines convert momentum to energy

• **3 blades on a rotating shaft**
  - Wind over the blades generates lift
  - which turns the shaft
  - to power the generator.
  - Controls yaw the turbine into the wind

• **Power in the wind;**

\[ Power = \frac{1}{2} \rho AC_p V_\infty^3 \]

\[ C_{P_{\text{max}}} \approx 0.59 \]

50 m radius = 7,853 m²
Winds of 10 m/s, at sea level
Power = 2.84 MW (1,500-3,000 homes)
Energy available depends on the wind and turbine

Examples of wind frequency distributions

The turbine power curve

Power captured, $E$

$$E = \int P(U) f(U) dU$$

Capacity factor, $c.f.$

$$c.f. = \frac{E}{n(\text{turbines}) \times P(\text{rated})}$$
US Commercial Turbine Development

The 1980's
- Altamont Pass, CA
- Kenetech 56-100kW, 17m Rotor
- Altamont Pass, CA
- Kenetech 33-300kW, 33m Rotor

The 1990's
- Buffalo Ridge, MN
- Zond Z-750kW, 48m Rotor
- 500kW
- 300kW
- 750kW

2000 & Beyond
- Arklow, Scotland
- GE 3.6MW, 104m Rotor
- 1.5 MW
- 2.5 MW
- 5 MW
- 3.6 MW
- Land Based
- Offshore
- Medicine Bow, WY
- Clipper 2.5MW, 93m Rotor

NATIONAL RENEWABLE ENERGY LABORATORY
Designing a wind farm
Colorado has a significant wind resource
Finding the right location for a wind farm

1. Identify the region or state
2. Look for transmission
3. Lease land
4. Measure and model locally
5. Optimize the site layout

Transmission map from http://www.coloradoenergy.org/corrd/
Prospecting using temporary towers

- Quantify the wind resource at hub height
  - Annual distribution
  - Seasonal cycle
  - Diurnal cycle

Horizontal and vertical extrapolation


Need to extrapolate measurements from one tower across the site

- Use mesoscale models (WRF, ARPS, MM5)
- Or CFD (Ventos, StarCCM, Fluent)
- Or linear models (WASP)

Map flows for each wind speed and direction

- n direction bins
- n wind speed bins

Estimate wind speed, direction and turbulence at each point

**Fig. 4.** Turbulence intensity at 50 m agl for north-westerly winds, direction 305°. White lines are streaklines of the flow. Black lines are contour height levels. White dots show turbine and mast locations.
Turbine Selection

Site-wide wind frequency distribution

What is the annual average wind speed, maximum wind speed, and turbulence intensity?
Site optimization: wake effects

S. Emis, Meteorological Explanation of Wake Clouds at Horns Rev Wind Farm, DEWI magazine. (http://www.dewi.de/dewi/fileadmin/pdf/publications/Magazin_37/07.pdf)

Photographer C. Steiness © Vattenfall
Site optimization: turbine-turbine interaction

- Wakes lead to regular turbine spacing in flat terrain or offshore
  - Was 7-10 D downwind, now 10-20 D
  - Was 3-5 D cross wind, now 5-10 D

- Several different wake propagation models
  - Park
  - Eddy viscosity
  - Dynamic Wake Meandering

Site optimization – GIS tools

• Want the best turbine layout for the site
  o Minimise costs
  o Maximise income
  o Minimise cost of energy
  o Within constraints

• Many commercial tools
  o Wind farmer, WindPRO,

• An Open Source tool
  o www.awsopenwind.org

Open Wind: screenshot from http://www.awsopenwind.org
Optimization gives very different results

Right, Siemens 2.0 MW machines in Copenhagen Harbor

Left, GE 1.5 MW machines in Fort Sumner, NM
Optimization gives very different results

Whitelee Wind Farm, Scotland (140 Siemens 2.3 MW)
Where current methods struggle
Complex flow environments

- Over forests
- Downwind of hills
- In passes
- In low level jets
- On the coast
- Stratification
Complex flow environments

- Over forests
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The Low Level Jet observed at Lamar (R. Banta, NOAA and Neil Kelley, NWTC)

Uncertainties in wind speed

Wind speed uncertainty (~7%)

- Array loss modeling
- Site wind measurement accuracy
- Flow model
- Long-term wind climate
- Terrain data

Power Curve

Source: typical figures from presentations from GL-GH, DNV Kema, Sgurr Energy

Source: GE-energy.com, factsheet for GE 1.5-77 (Class II) wind turbine
Uncertainties in annual power production

- Many different sources of uncertainty in AEP
  - Power curve
  - Wind resource / interannual variability
  - Wind modeling
  - Turbine availability
  - Grid availability

P$_{xx}$: the amount of electricity generation forecast to be exceeded in xx% of years

DSCR: Debt service coverage ratio, or ratio of income to interest on debt (loans)

Adapted from A. Tindal “Financing wind farms and the impacts of P90 and P50 yields” EWEA Wind Resource Assessment Workshop, May 2011
Systems engineering
Katherine Dykes
NREL’s cost and scaling model

- Current cost model uses parameterized functional relationships calibrated to historical trends
- Originated with detailed design studies in early 2000s (WindPACT)
- Evolution of technologies since WindPACT difficult to capture in parametric model
- Desire exists to do forward looking analysis and understand how design parameters impact highly coupled physical system

Current structure of cost model
System Engineering Program Objectives

- Implement software platform for integrated wind plant techno-economic modeling that maintains flexibility, extensibility and scalability
- Development includes four general phases:
  1. physical turbine and cost of energy models
  2. plant layout tools accounting for turbine interactions affecting loads and energy production
  3. detailed component design for studying innovation impacts on overall system performance
  3. models for non-traditional design criteria such as utility, community, and environmental impacts.
Integrated analysis tool using:
1. models of varying levels of fidelity across
2. different levels of a wind energy system
3. performing a variety of multi-disciplinary analyses from sampling to optimization
Systems Engineering Tool Development

- Governing module: work flows integrate models together in structured ways – linking inputs and outputs for appropriate system level analysis (use of NASA’s OpenMDAO software)
- Optimization / analysis tool: different analysis algorithms are used to drive model analysis (internal to OpenMDAO or via Sandia’s DAKOTA software)
Coordinated Analysis: integration of various models with the goal of full system representation while preserving use of different levels of fidelity representing different sub-systems.
Systems Engineering Tool Development

• **Current Status and Plans:**
  – Initial tool and analysis completed this year including models for each aspect of the wind plant: capital costs, energy production, balance of plant, operations & maintenance (ECN offshore model) and finance
    • Focus on NREL 5 MW reference turbine and plant for DOE baseline offshore wind project
    • Additional models include turbine aerodynamic noise (using FAST) and a detailed cash flow model (based on NREL SAM model)
  – Subsequent years will focus on improved fidelity modeling for turbine:
    • Plant (incorporation of plant layout model including wake effects) via OpenWind
    • Incorporation of multiple offshore substructure cost and sizing tools for jackets and floating platforms (spar, TLP, semi-submersible)
    • Incorporation of NREL FAST aeroelastic code suite
  – Workshop planned for Fall / Winter FY13
    • Invited presentations and abstract submissions for posters on topics for wind system optimization, systems engineering, integrated turbine-plant design
    • Side-meeting on harmonization of interfaces across turbine and plant models
    • Side-meeting for detailed review of NREL models and overall tool
Closing
Levelized Cost of Electricity

**Construction Validation:** (reduced transportation and logistics variability)

**Generation Validation:** (reduced wind plant underperformance)

**Operations Validation:** (reduced useful life variability)

**Discount Rate**

**LCOE ($/kWh)**

- Rotor
- Drive Train
- Tower
- Balance of Station
- Plant Perf. Optimization
- O&M/LRC
- Deployment Barriers & Costs

*All LCOE are unsubsidized*
Ongoing research into many areas

Improvements being made in:

• Measuring and modeling site conditions
• Turbine selection
• Understanding turbine response to inflow conditions
• Connections between site conditions and losses
• Optimization frameworks and methods
Extra slides
Which Components Fail?

Energy losses are not trivial

100 MW wind farm @ 25% c.f. @ $100/MWh

- Annual income without losses: $21,900,000
- 1% loss: $219,000
- May well be other financial penalties

Typical figures from presentations from GL-GH, DNV Kema, Sgurr Energy