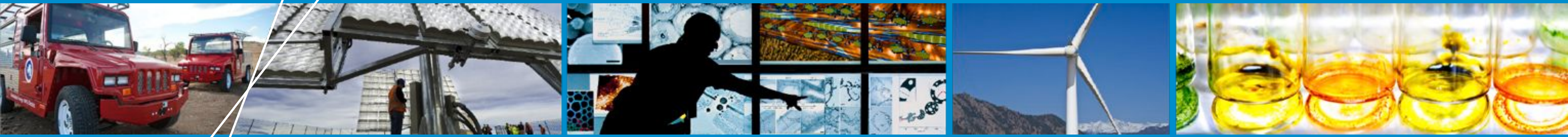
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Site selection, optimisation and energy production



Andrew Clifton, Katherine Dykes

National Wind Technology Center

Webinar for Iowa State University, October 12 2012

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;**

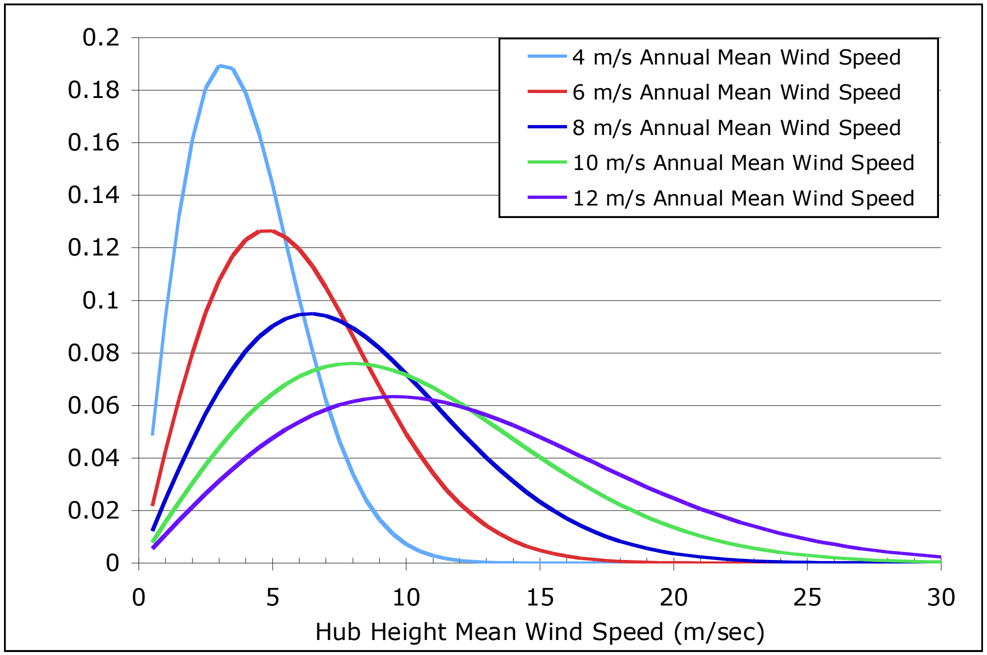
$$Power = \frac{1}{2} \rho A C_P V_\infty^3$$

$$C_{P\max} \cong 0.59$$

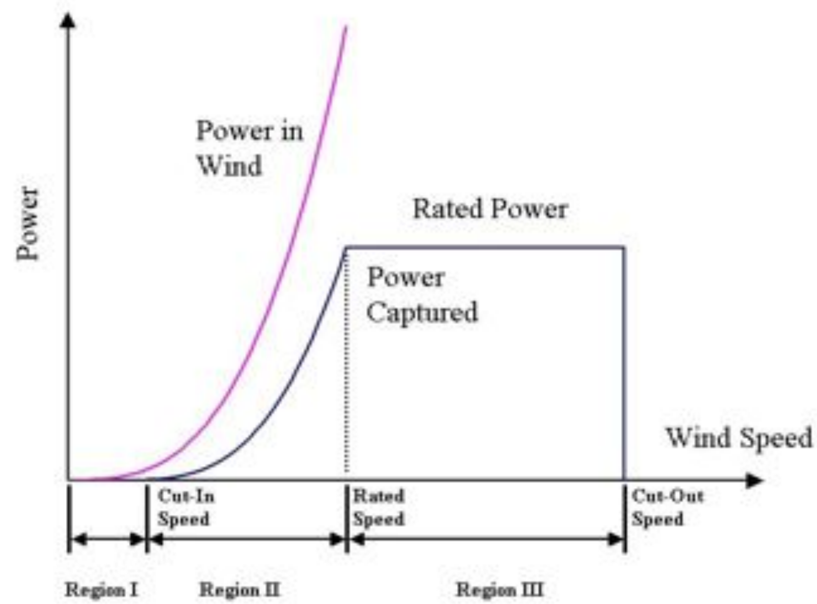
50 m radius = 7,853 m^2
Winds of 10 m/s, at sea level
Power = 2.84 MW (1,500-3,000 homes)

Energy available depends on the wind and turbine

Examples of wind frequency distributions



The turbine power curve



Power captured, E

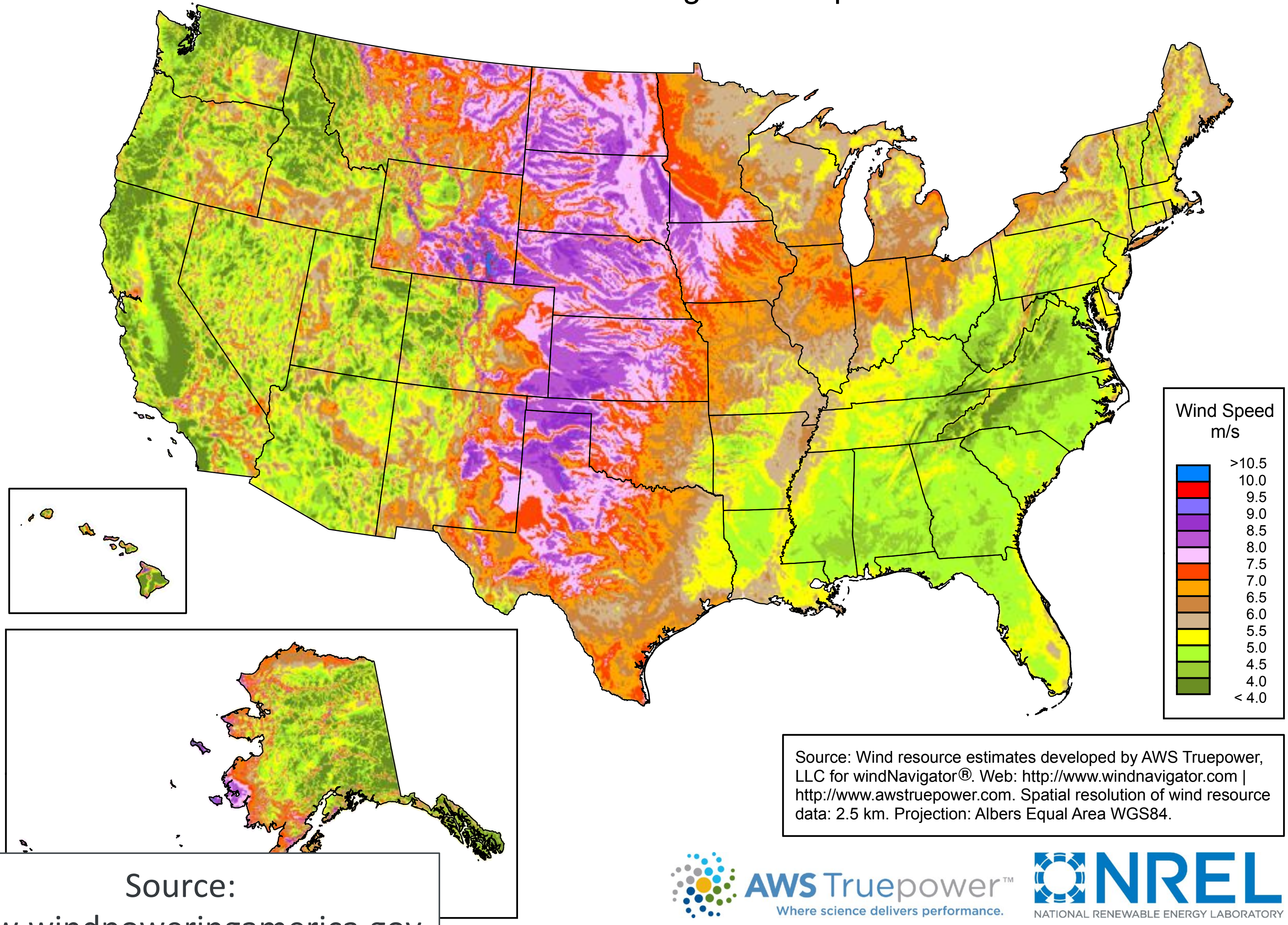
$$E = \int P(U) f(U) dU$$

Convolve the power curve and frequency distribution

Capacity factor, c.f.

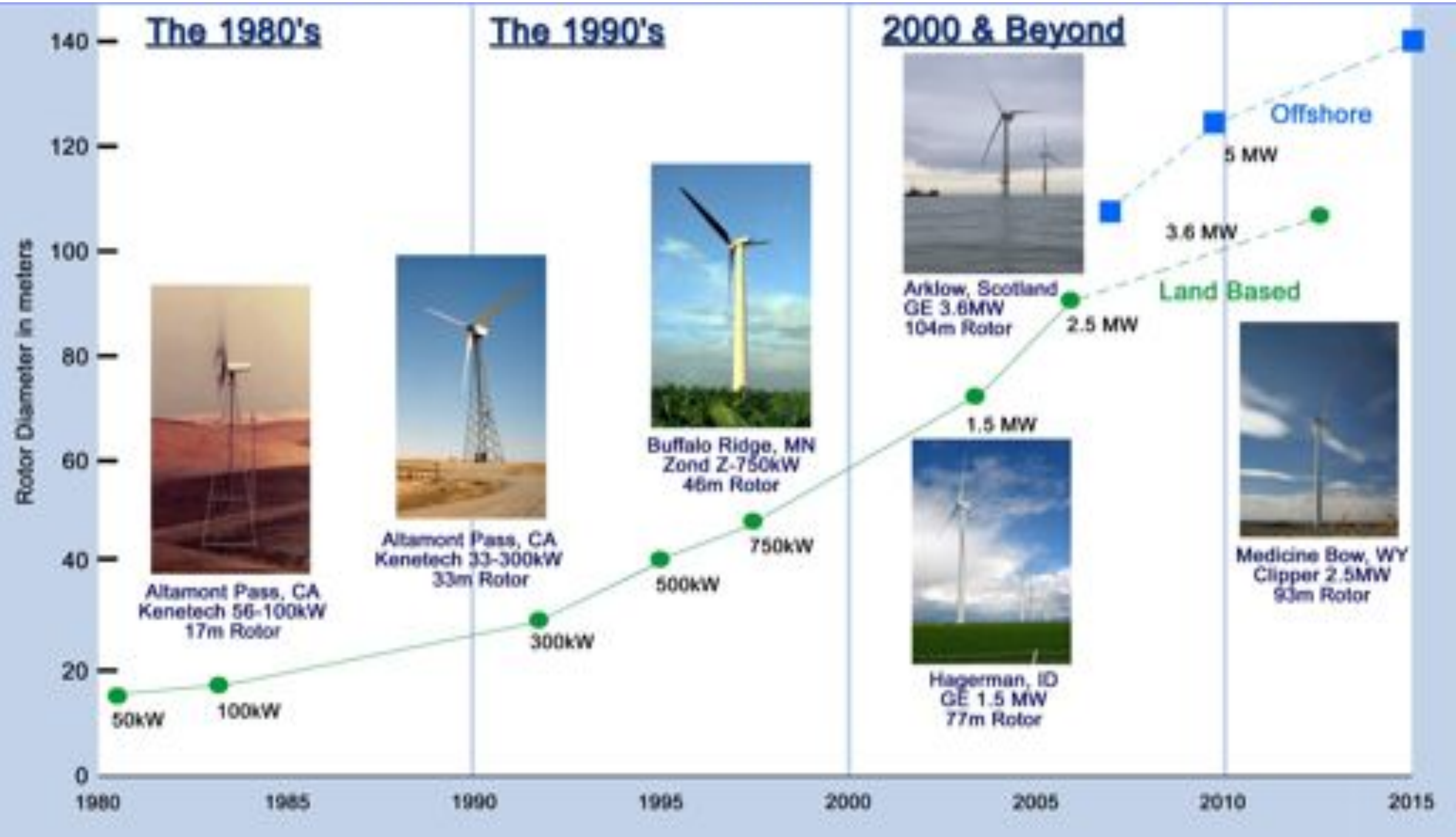
$$c.f. = \frac{E}{n(turbines) \times P(rated)}$$

United States - Annual Average Wind Speed at 80 m

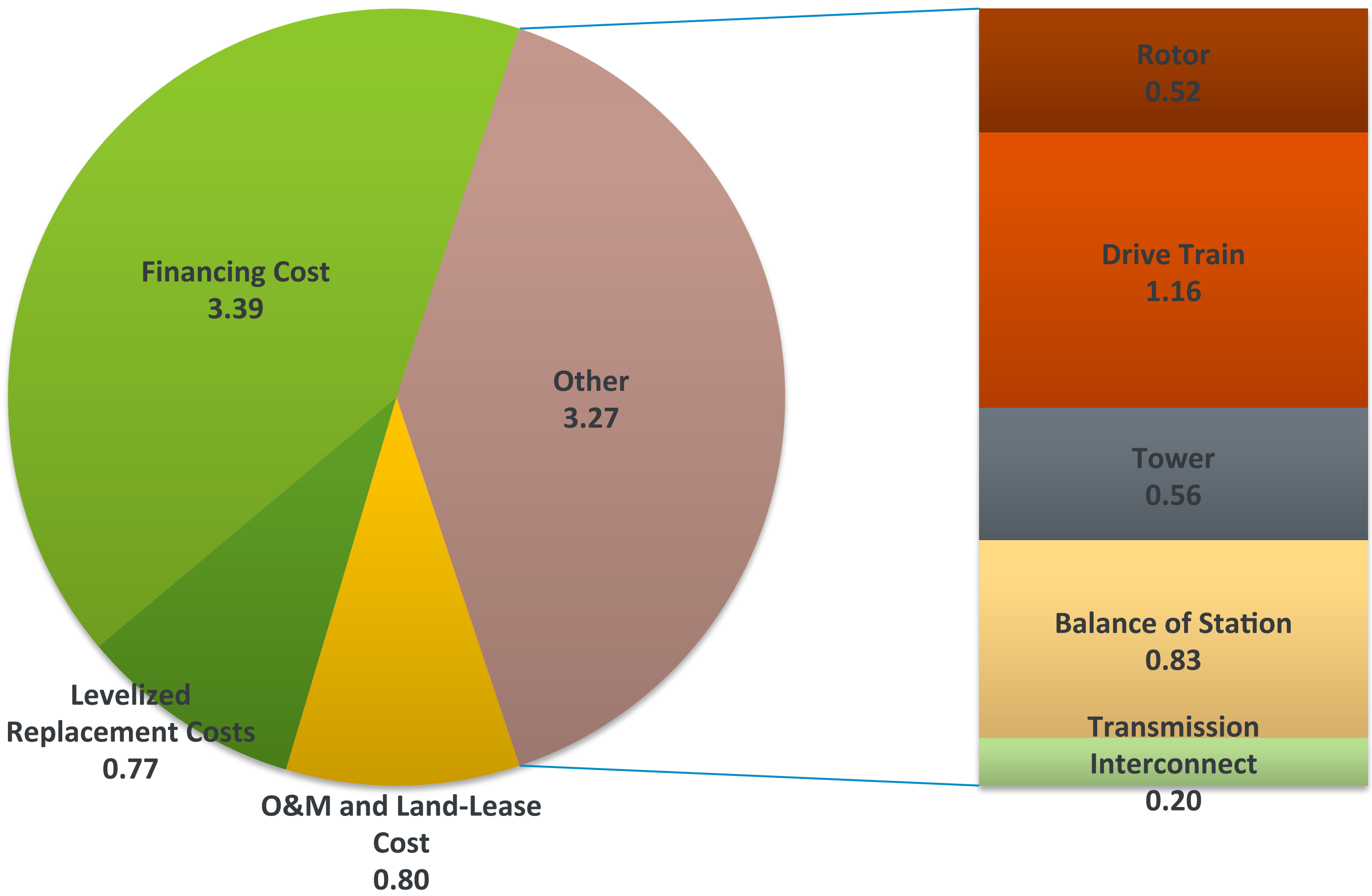


Source:
www.windpoweringamerica.gov

US Commercial Turbine Development

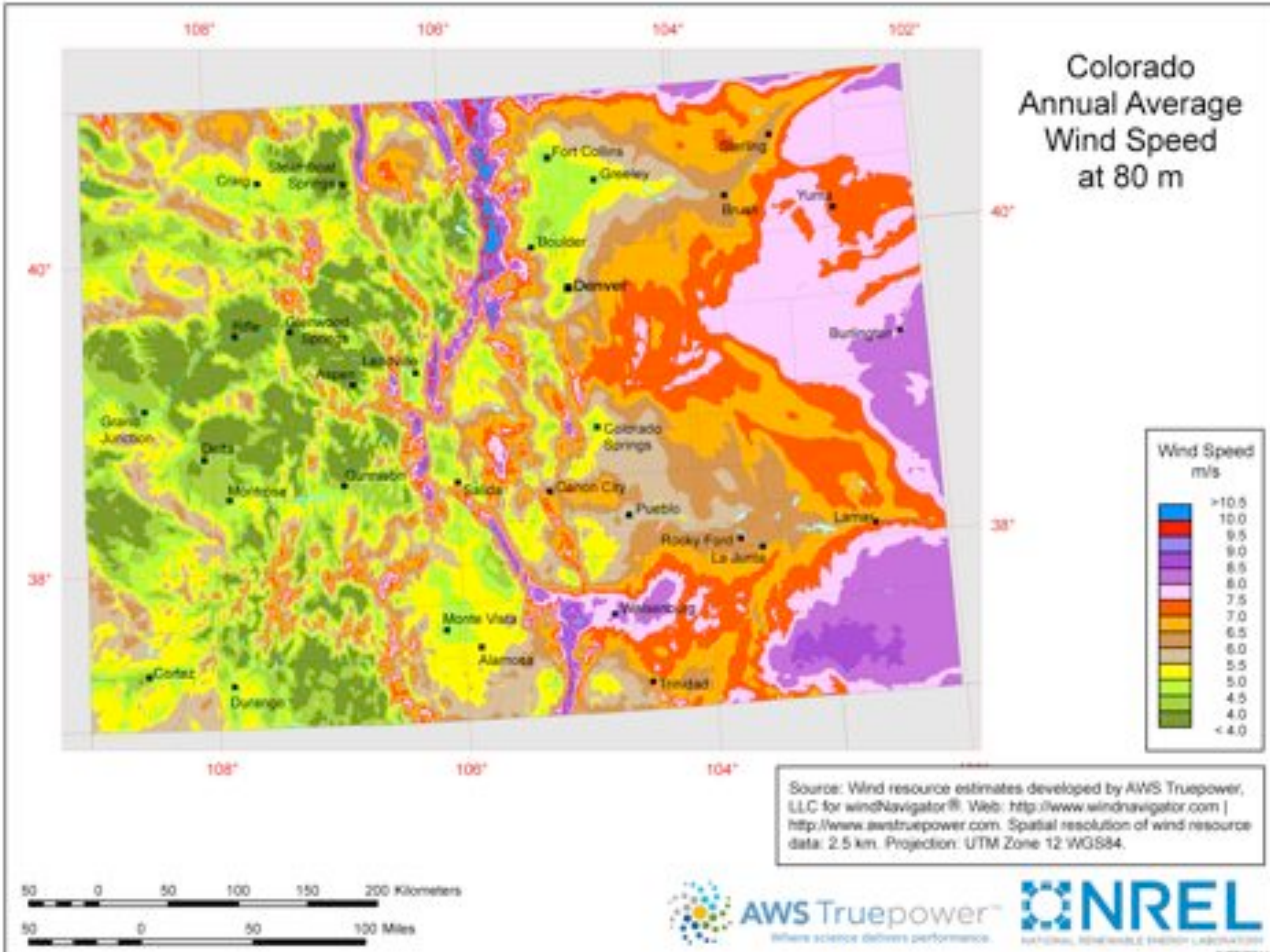


Levelized Cost of Electricity (1.5 MW, on land)



Designing a wind farm

Colorado has a significant wind resource



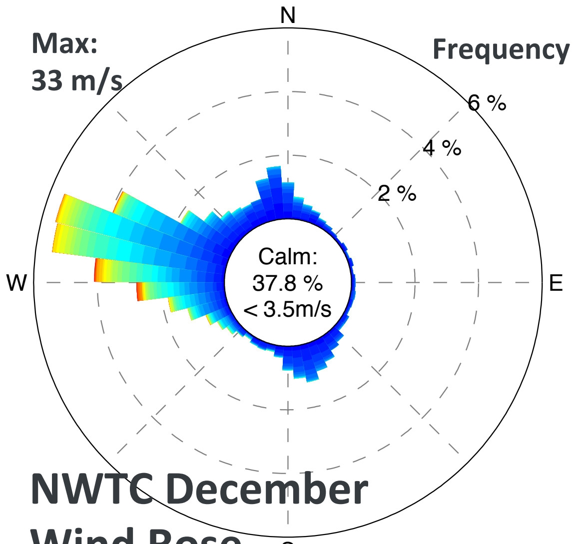
Finding the right location for a wind farm

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



NWTC December Wind Rose

Michael Brower. *Wind Resource Assessment: A Practical Guide to Developing a Wind Project*. Wiley, 2012. DOI: 10.1002/9781118249864.

Horizontal and vertical extrapolation

C. Abiven, J.M.L.M. Palma, O. Brady. *High-frequency field measurements and time-dependent computational modelling for wind turbine siting*. J. Wind Eng. Ind. Aerodyn. 99 (2011) 123–129

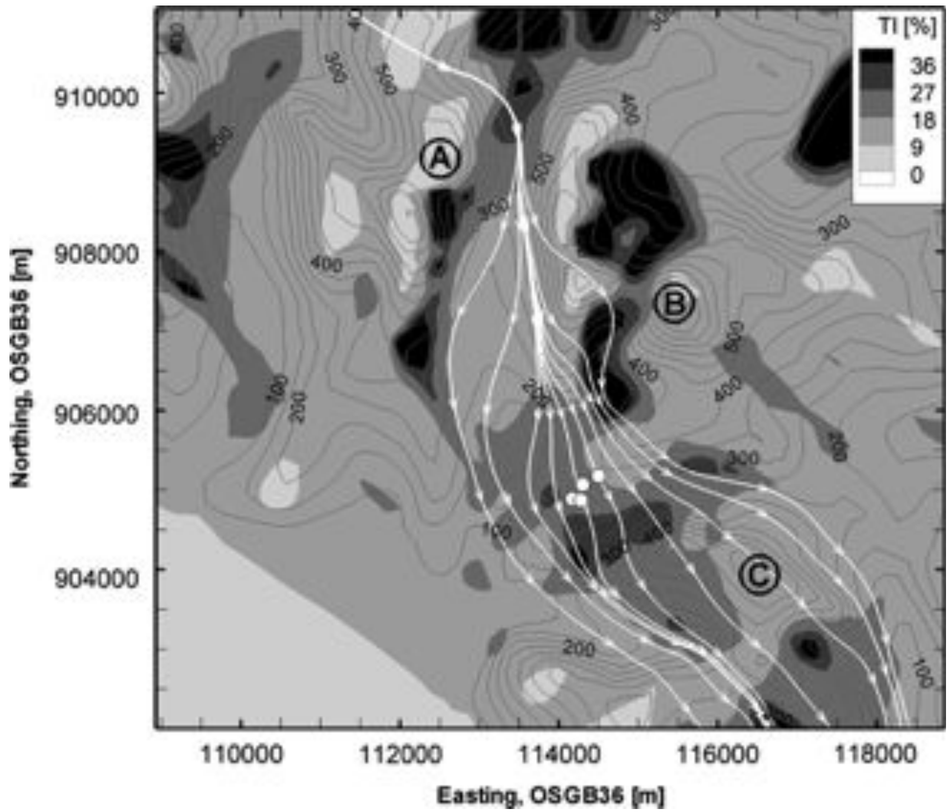


Fig. 4. Turbulence intensity at 50 m agl for north-westerly winds, direction 305°. White lines are streaklines of the flow. Black lines are contour height levels. White dots show turbine and mast locations.

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)

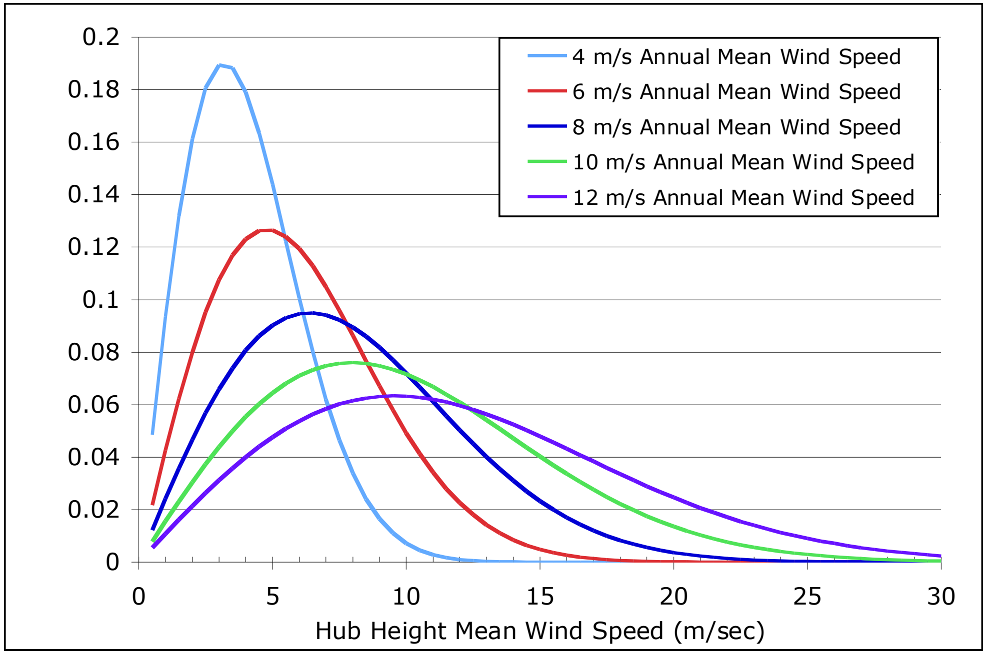
Map flows for each wind speed and direction

- n direction bins
- n wind speed bins

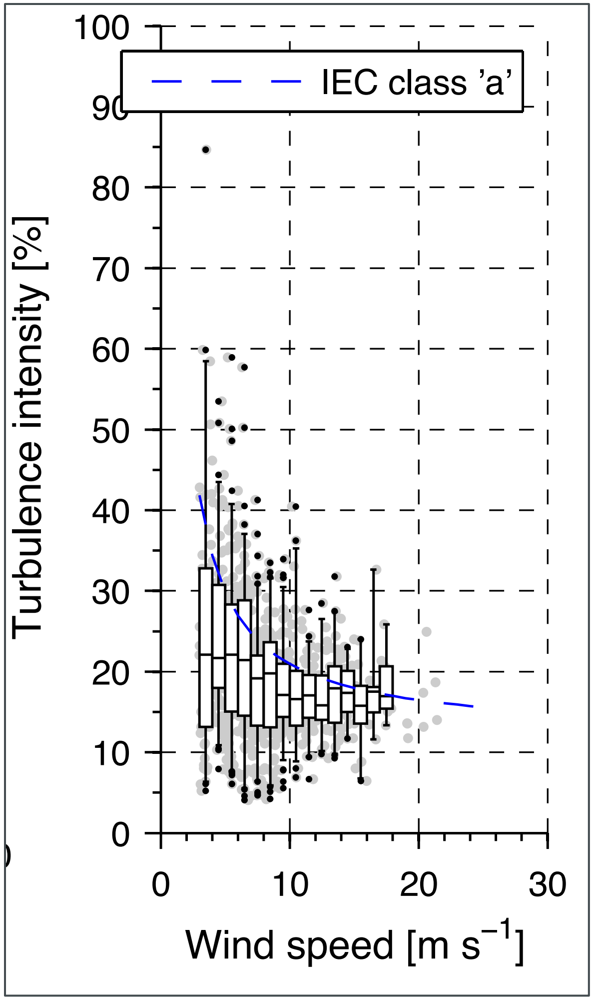
Estimate wind speed, direction and turbulence at each point

Turbine Selection

Site-wide wind frequency distribution



Turbulence intensity



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)
See also K.S. Hansen and R.J. Barthelmie and L.E. Jensen and A. Sommer, "The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm", Wind Energy (2012), DOI 10.1002/we.512

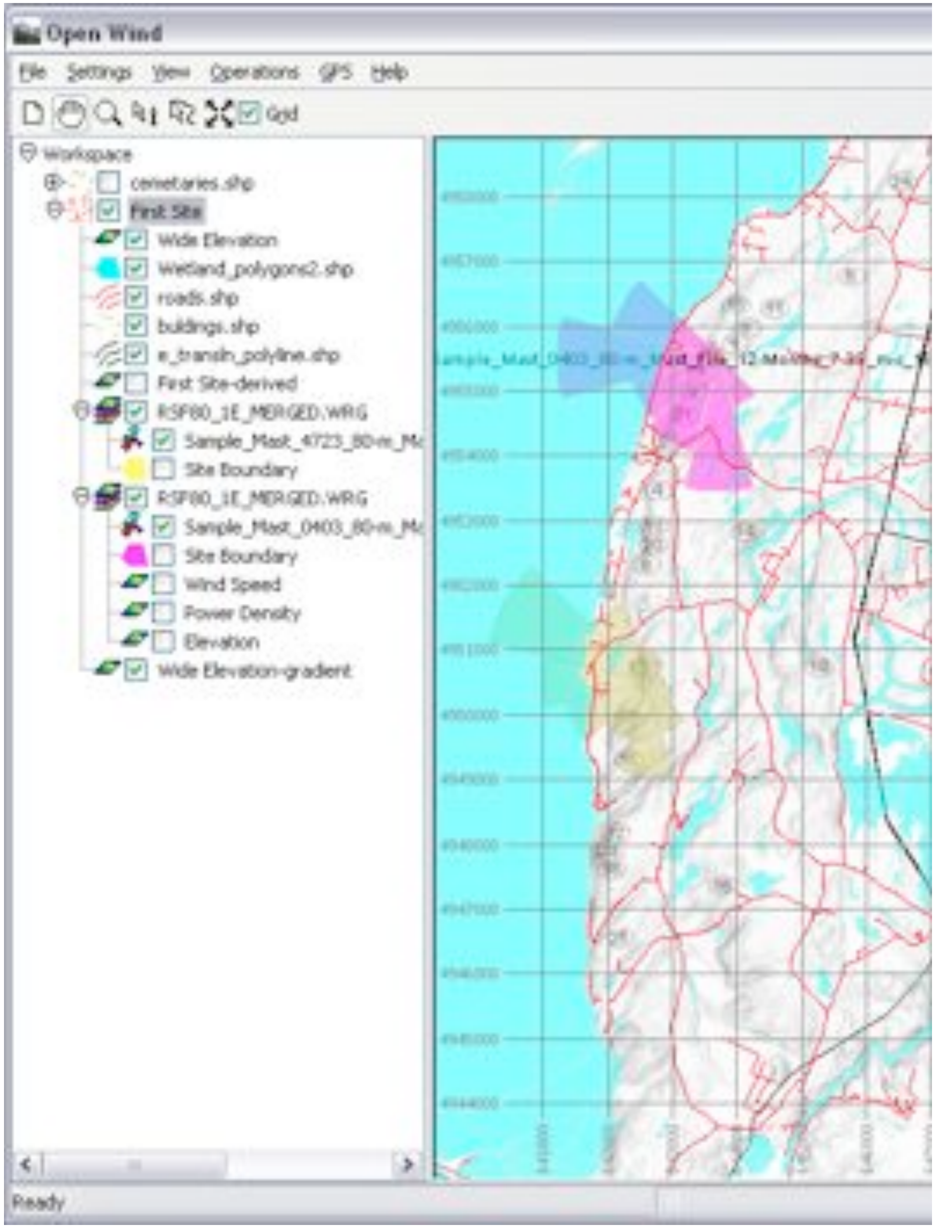
Site optimization: turbine-turbine interaction

- **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

B. Sanderse. Aerodynamics of wind turbine wakes. Technical Report E–09-016, Energy Research Center of the Netherlands, 2009.

Site optimization – GIS tools

- **Want the best turbine layout for the site**
  - Minimise costs
  - Maximise income
  - Minimise cost of energy
  - Within constraints
- **Many commercial tools**
  - Wind farmer, WindPRO,
- **An Open Source tool**
  - www.awsopenwind.org



Open Wind: screenshot from http://www.awsopenwind.org

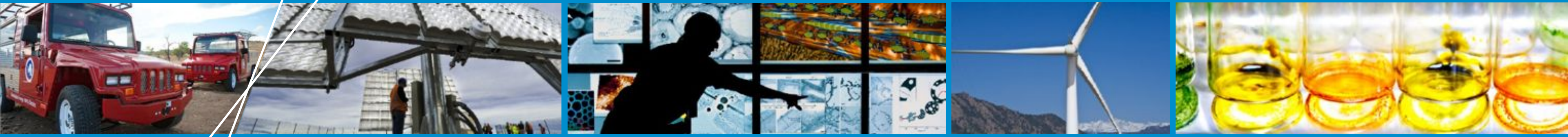
Optimization gives very different results

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

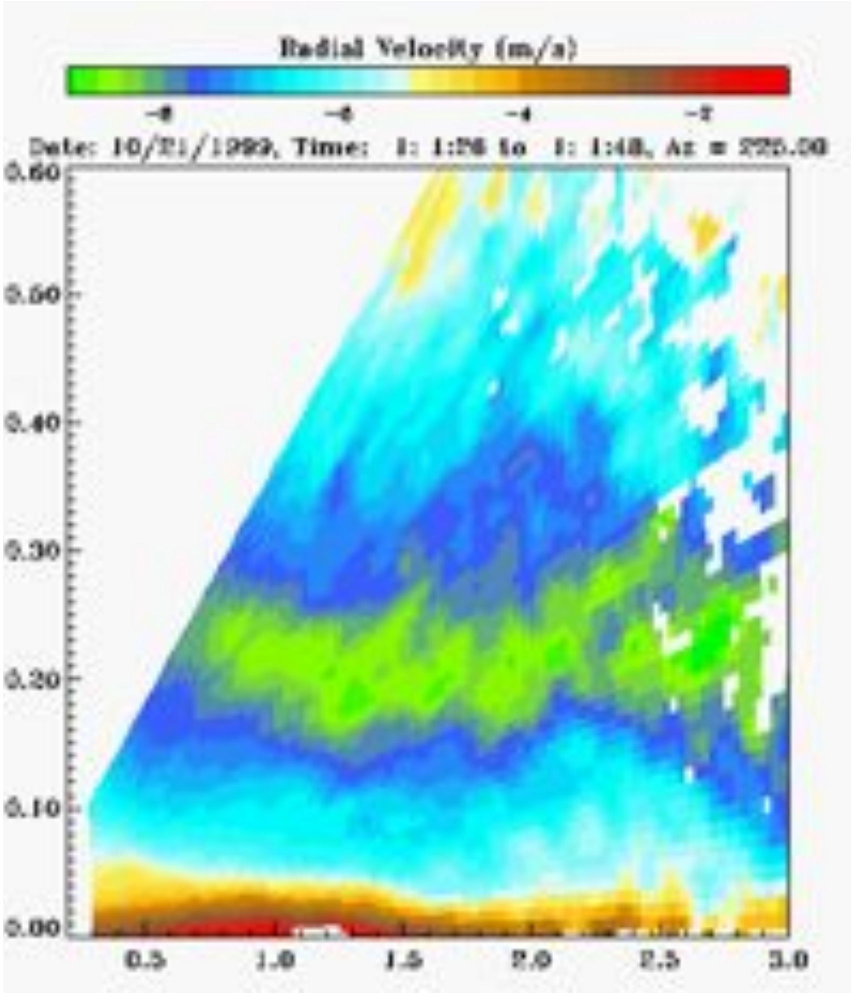
Complex flow environments

- Over forests
- Downwind of hills
- **In passes**
- In low level jets
- On the coast
- Stratification

Complex flow environments

- Over forests
- Downwind of hills
- In passes
- **In low level jets**
- On the coast
- Stratification

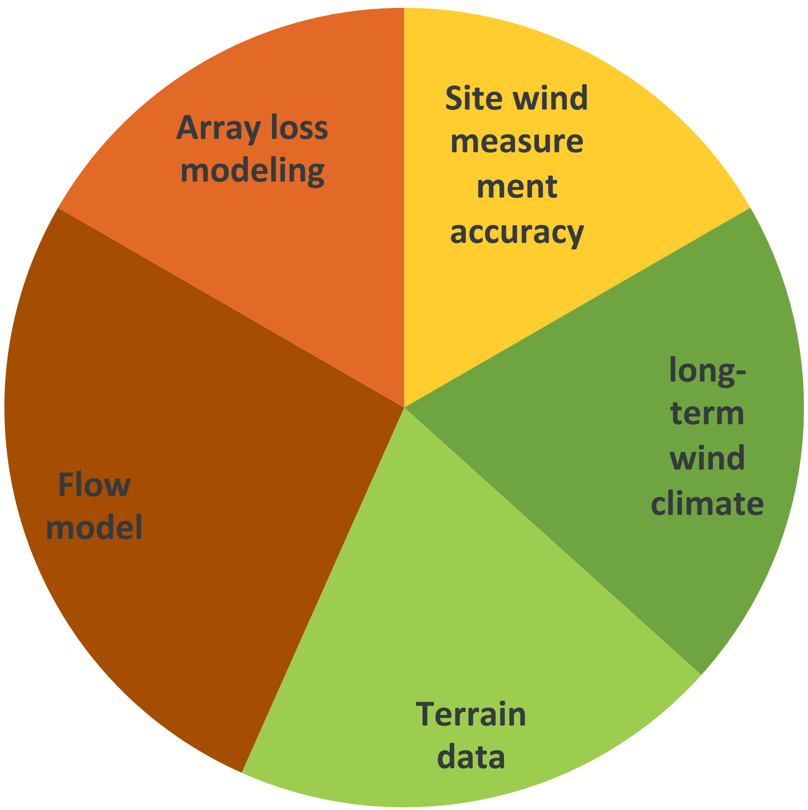
The Low Level Jet observed at Lamar
(R. Banta, NOAA and Neil Kelley, NWTC)



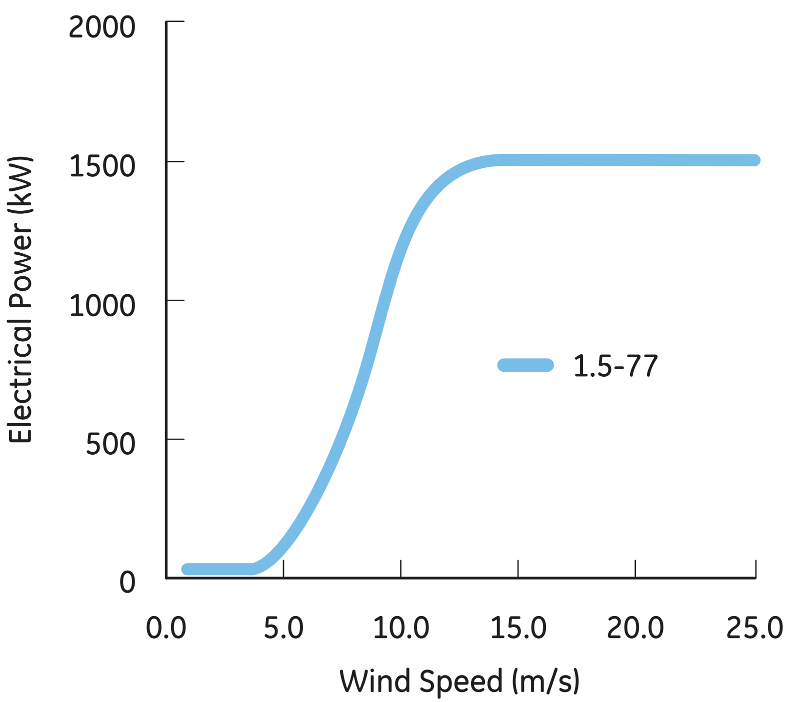
Neil D. Kelley. Turbulence-turbine interaction: The basis for the development of the turbsim stochastic simulator. Technical Report TP-5000-52353, NREL, 2011.

Uncertainties in wind speed

Wind speed uncertainty (~7%)



Power Curve



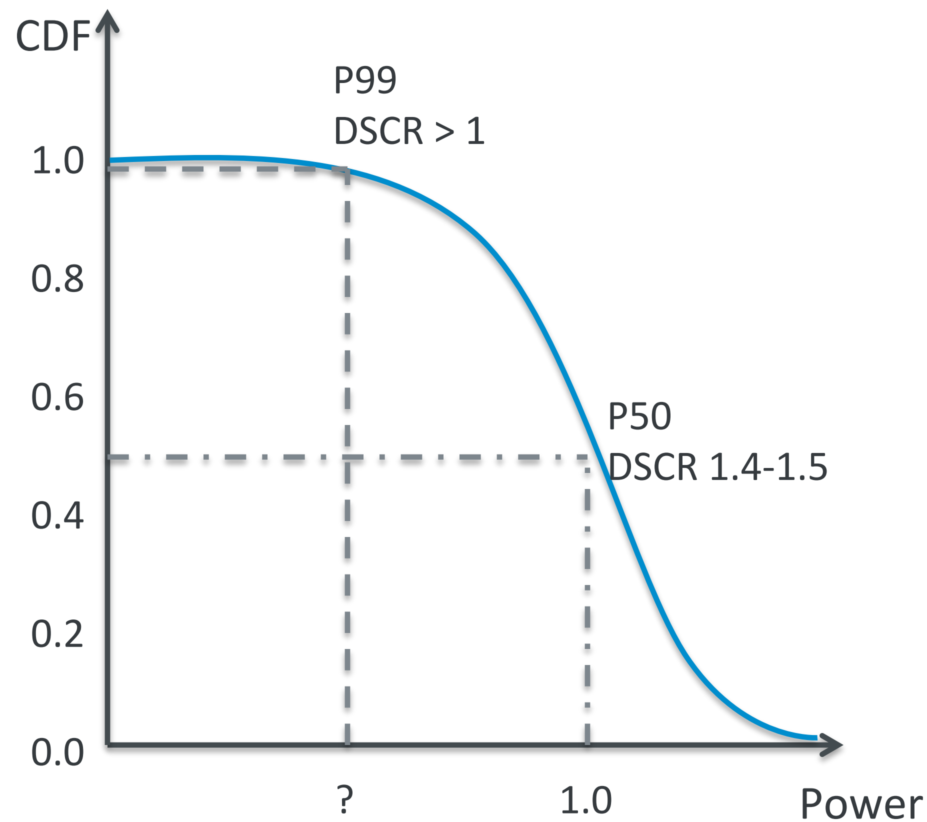
Source: typical figures from presentations from GL-GH, DNV Kema, Sgurr Energy

Source: GE-energy.com, factsheet for GE 1.5-77 (Class II) wind turbine

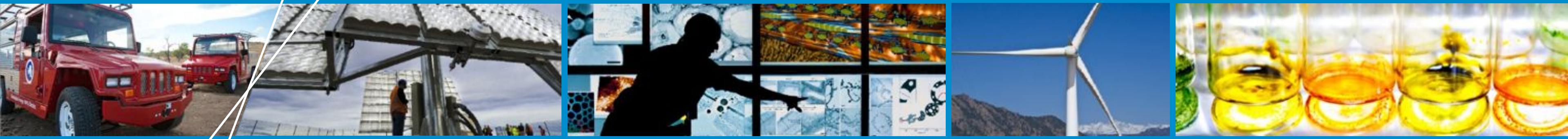
Uncertainties in annual power production

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

Pxx: 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



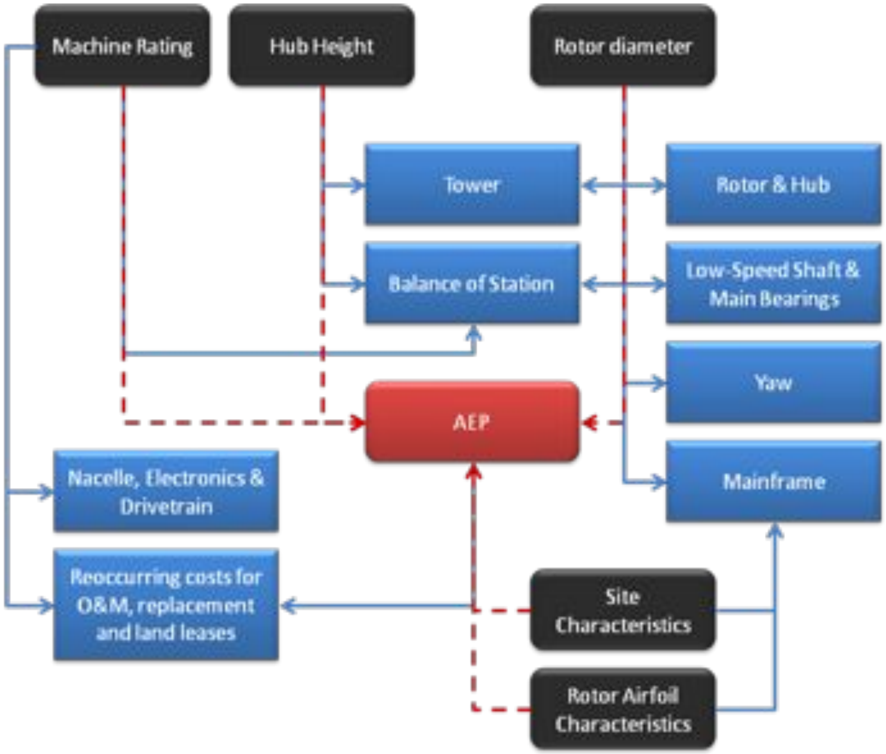
Systems engineering

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

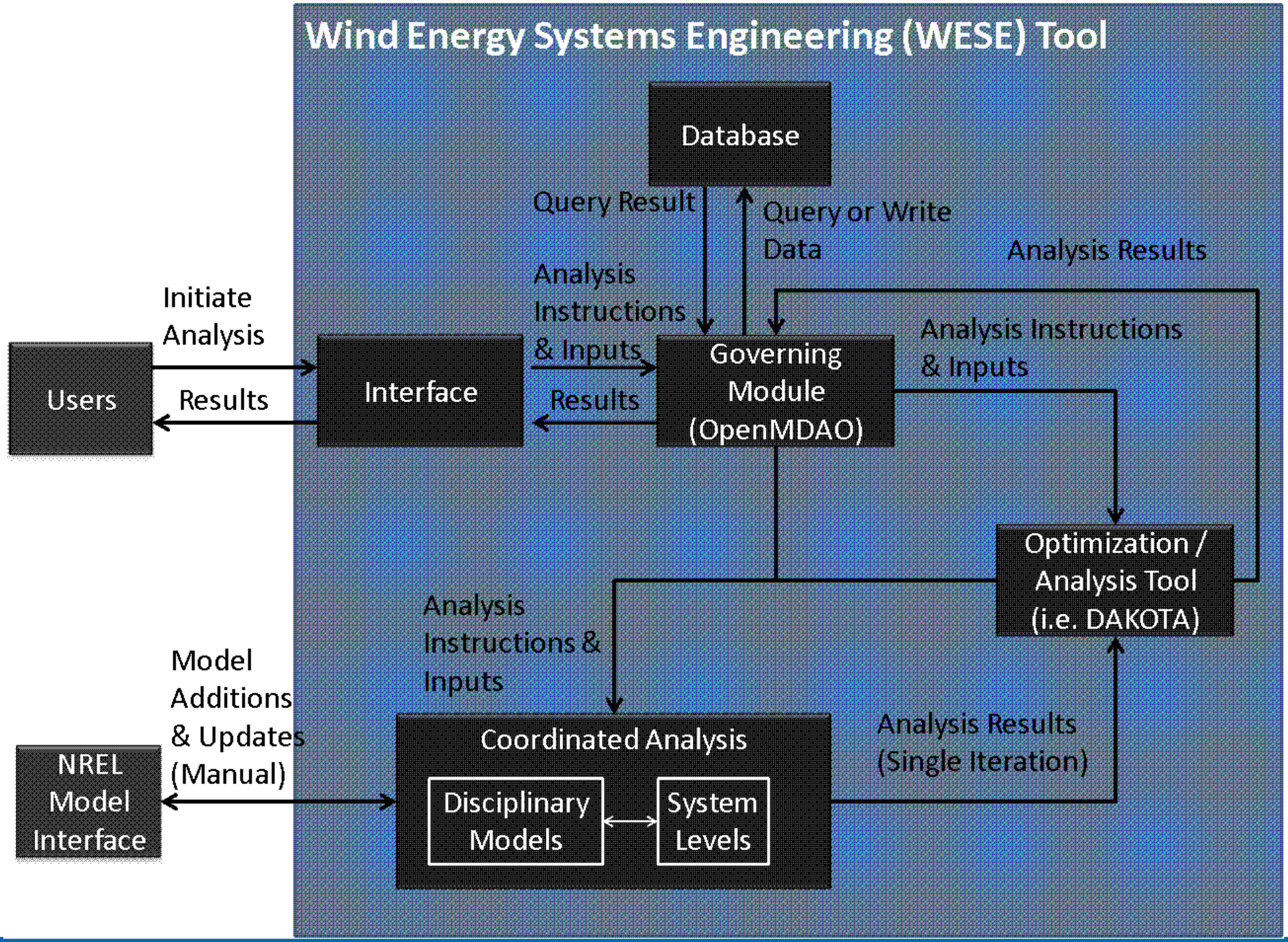
- Implement software platform for integrated wind plant techno-economic modeling that maintains flexibility, extensibility and scalability
- Development includes four general phases:

  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.

Systems Engineering Tool Development

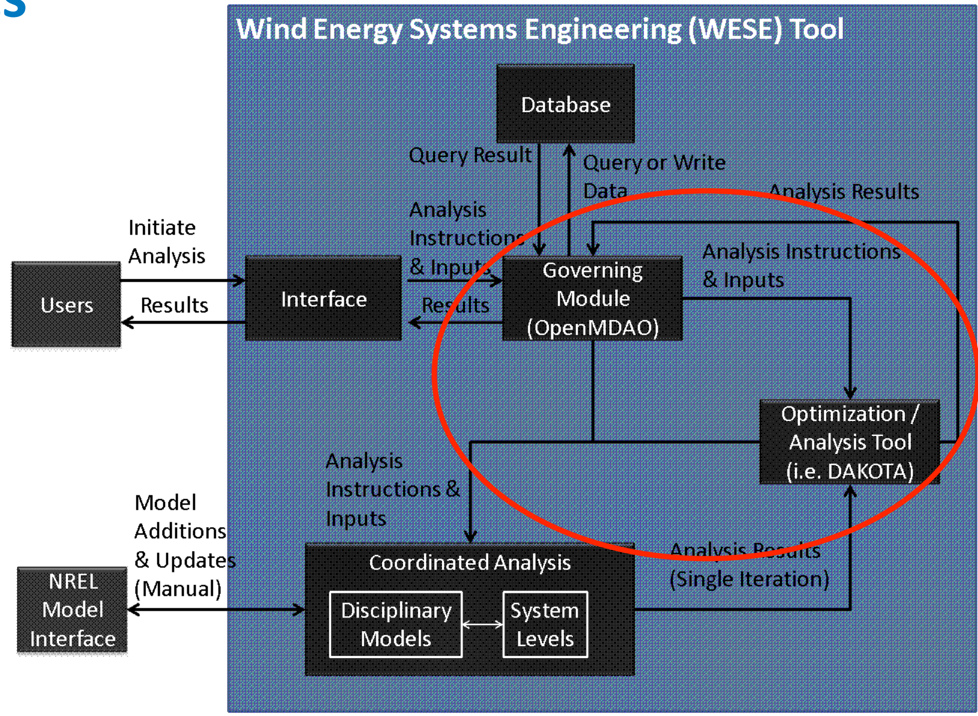
Integrated analysis tool using:

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



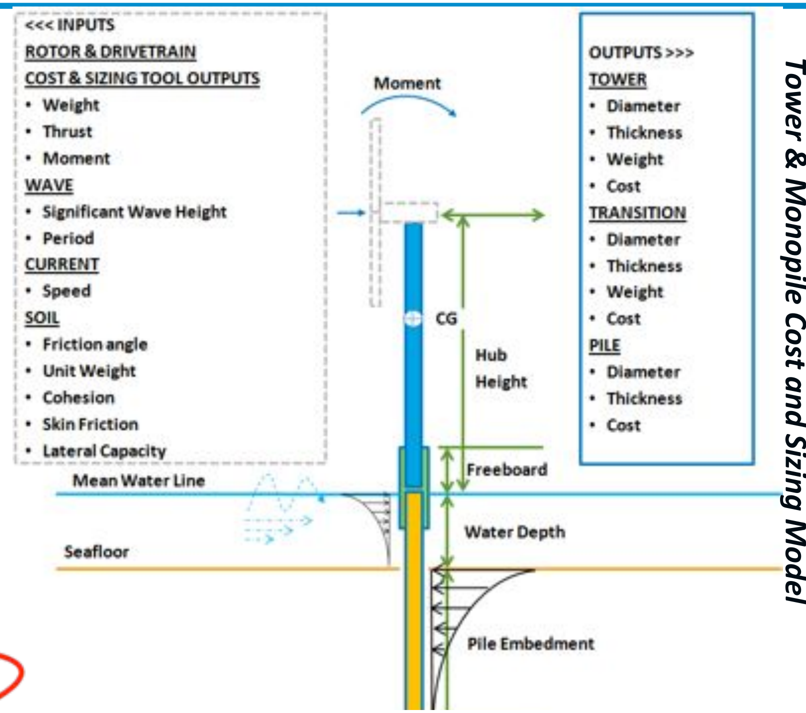
Systems Engineering Tool Development

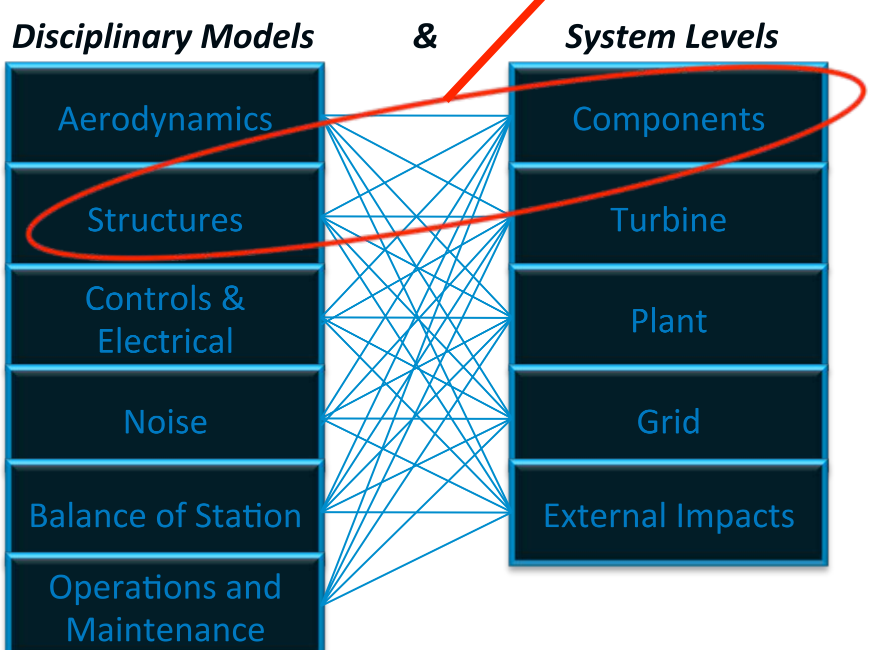
- **Governing module: work flows integrate models together in structured ways – linking inputs and outputs for appropriate system level analysis (use of NASA's OpenMDAO software)**
- **Optimization / analysis tool: different analysis algorithms are used to drive model analysis (internal to OpenMDAO or via Sandia's DAKOTA software)**

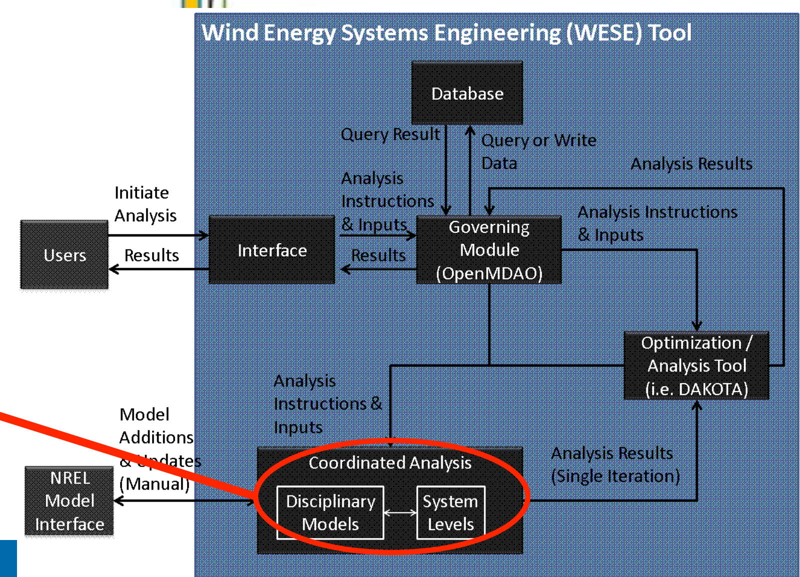


Systems Engineering Tool Development

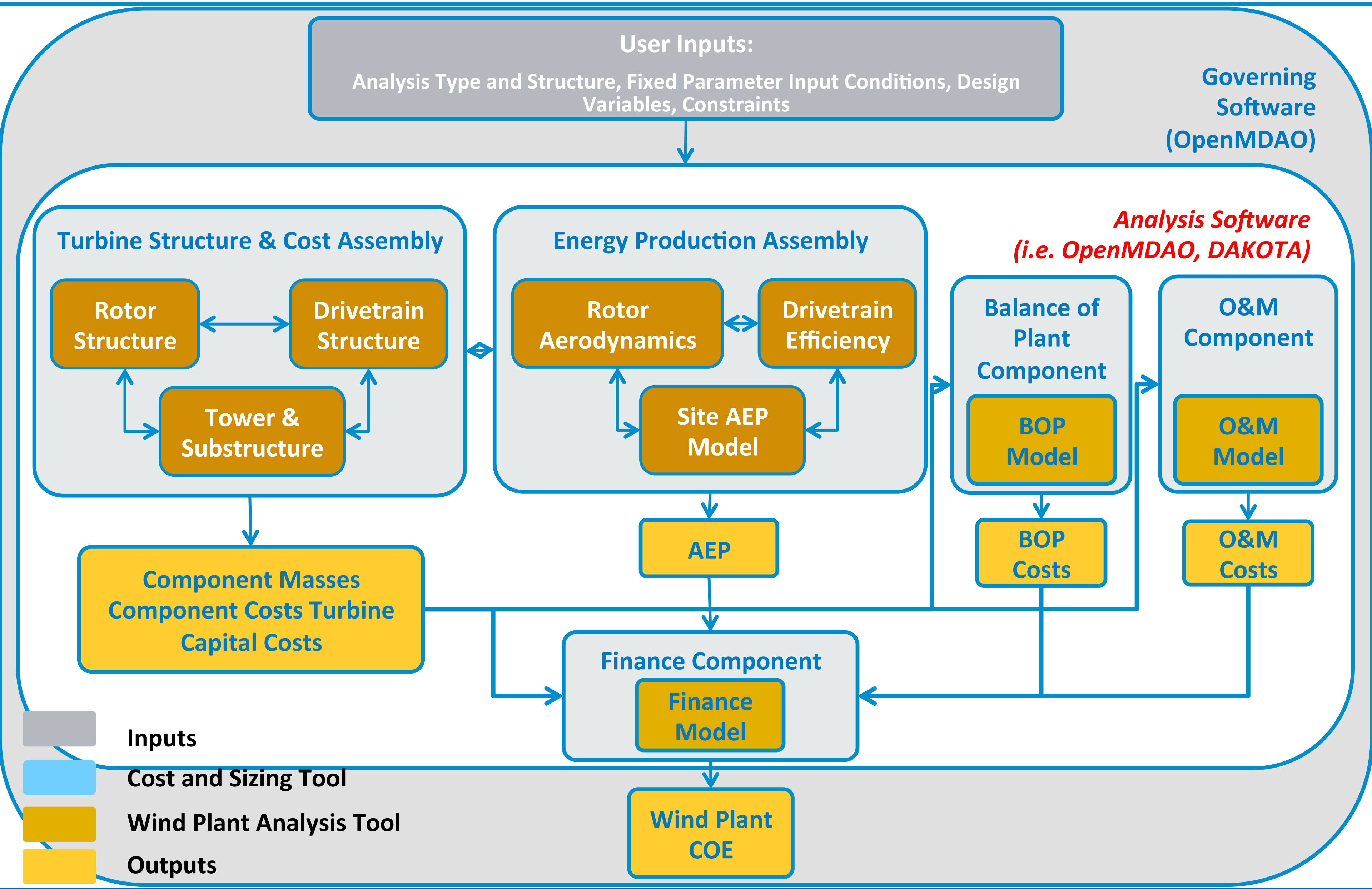
Coordinated Analysis: integration of various models with the goal of full system representation while preserving use of different levels of fidelity representing different sub-systems





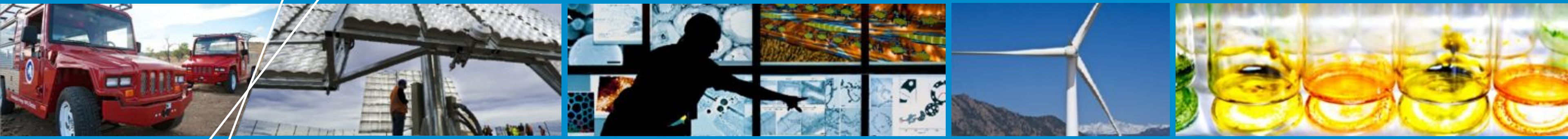


Systems Engineering Software



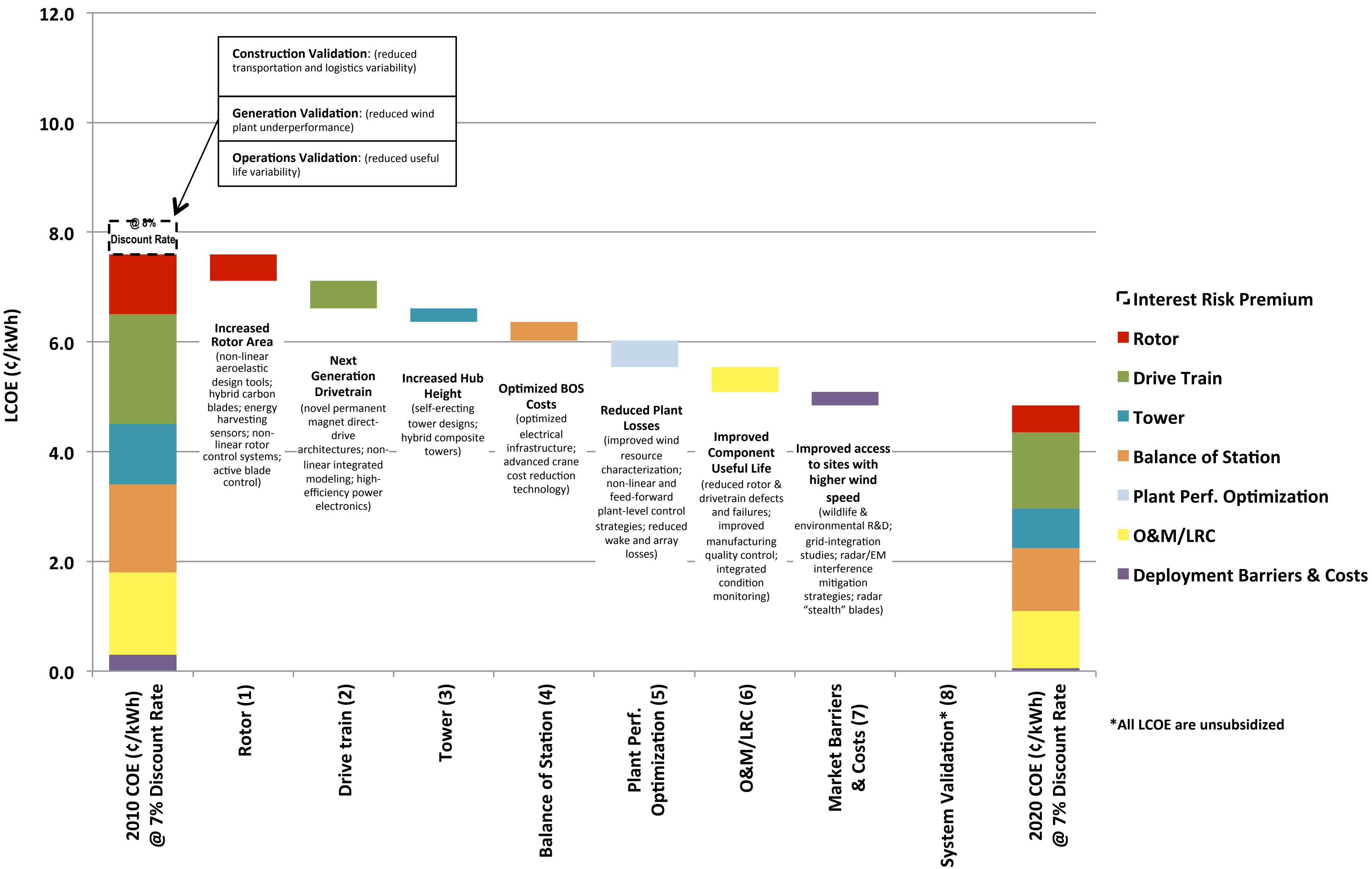
Systems Engineering Tool Development

- **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



*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

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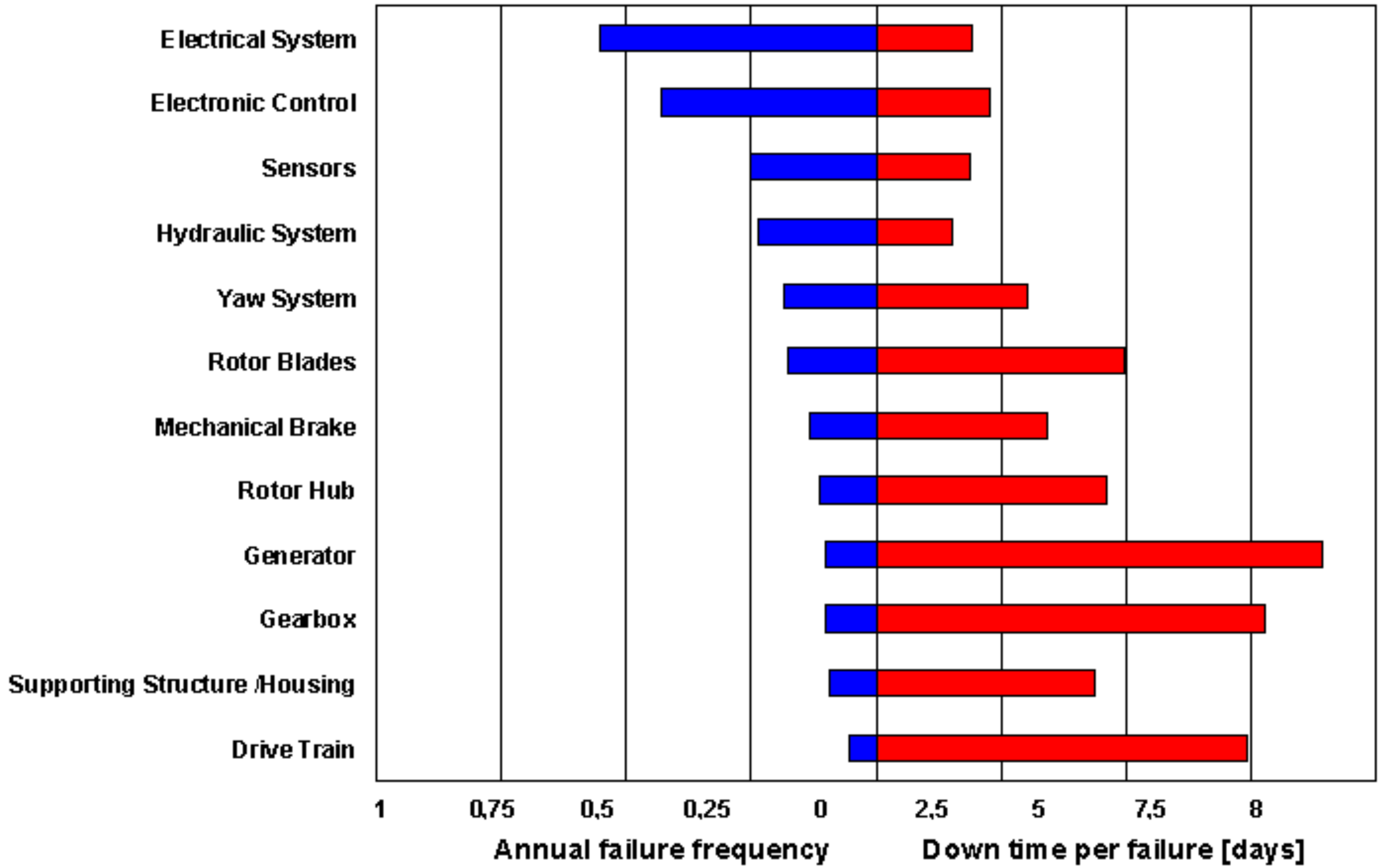
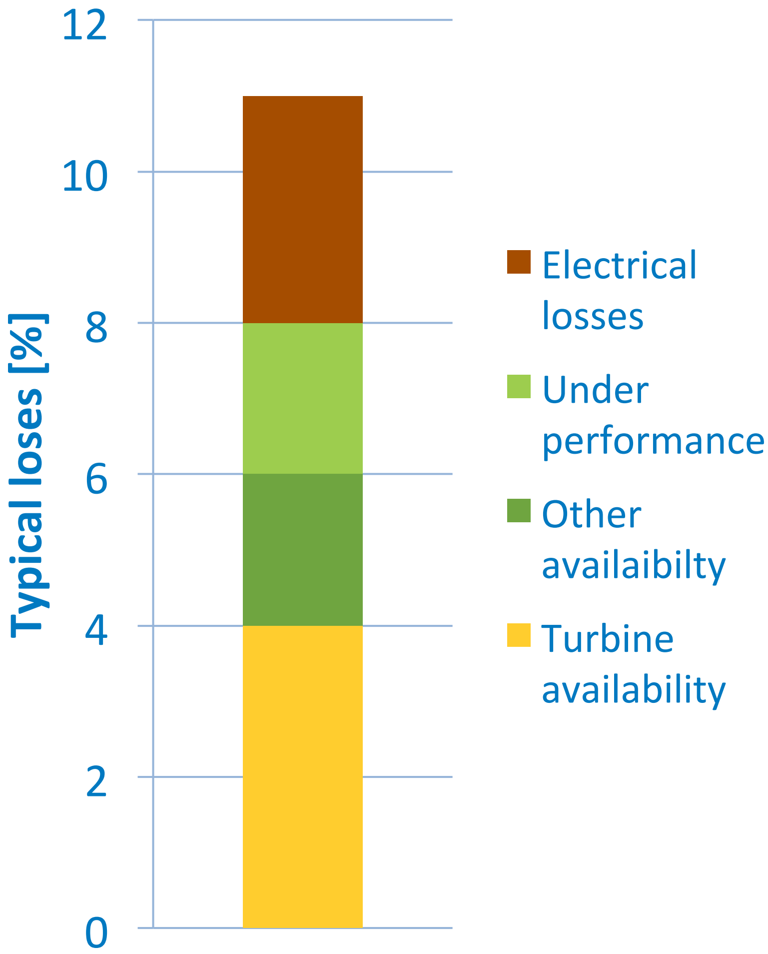
Extra slides

Which Components Fail?

CJ. Crabtree, Y. Feng, and P.J. Tavner. Detecting incipient wind turbine gearbox failure: A signal analysis method for on-line condition monitoring. In *EWEC 2010*. European Wind Energy Conference, 2010.



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