

SAWEP Workshop

Wind Atlas for South Africa (WASA)



Cape Town, 4th March 2010

Wind farm calculations - Annual Energy Production

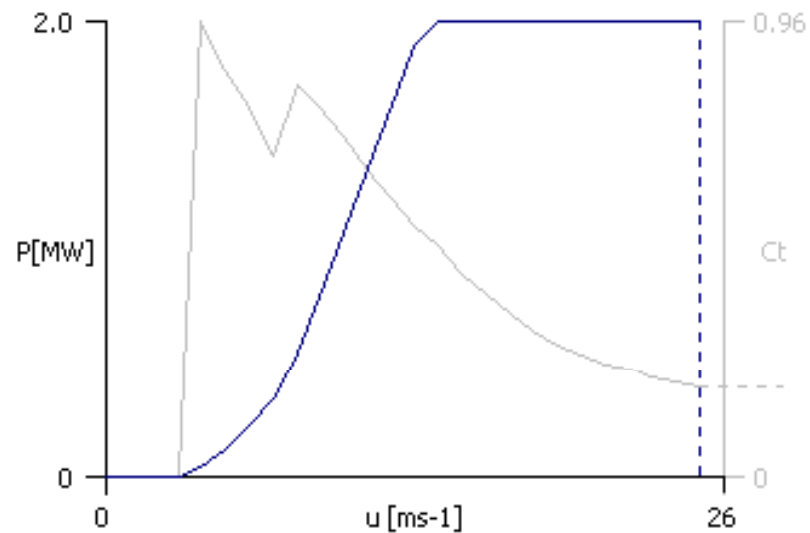
What is AEP?

- AEP = Annual Energy Production
 - Watt-hours produced over an average year, typically given in MWh or GWh per year
 - from a wind farm or
 - from a single wind turbine (in a wind farm)

Key concepts and terms

- Predicted wind climate: wind climate in terms of wind rose and sector-wise wind speed distributions (A , k)
 - calculated from the regional wind climate (wind atlas) for a specific site and height above terrain
- Gross energy production: (free) AEP from wind farm or single wind turbine
 - calculated disregarding wake effects
- Wake effect: mutual turbine-turbine 'shading' effects
 - expressed in terms of percentage power loss
- Net energy production: net AEP from wind farm
 - calculated taking the wake effects into account

Power and thrust curves



#	Speed m/s	Power kW	Ct
1*	4.00	39.000	0.9600
2*	5.00	117.000	0.8600
3*	6.00	222.000	0.7800
4*	7.00	340.000	0.6800
5*	8.00	550.000	0.8300
6*	9.00	799.000	0.7800
7*	10.00	1078.000	0.7200
8*	11.00	1365.000	0.6500
9*	12.00	1640.000	0.5900
10*	13.00	1891.000	0.5300
11*	14.00	2000.000	0.4900
12*	15.00	2000.000	0.4300
13*	16.00	2000.000	0.3900
14*	17.00	2000.000	0.3500
15*	18.00	2000.000	0.3100
16*	19.00	2000.000	0.2800
17*	20.00	2000.000	0.2600
18*	21.00	2000.000	0.2400
19*	22.00	2000.000	0.2300
20*	23.00	2000.000	0.2100
21*	24.00	2000.000	0.2000
22*	25.00	2000.000	0.1900

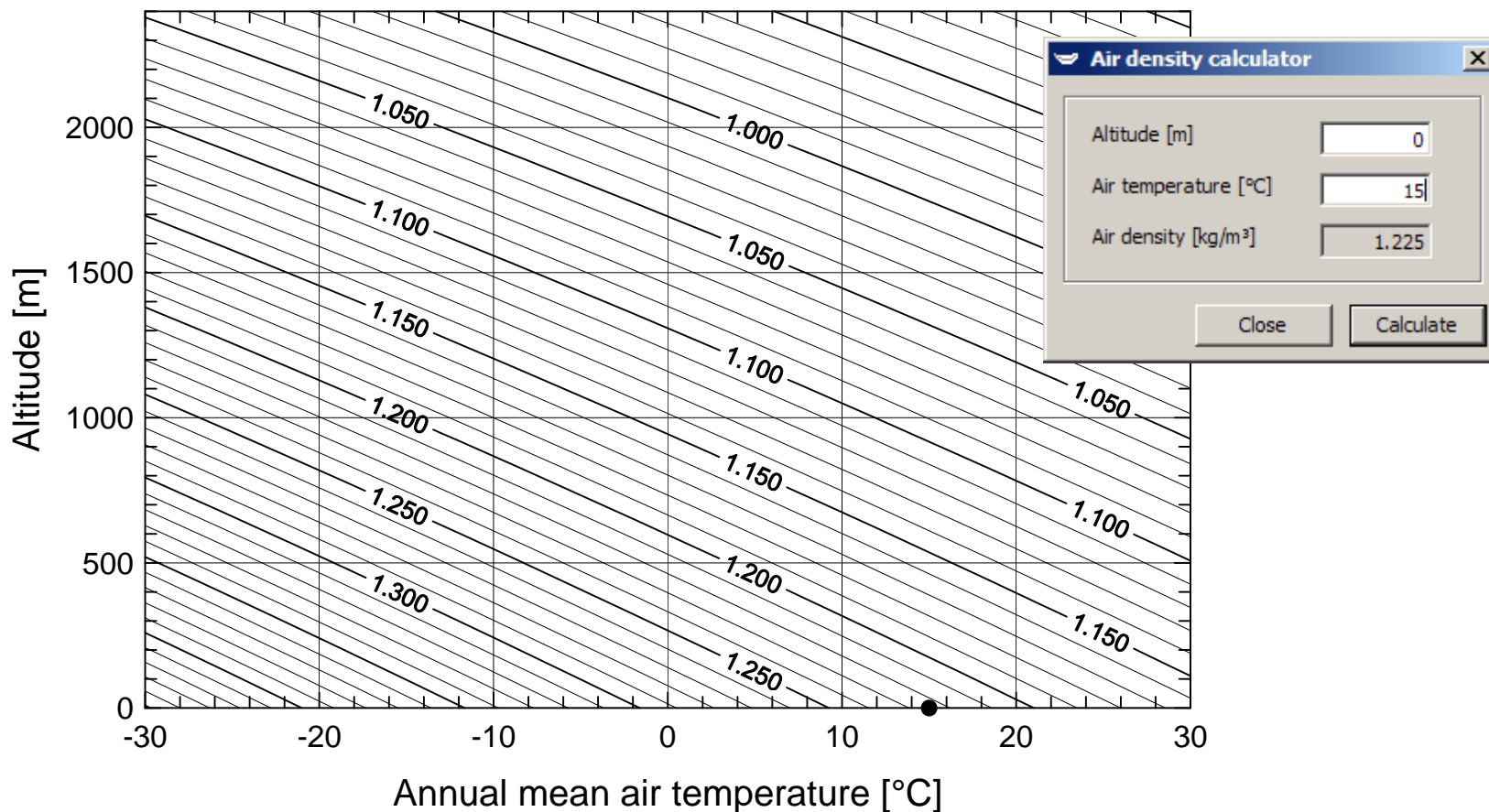
Thrust coefficient definition:

$$C_t = \frac{2F_t}{\rho\pi R^2 U^2}$$

Site-specific power and thrust curves

- Power curve depends on:
 - Air density (temperature and pressure)
 - Control system
- There is no simple scaling relationship between power curve and air density, it depends on e.g. stall or pitch regulation!
- Site-specific power and thrust curves are usually supplied by the wind turbine manufacturer.

Air density variation

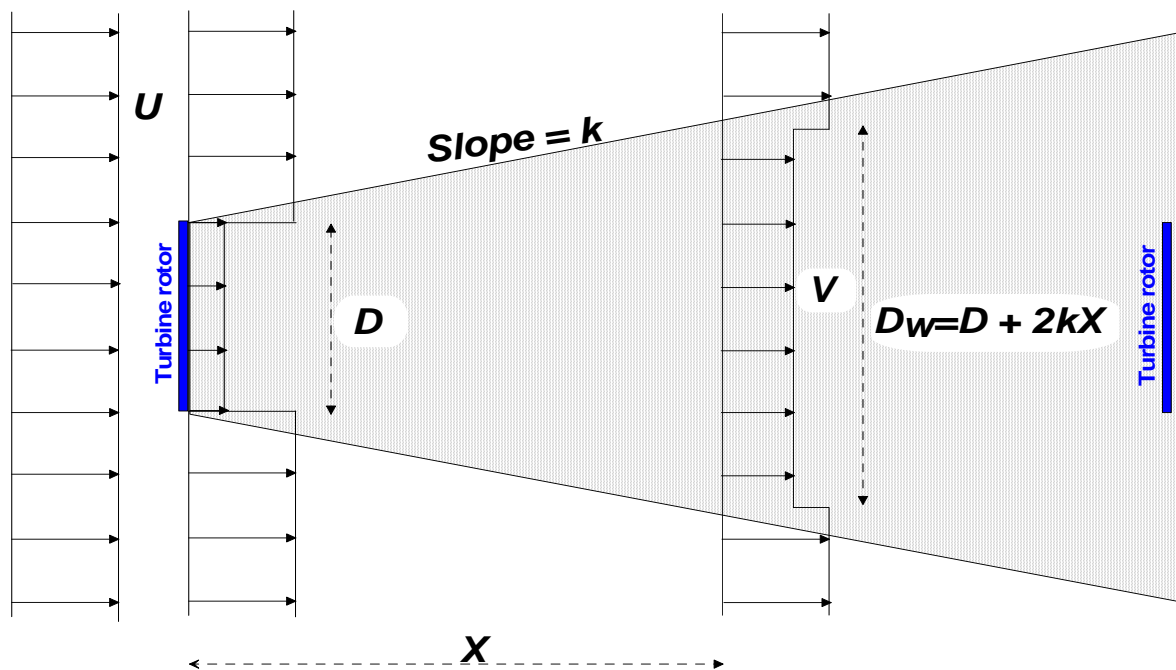


- Air density [kg/m³] as a function of altitude/elevation [m] and mean air temperature [°C] at the same altitude/elevation. Lapse rate 6.5 K/km and sea level pressure of 1013.25 hPa assumed.

Wakes at Horns Rev wind farm



Wake effects principle

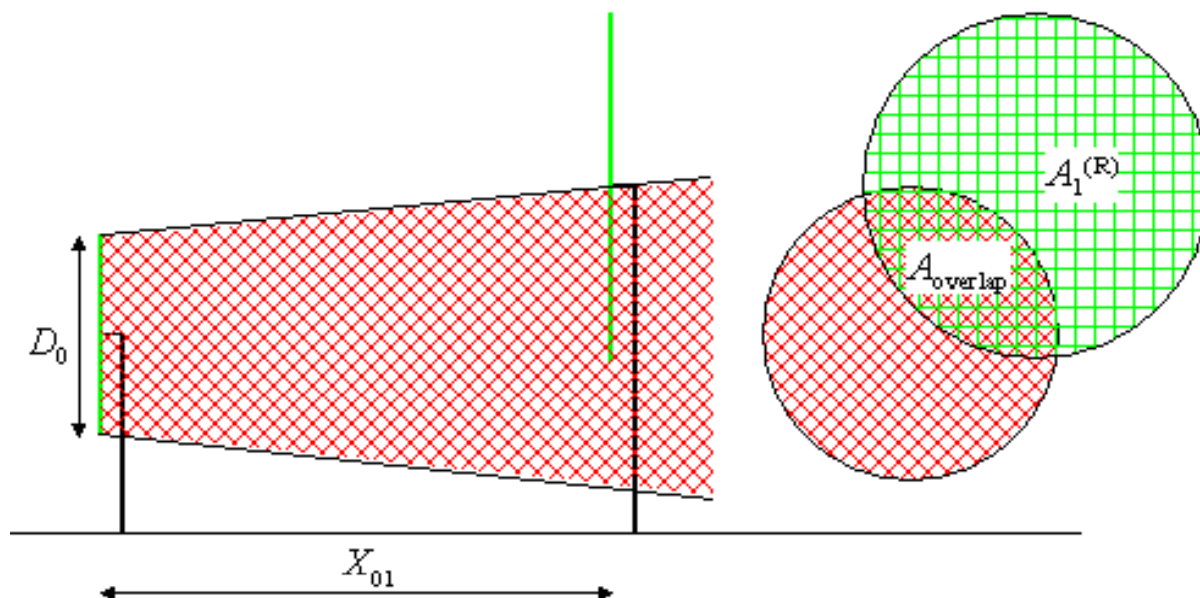


k : wake decay constant

Wake loss is often 4-5% or less

$$\delta V = U - V = U \left(1 - \sqrt{1 - C_t} \right) \left(\frac{D}{D + 2kX} \right)^2$$

Wake effects principle



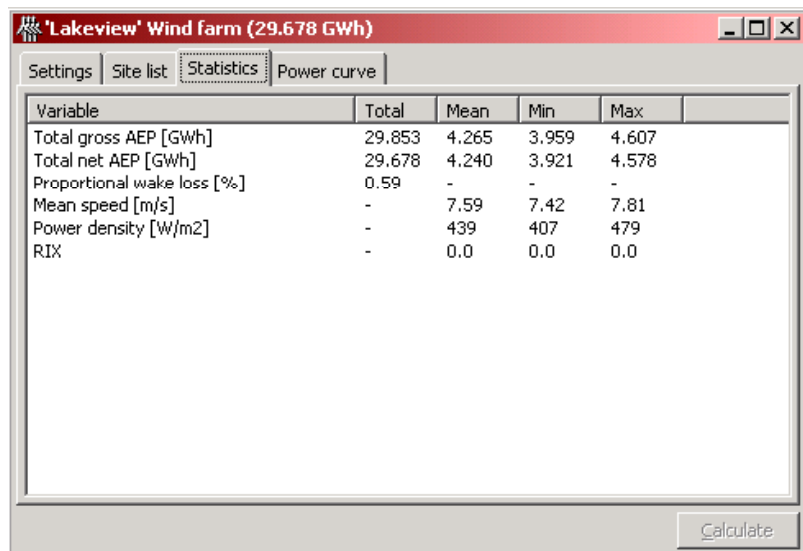
Wakes only partly overlapping downwind turbine rotors – due to horizontal *and* vertical non-concentricity.

Limitation:

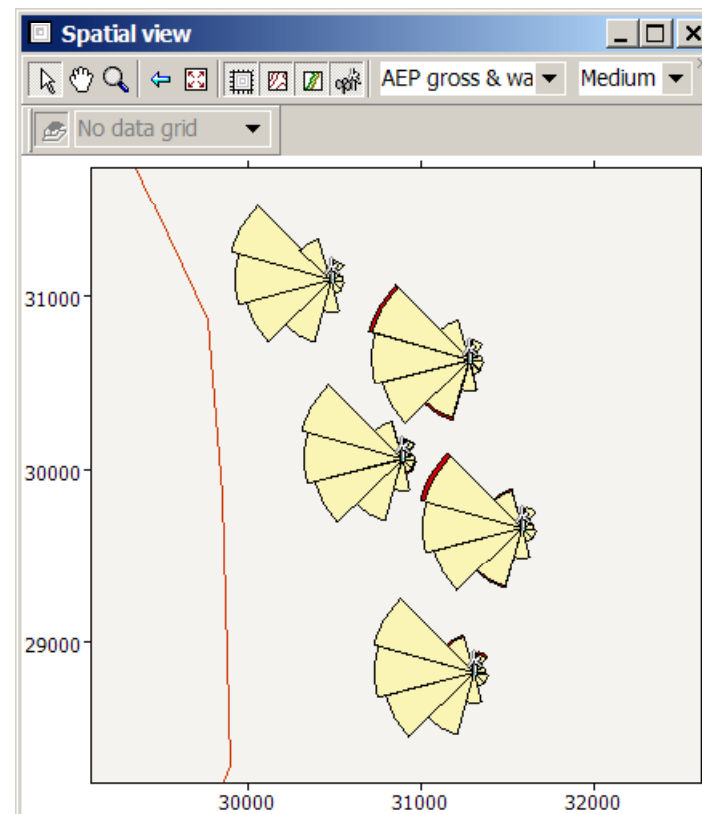
The wake model is not validated for extremely large wind farms, i.e. with >5 km extension.

$$\delta V_{01} = U - V_1 = U_0 \left(1 - \sqrt{1 - C_t}\right) \left(\frac{D_0}{D_0 + 2kX_{01}}\right)^2 \frac{A_{overlap}}{A_1^{(R)}}$$

Wind farm windows in WAsP

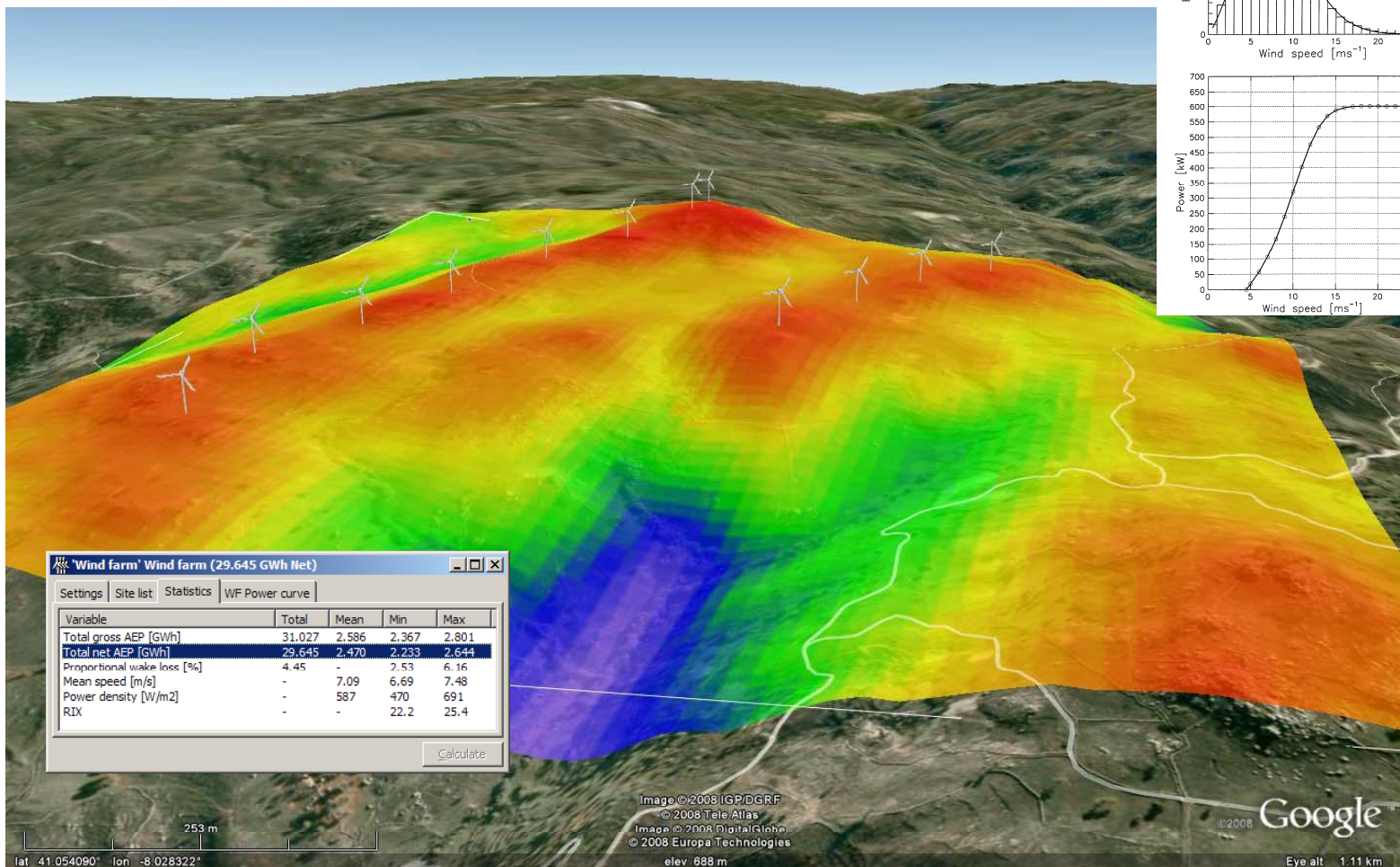


Statistics



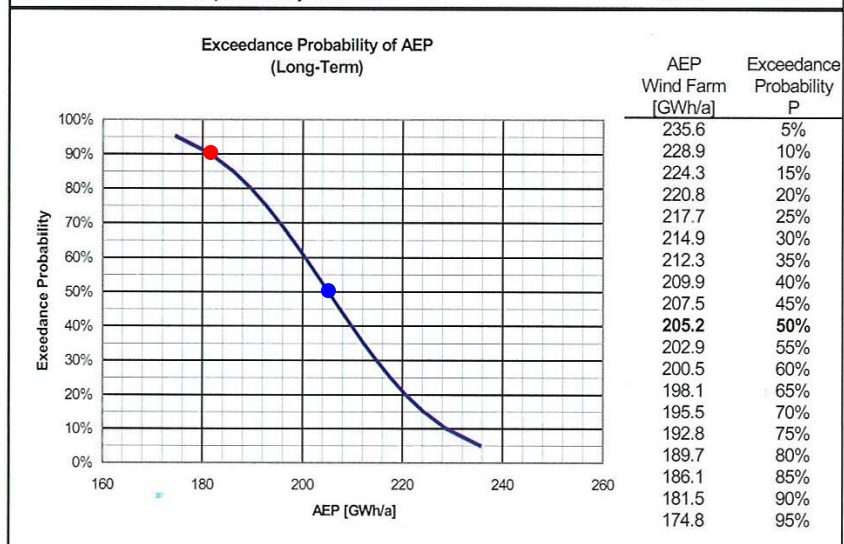
Spatial view – displaying also production roses and wake-loss

Wind farm layout and estimated production

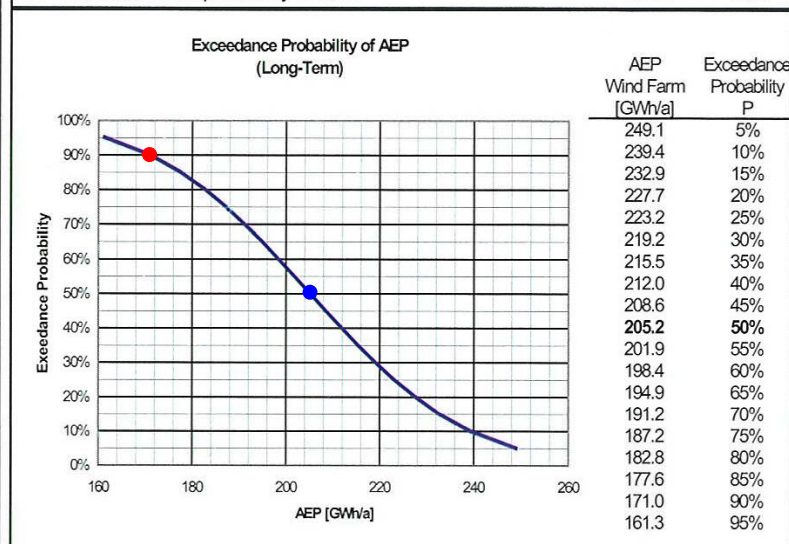


The challenge – exceedance statistics

Exceedance Probabilities, Uncertainty 9%	Wind Farm	per WT
Long-term AEP	205.2	3.87
AEP exceeded with a probability of 50%	205.2	3.87
AEP exceeded with a probability of 75%	192.8	3.64



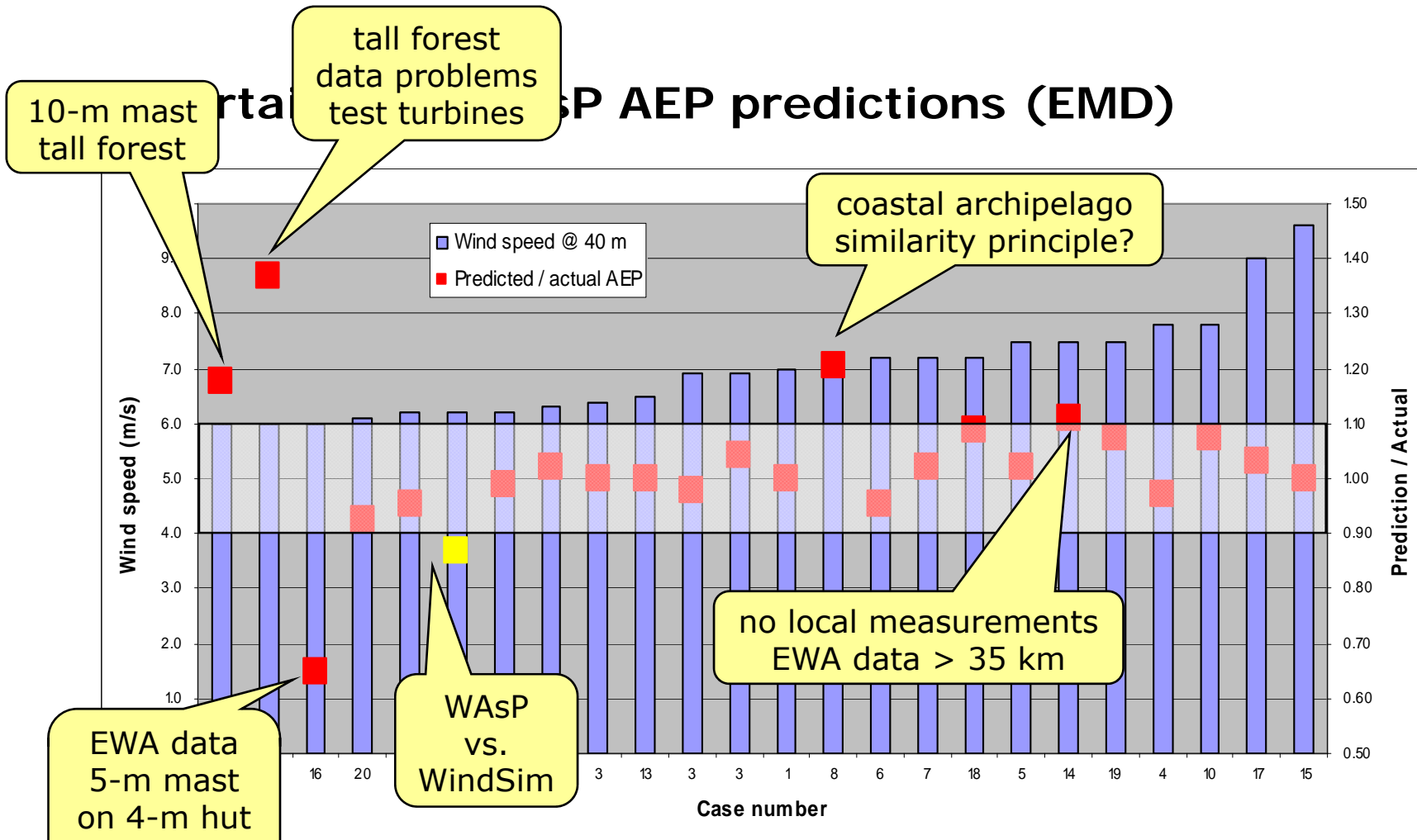
Exceedance Probabilities, Uncertainty 13%	Wind Farm	per WT
Long-term AEP	205.2	3.87
AEP exceeded with a probability of 50%	205.2	3.87
AEP exceeded with a probability of 75%	187.2	3.53



H. Klug (2006)

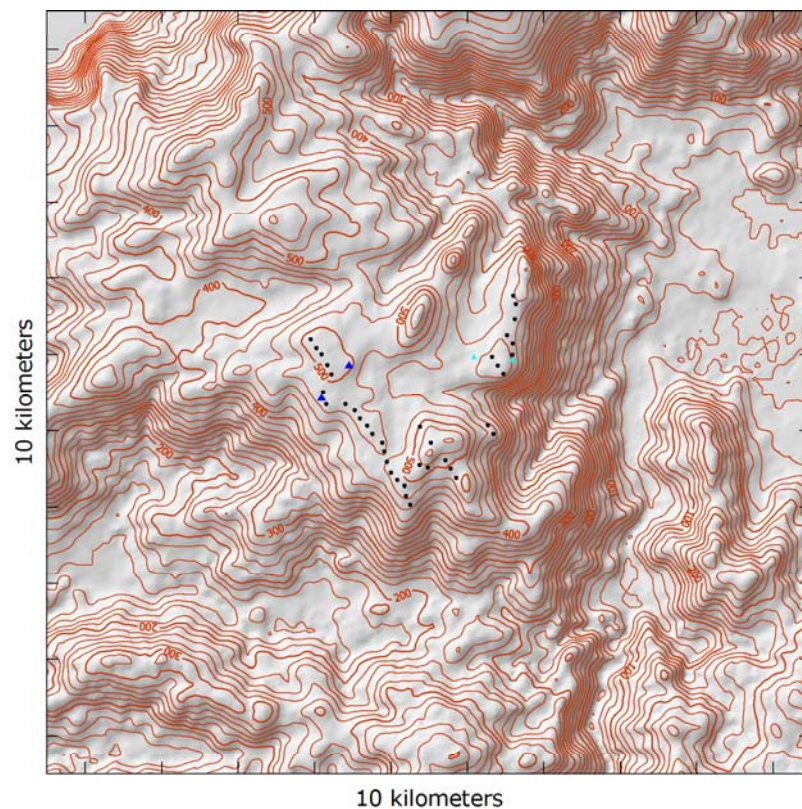
- P_{50} (•), P_{75} and P_{90} (•) commonly quoted
- Second opinion / due diligence often applied
- Lots of work needs to be done in this field...

WASP AEP predictions (EMD)



- <http://www.emd.dk/Documentation/Introduction> (2002)

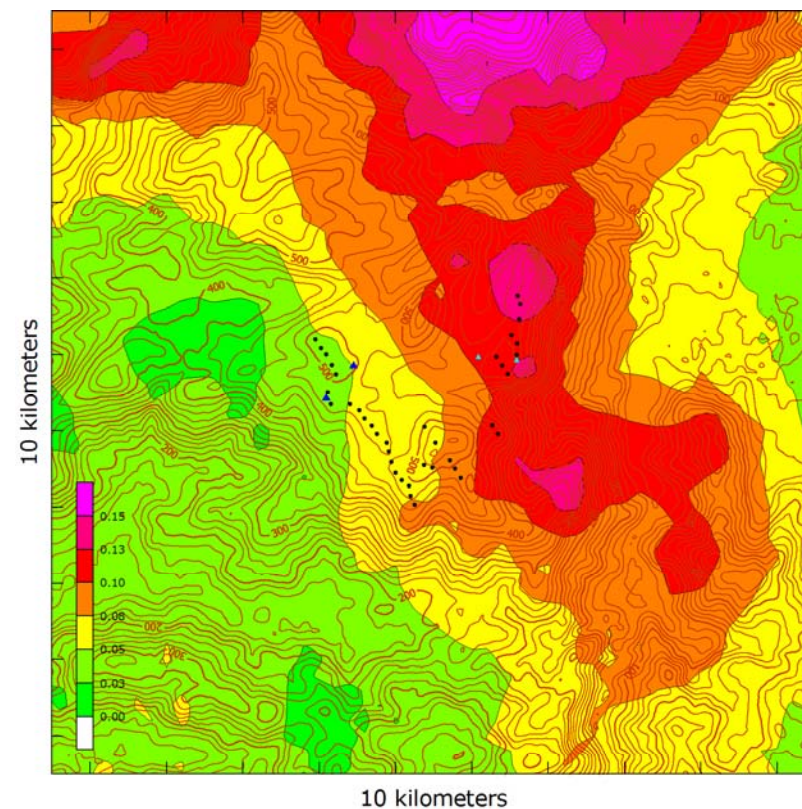
Wind farm in complex terrain



- Elevation map w/ 20-m contours
- 23-MW wind farm w/ 38 turbines
- Two reference met. stations (▲)

Risø DTU

National Laboratory for Sustainable Energy



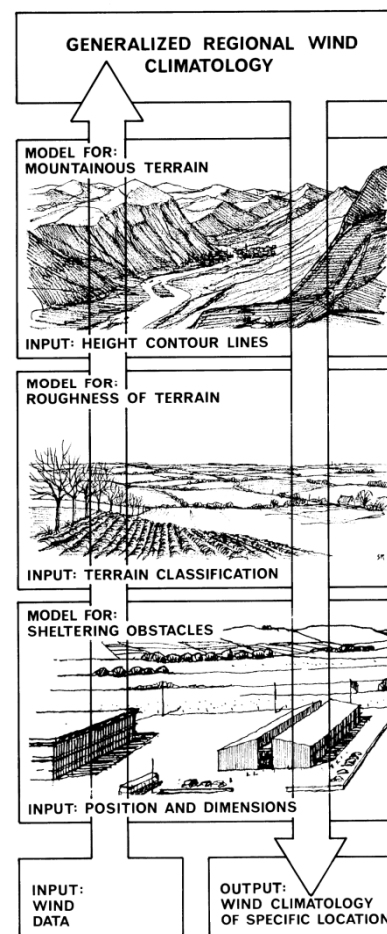
- RIX coloured map, range 0-18%
- Turbine site RIX range: 4-14%
- Met. station RIX range: 4-5%

Prediction of power production

- Measured power productions, wind speeds and directions over one year available for analysis
- Measured wind farm power production overestimated by 13% using standard WAsP procedure
- Δ RIX correction procedure applied:
 - Correction based on Portuguese data set (similarity)
 - Percentage applied to each turbine site
 - Corrected wind farm power curve applied
- After correction, the AEP is overestimated by only 3%
 - Prediction error of actual AEP decreased by 70%
 - Site is also partly forested...

Factors in the uncertainty assessment

- Short-term wind climate
 - measurements
- Long-term wind climate
 - reference data (MCP)
- Wind resource modelling
 - physical models (WAsP, ...)
 - statistical models and fits (Weibull, ...)
- Wind turbine generator data
 - power and thrust curves
 - hub height and rotor diameter
- Wind farm characteristics
 - wind turbine positions (coordinates)
 - wake modelling
 - large-scale effects
- Availability, electrical losses, etc.?
 - simulated, given or estimated
- The human factor...



Best practices in rugged terrain (Risø + GH)

Measurement programme [bankable]

- Two or more masts required
 - sited according to similarity principle (including forestry)
 - cover range of RIX over site
 - distances not greater than 1 km
 - supported by remote LT mast

Topographical inputs

- Minimum size of map
 - Elevation: 10 km from any site
 - Land-use: $\max(100 \times h, 10 \text{ km})$
- Detail and accuracy of map
 - wind farm site: 2-m contours
 - nearby terrain: 10-m contours
 - further away: 10-50 m contours
 - SRTM data may be used, but must be quality-controlled and detailed

WAsP modelling

- RIX and Δ RIX analyses required
- Use similarity principle if and when applying Δ RIX correction procedure
- Standard heights in wind atlas
 - change one level to hub height
 - never change 10-m level!
- Standard roughnesses in wind atlas
 - other classes may be added or roughness lengths changed
 - never change $z_0 = 0 \text{ m}$ class!
- Heat flux parameters
 - may be adapted to site

Future

- Evidently, 'best practices' is not a long-term substitute for further research and improved models!