SAWEP Workshop
Wind Atlas for South Africa (WASA)

Cape Town, 4th March 2010

WAsP Engineering Introduction
and
Extreme winds and design conditions for turbine

By

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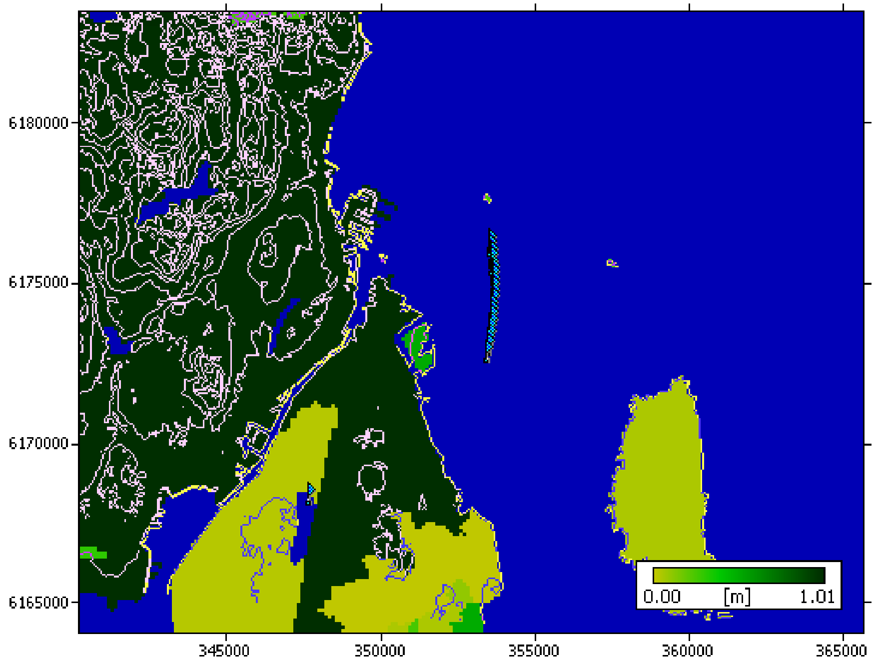
The models behind WAsP Engineering

- LINCOM, a linearized flow model
- Fetch- and wind-speed-dependent water roughness
- Spatial structure of turbulence over flat terrain
- Modification of turbulence due to orography and roughness changes
- Turbulence simulation
- Extreme wind statistics

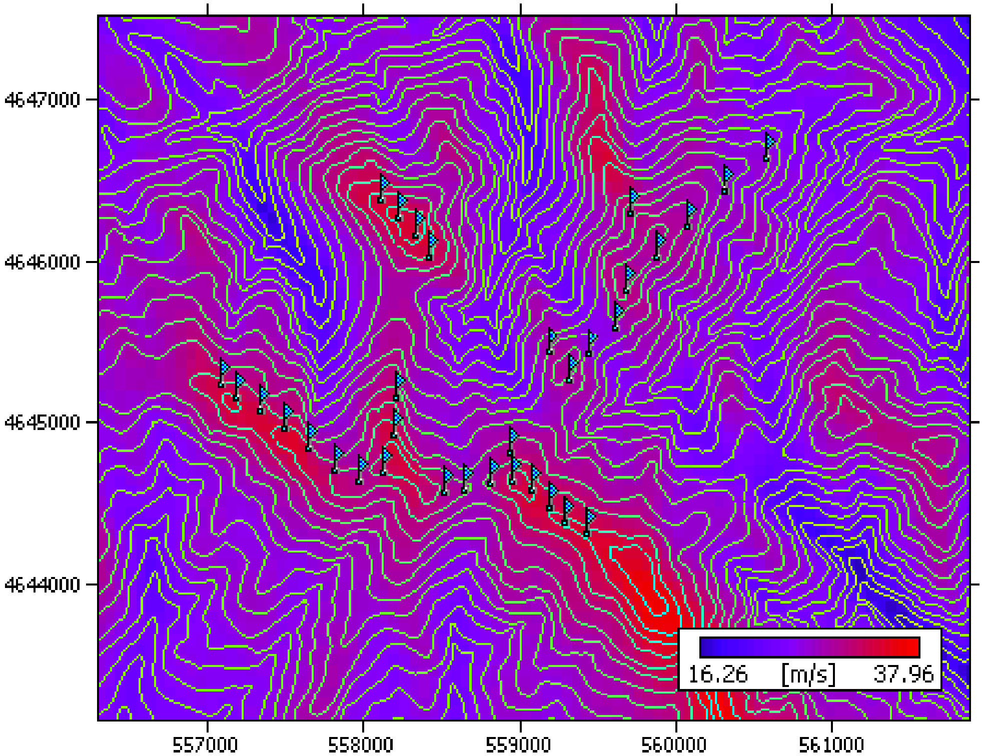
Examples of problems

Middelgrunden wind Farm to the east of Copenhagen:



How much is turbulence and the 50-year wind affected by Copenhagen?

Complex terrain



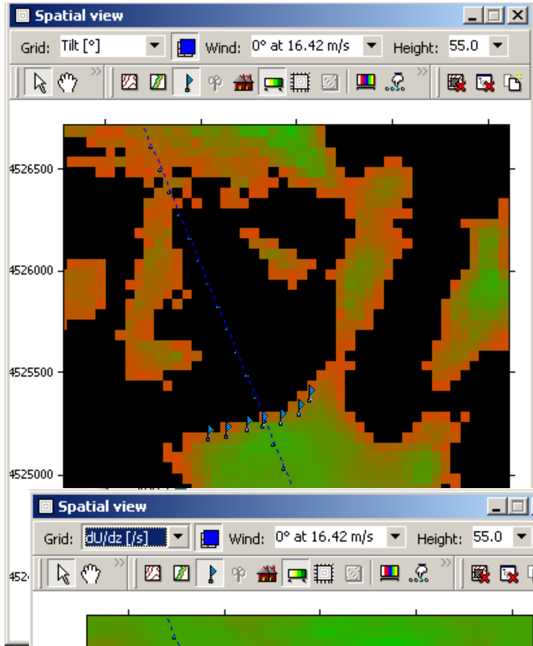
- *How much is the 50 year wind enhanced?*
- *How is the local turbulence?*
- *Are local shear and flow inclination angles too high?*
- *How steep is the terrain?*

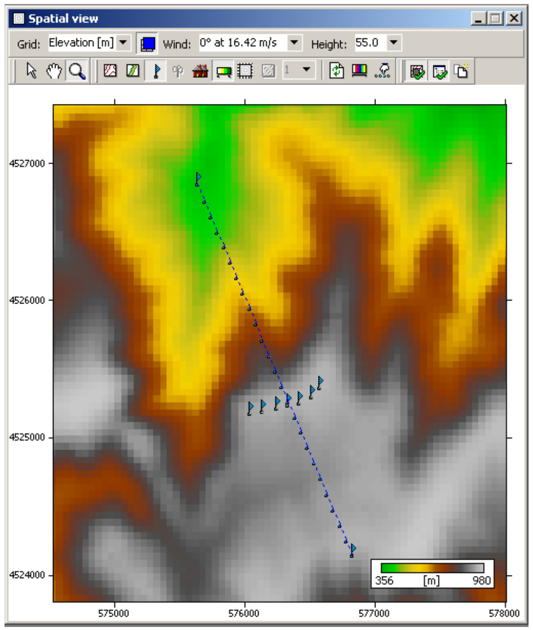
Check of different wind directions in complex terrain ?

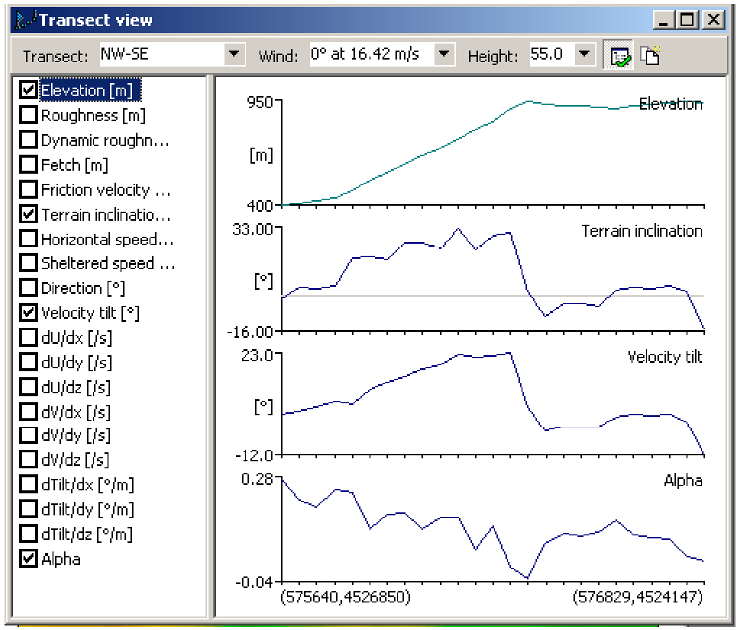
Winds from 330º

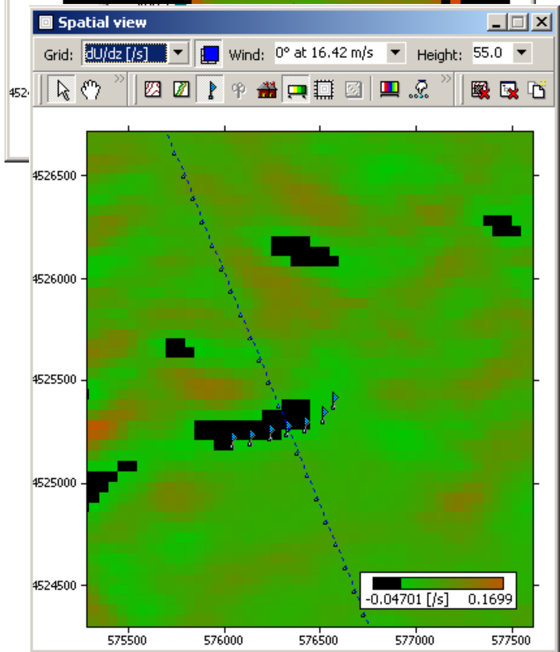
flow inclination OK at turbine positions

negative velocity gradient at some positions



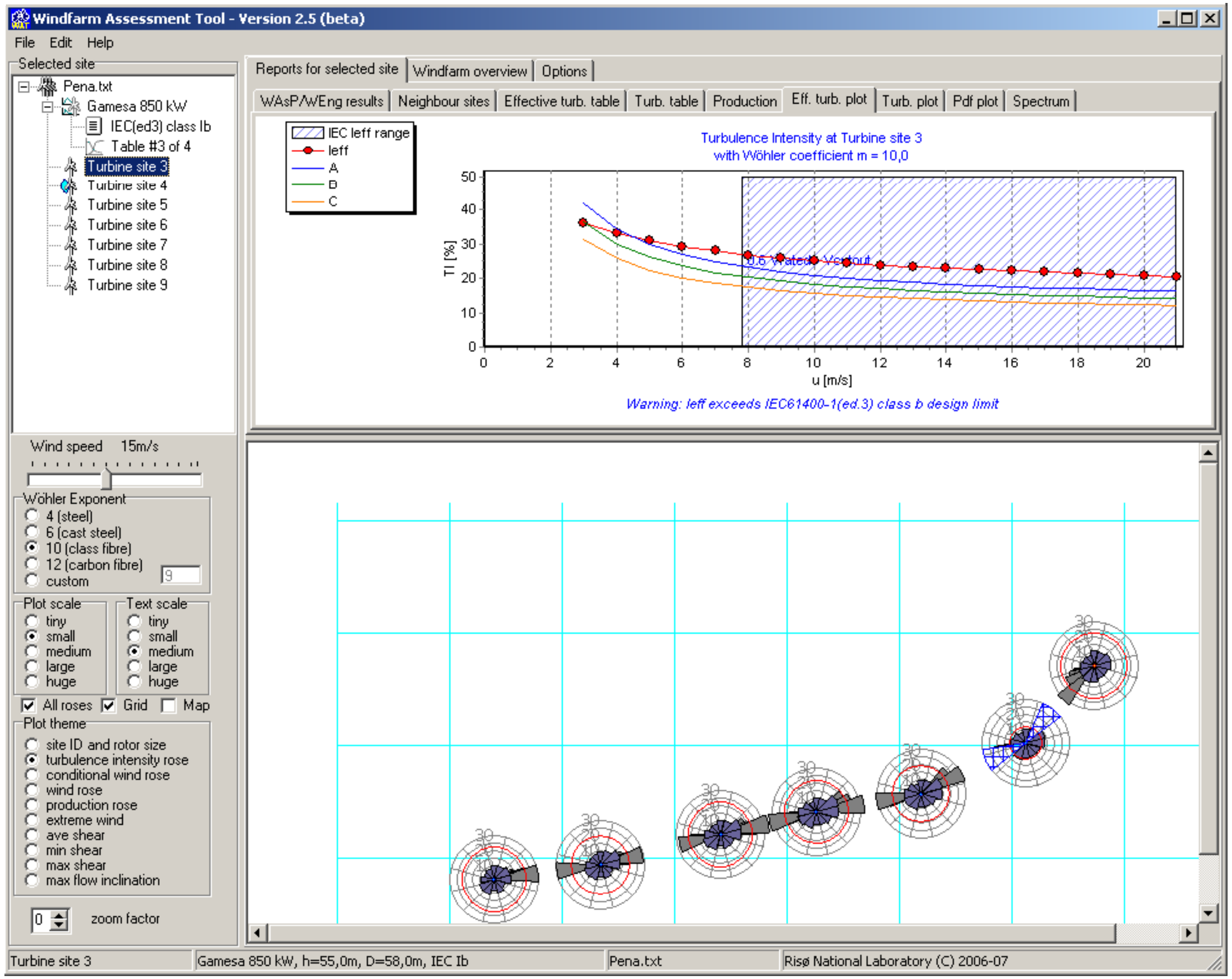






Windfarm Assessment Tool

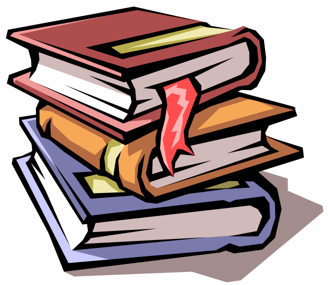
Check IEC 61400-1 site assessment rules, including effective turbulence by Frandsen model



Lexicon

- Orography
- Obstacles
- Surface roughness
- Wind profile
- Friction velocity
- Fetch
- Displacement height
- Atmospheric stability
- Velocity shear
- Flow inclination angle
- Flow speed up factor
- Flow separation

- Measured wind
- Geostrophic wind
- Reduced geostrophic wind
- Geostrophic drag law
- Power spectrum
- Taylor's hypothesis
- Micro-/Meso-/Macroscale
- Weibull distribution mkel1
- Gumbel plot



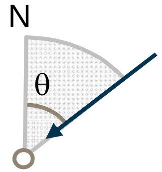
Slide 7

mkel1 added Weibull and Gumbel, is that ok?

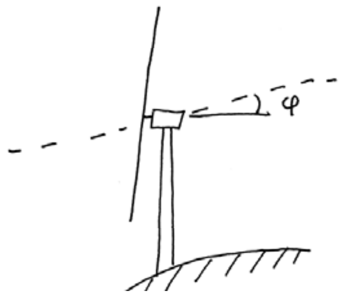
Mark Kelly, 08/01/2009

Wind direction, flow angle, shear

- **Wind direction** is the compass direction *from where the wind is coming*



- **Flow inclination** is the tilt angle (φ) of the velocity vector with respect to horizontal

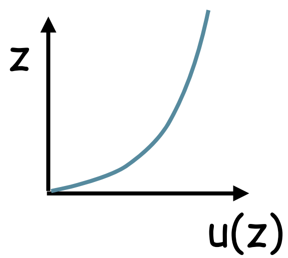


- **Wind shear** is the vertical gradient of the horizontal variation of the wind speed

$$\frac{\Delta u}{\Delta z} = \frac{u(z_2) - u(z_1)}{z_2 - z_1}$$

- **Wind shear exponent** (α) is defined by a power-law fit to the wind profile,

$$u(z) = u_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha}$$



$$\frac{d}{dz} u_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha} = \alpha \, u_{\text{hub}} / z_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha - 1}$$

$$\Rightarrow \quad \alpha_{\text{fit}} = \frac{z_{\text{hub}}}{u_{\text{hub}}} \frac{du}{dz}\bigg|_{\text{hub}} \qquad \text{(e.g.} \quad \alpha_{\text{fit}} = \frac{1}{\ln(z_{\text{hub}}/z_0)} \text{ for a log-profile)}$$

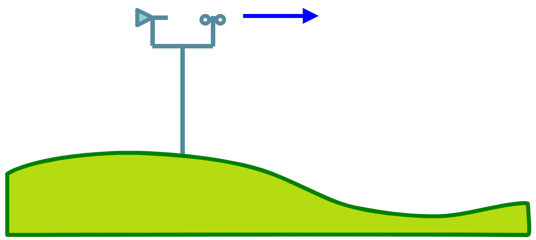
Three types of winds in WAsP Engineering

Geostrophic wind:

{u, Dir} above atmospheric boundary layer

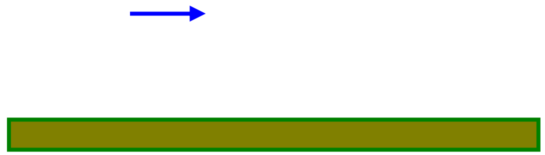
Measured wind:

u and Dir observed at h in real terrain



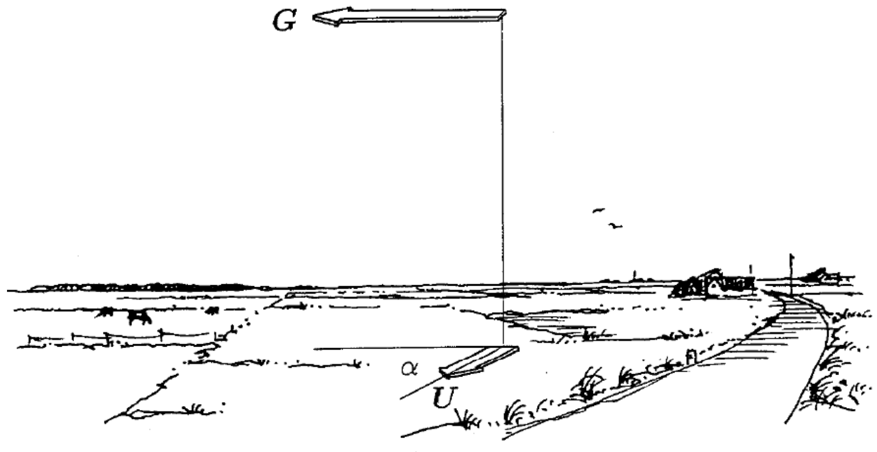
Reduced geostrophic wind:

u and Dir at reference h over idealized flat terrain with uniform z_0

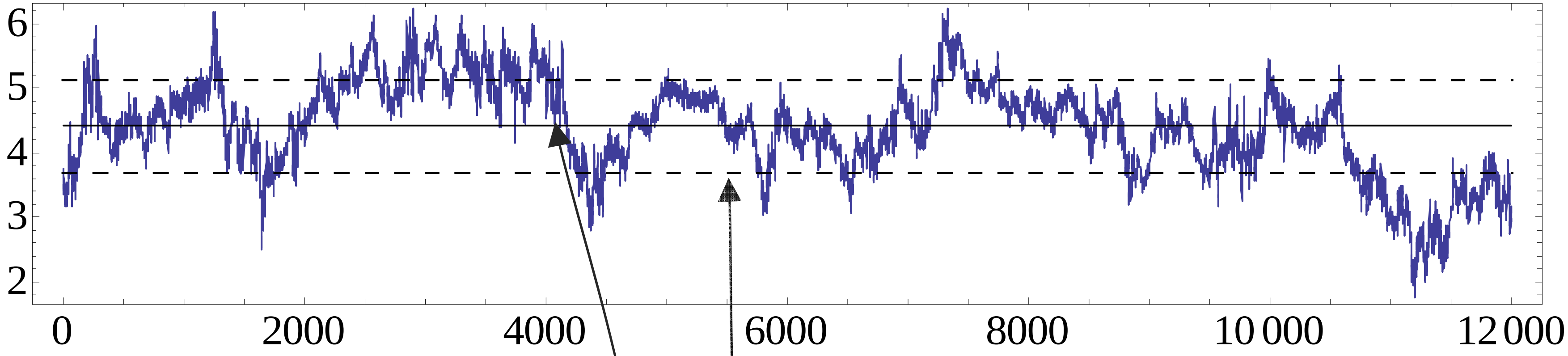


<u>Geostrophic drag law</u>

$$G = \frac{u_*}{\kappa}\sqrt{\left[\ln\frac{u_*}{fz_0} - A\right]^2 + B^2}, \qquad \tan\alpha = \frac{B}{\ln\frac{u_*}{fz_0} - A}$$



Turbulence



Reynolds' decomposition

$$u = \langle u \rangle + u'$$

Standard variation and turbulence intensity

$$\sigma_u = \sqrt{\langle u'^2 \rangle} \qquad I_u = \frac{\sigma_u}{\langle u \rangle}$$

Distribution among velocity components for neutral conditions and flat terrain

$$\sigma_u = A u_* \qquad \sigma_v \approx 0.75 \sigma_u \qquad \sigma_w \approx 0.5 \sigma_u \qquad A \approx 2.5$$

Schematic spectrum

Turbulence and flow description

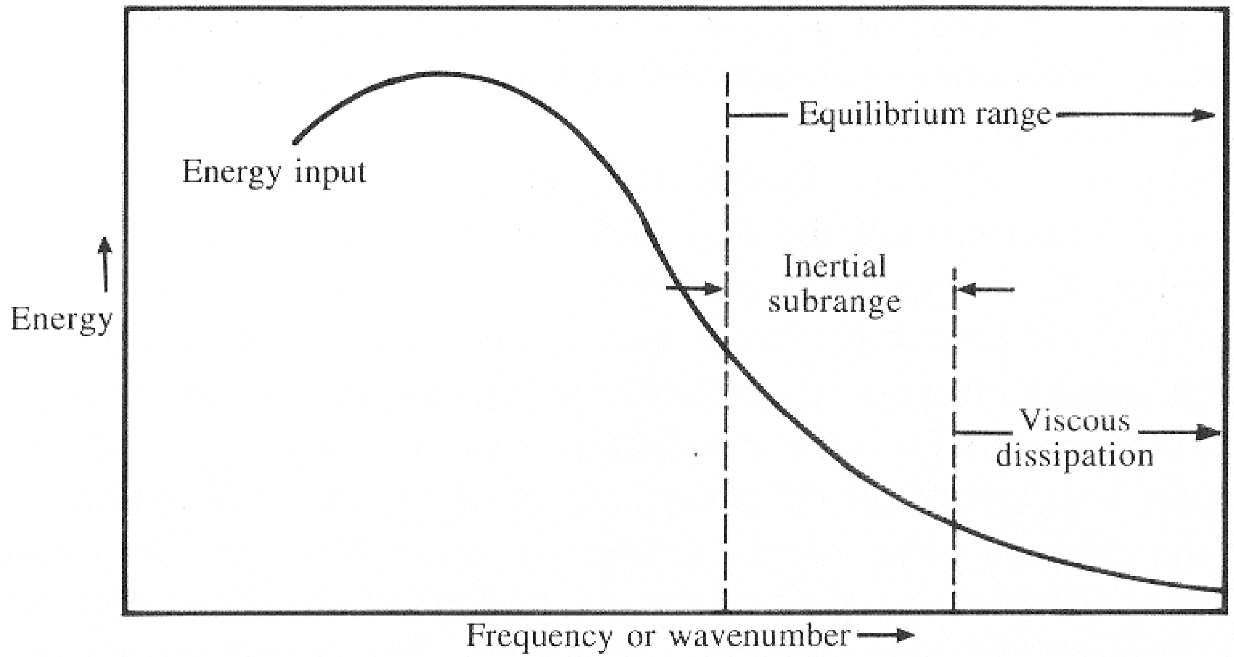
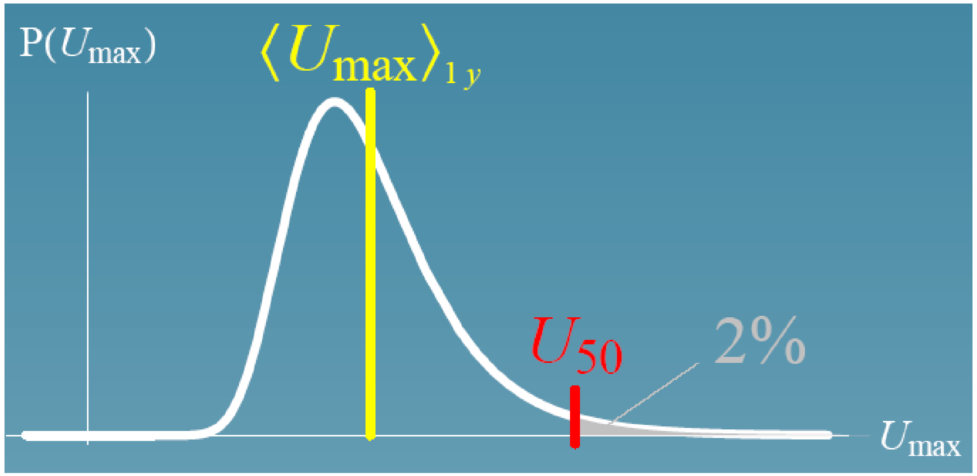


Fig. 2.1 Schematic representation of the energy spectrum of turbulence.

Extreme winds and Definitions

1. The *50 year wind* is the wind speed which on average is exceeded once in 50 years by the 10 minute averaged wind speed
2. The 50 years is called the *return period*
3. The 10 minutes is called the *averaging time*

Distribution of one-year maxima & extrapolation to 50 years

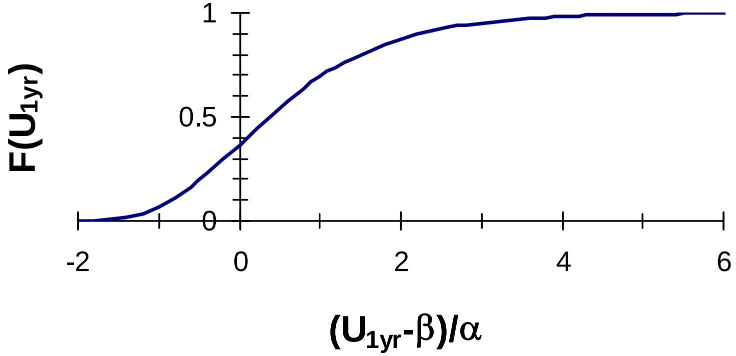


$$P(u \geq u_{50}) = 1 - F(u_{50}) = T_1 / T_{50} \Rightarrow$$

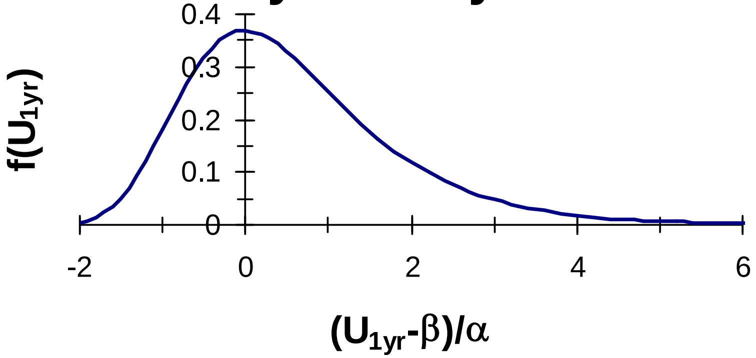
$$F(u_{50}) = 1 - T_1 / T_{50}$$

The Gumbel extreme distribution

Cumulated probability



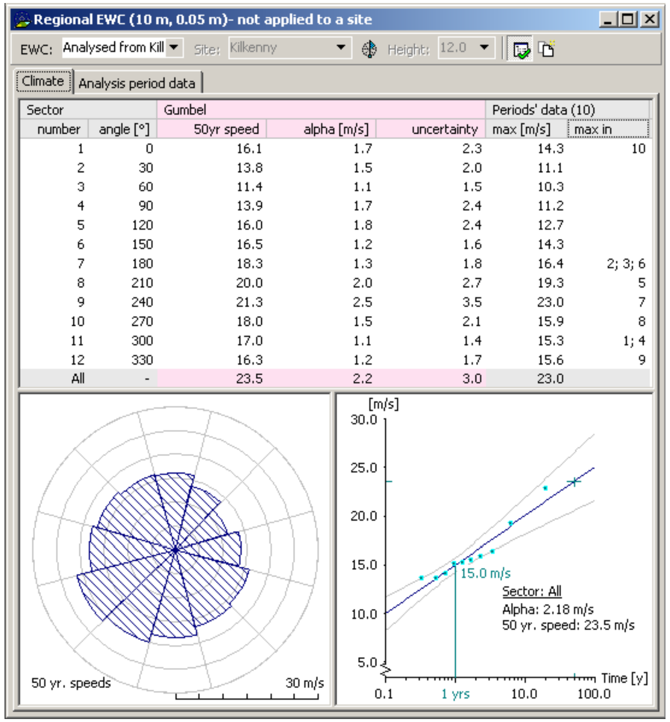
Probability density function



$$\mathrm{F}(U) = \exp\left(-\exp\left(-(U-\beta)/\alpha\right)\right)$$

$$f(U) = \exp\left(-\exp\left(-(U-\beta)/\alpha\right)\right)\exp\left(-(U-\beta)/\alpha\right)\Big/\alpha$$

Linear plot using return periods



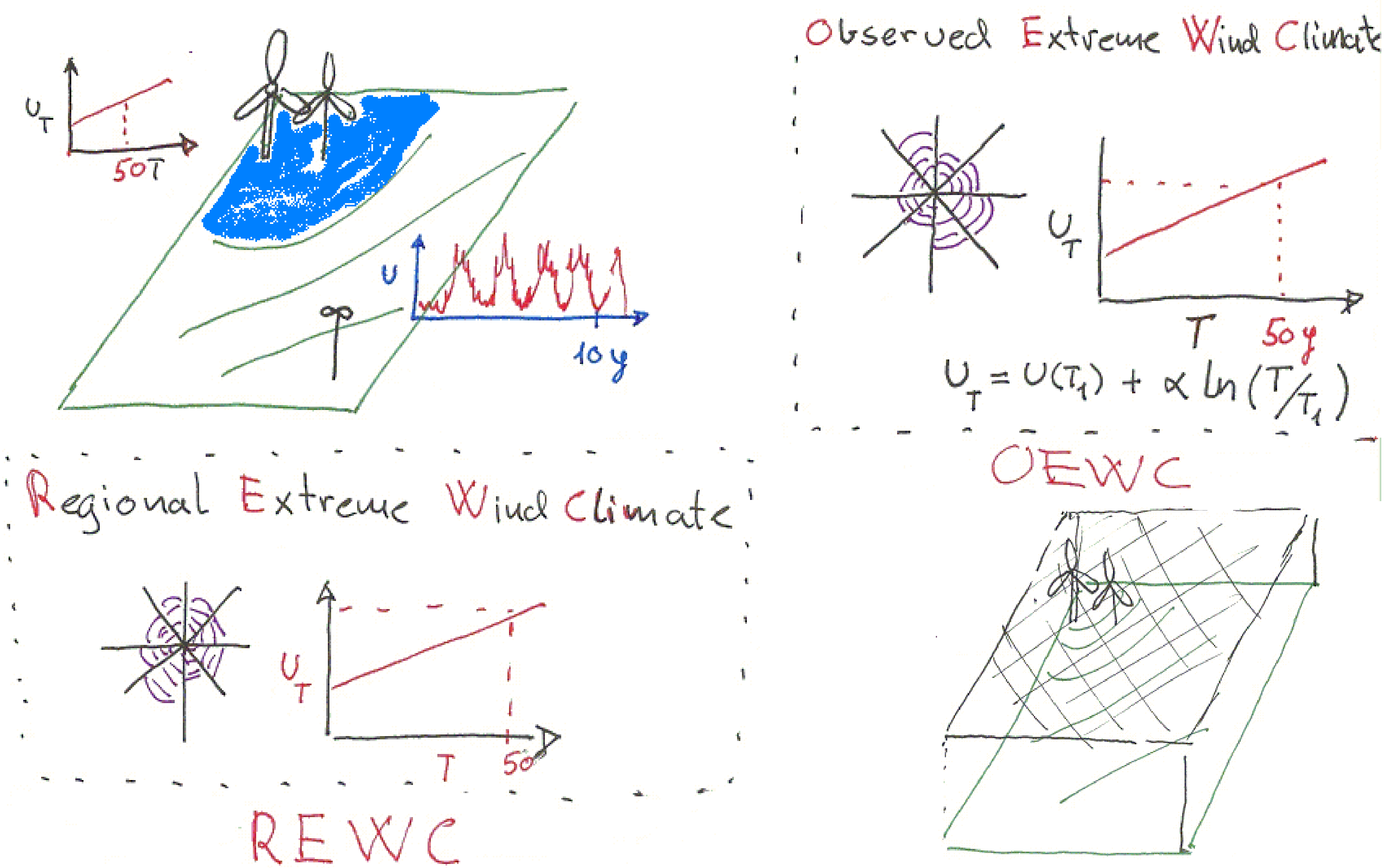
Sector		Gumbel			Periods' data (10)	
number	angle [°]	50yr speed	alpha [m/s]	uncertainty	max [m/s]	max in
1	0	16.1	1.7	2.3	14.3	10
2	30	13.8	1.5	2.0	11.1	
3	60	11.4	1.1	1.5	10.3	
4	90	13.9	1.7	2.4	11.2	
5	120	16.0	1.8	2.4	12.7	
6	150	16.5	1.2	1.6	14.3	
7	180	18.3	1.3	1.8	16.4	2; 3; 6
8	210	20.0	2.0	2.7	19.3	5
9	240	21.3	2.5	3.5	23.0	7
10	270	18.0	1.5	2.1	15.9	8
11	300	17.0	1.1	1.4	15.3	1; 4
12	330	16.3	1.2	1.7	15.6	9
All	-	23.5	2.2	3.0	23.0	

$$\mathrm{F}(U_T) = 1 - T_0/T$$

$$(U_T - \beta)/\alpha = -\ln\left(-\ln\left(1 - T_0/T\right)\right)$$

$$U_T \approx \alpha \ln\left(T_0/T\right) + \beta$$

WEng extreme winds by observation



WEng extreme winds by reanalysis data (form NCEP/NCAR)

Pressure at model surface P_s

$$P_0 = P_s \exp\left(\frac{gh}{RT_m}\right)$$

Pressure at the sea level P_o

$$u_g = -\frac{1}{f\rho}\frac{\Delta P}{2a\Delta\phi}, \quad v_g = \frac{1}{f\rho}\frac{\Delta P}{2a\Delta\lambda\cos\phi}$$

Geostrophic wind by pressure gradient

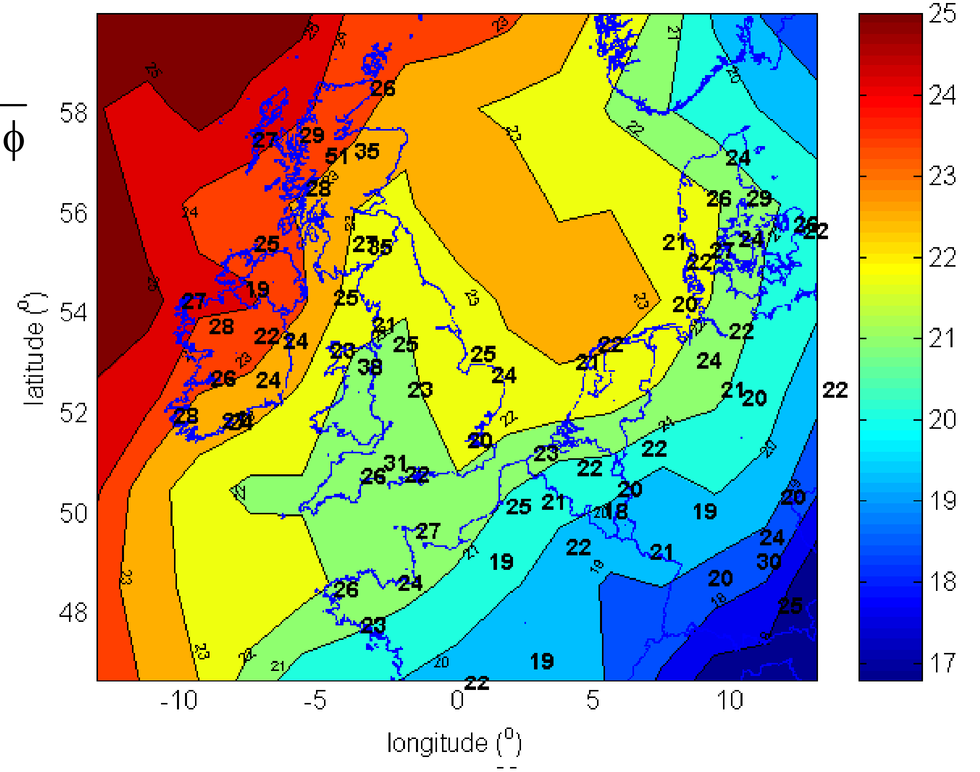
$$G = \sqrt{u_g^2 + v_g^2} = \frac{u_*}{\kappa}\sqrt{\left(\ln\frac{u_*}{fz_0} - A\right)^2 + B^2}$$

Surface wind at 10 m with z_0=5cm

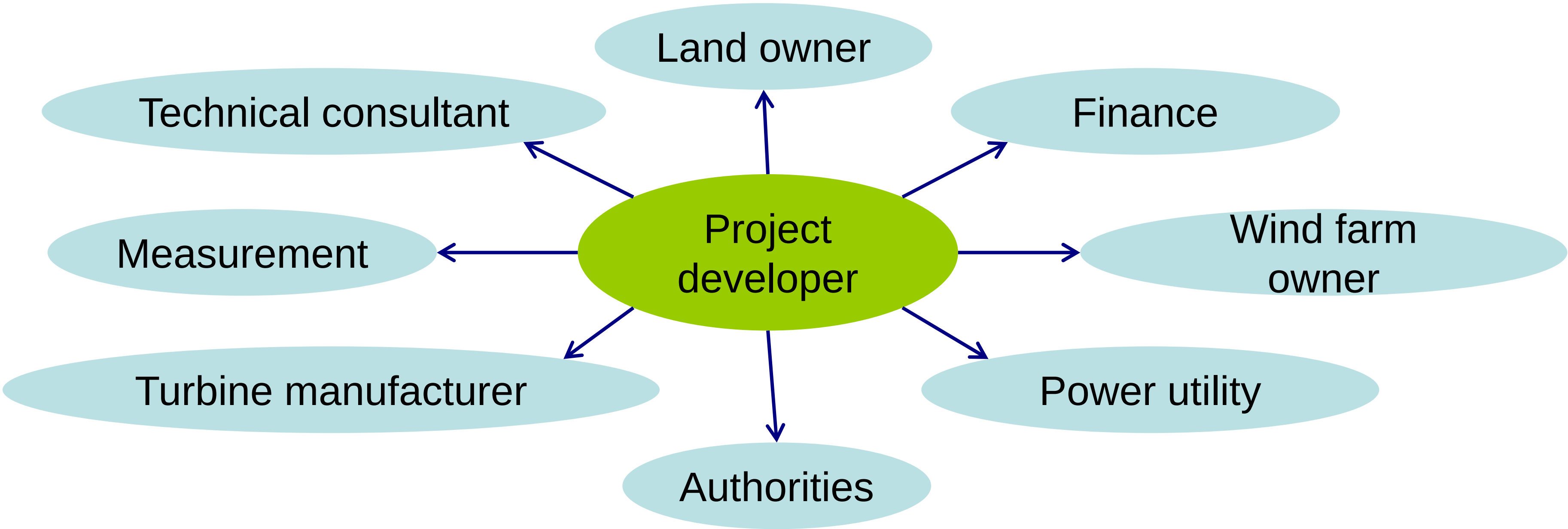
$$u_{10} = \frac{u_*}{\kappa}\ln\frac{10m}{z_0}$$

Regional extreme wind climate (REWC)

WP5 will create an atlas based on Meso-scale simulations



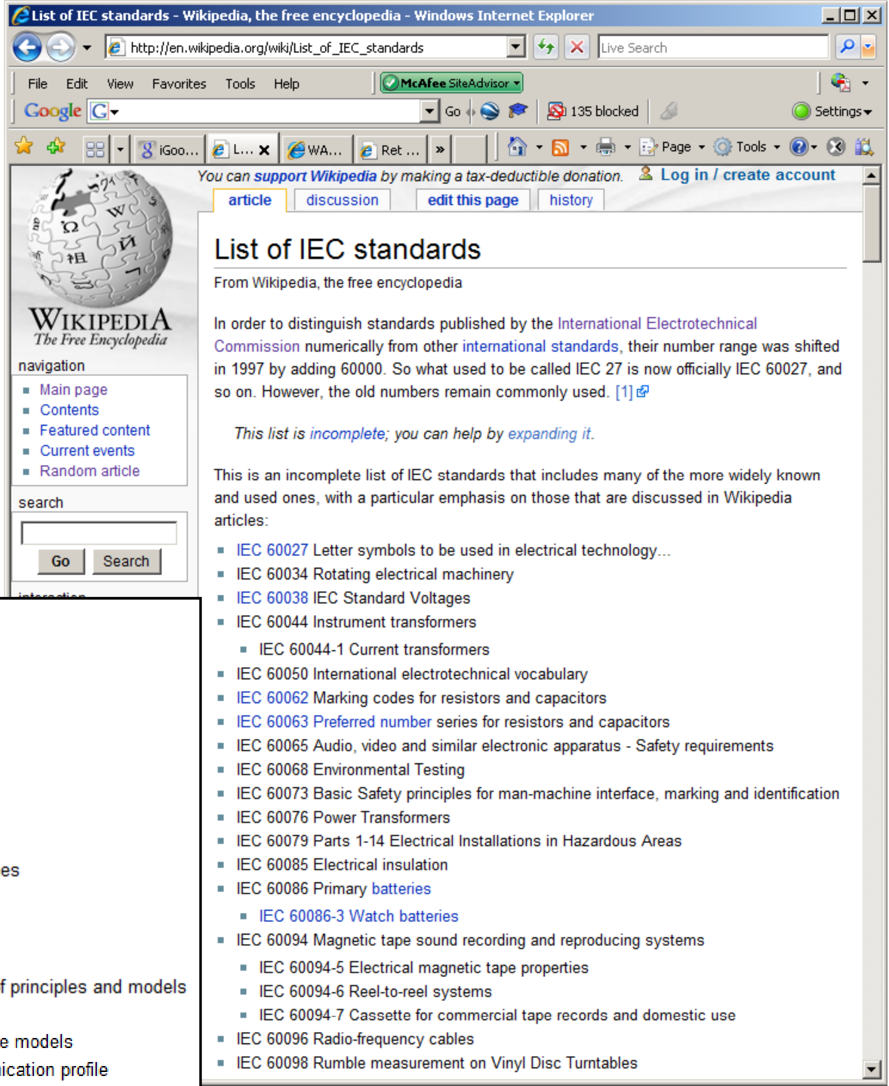
WEng and IEC 61400-1 site assessment



Engineering standards

National standards
Dansk Standard (DS)
British Standard (BS)
Deutsche Institut für Normung (DIN)
+ many others

International standards
Intl. Organization for Standardization (ISO)
Intl. Electrotechnical Commission (IEC)
+ many others


List of IEC standards - Wikipedia, the free encyclopedia - Windows Internet Explorer

http://en.wikipedia.org/wiki/List_of_IEC_standards

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List of IEC standards

From Wikipedia, the free encyclopedia

In order to distinguish standards published by the International Electrotechnical Commission numerically from other international standards, their number range was shifted in 1997 by adding 60000. So what used to be called IEC 27 is now officially IEC 60027, and so on. However, the old numbers remain commonly used. [1]

This list is incomplete; you can help by expanding it.

This is an incomplete list of IEC standards that includes many of the more widely known and used ones, with a particular emphasis on those that are discussed in Wikipedia articles:

- IEC 60027 Letter symbols to be used in electrical technology...
- IEC 60034 Rotating electrical machinery
- IEC 60038 IEC Standard Voltages
- IEC 60044 Instrument transformers
  - IEC 60044-1 Current transformers
- IEC 60050 International electrotechnical vocabulary
- IEC 60062 Marking codes for resistors and capacitors
- IEC 60063 Preferred number series for resistors and capacitors
- IEC 60065 Audio, video and similar electronic apparatus - Safety requirements
- IEC 60068 Environmental Testing
- IEC 60073 Basic Safety principles for man-machine interface, marking and identification
- IEC 60076 Power Transformers
- IEC 60079 Parts 1-14 Electrical Installations in Hazardous Areas
- IEC 60085 Electrical insulation
- IEC 60086 Primary batteries
  - IEC 60086-3 Watch batteries
- IEC 60094 Magnetic tape sound recording and reproducing systems
  - IEC 60094-5 Electrical magnetic tape properties
  - IEC 60094-6 Reel-to-reel systems
  - IEC 60094-7 Cassette for commercial tape records and domestic use
- IEC 60096 Radio-frequency cables
- IEC 60098 Rumble measurement on Vinyl Disc Turntables

- IEC 61400 Wind turbines
  - 61400-1: Design requirements
  - 61400-2: Design requirements for small wind turbines
  - 61400-3: Design requirements for offshore wind turbines
  - 61400-11: Acoustic noise measurement techniques
  - 61400-12: Wind turbine power performance testing
  - 61400-12-1: Power performance measurements of electricity producing wind turbines
  - 61400-13: Measurement of mechanical loads
  - 61400-14: Declaration of apparent sound power level and tonality values
  - 61400-21: Measurement and assessment of power quality characteristics of grid connected wind turbines
  - 61400-23: Full-scale structural testing of rotor blades
  - 61400-24: Lightning protection
  - 61400-25: Information and information exchange for wind power plants[1]
    - 61400-25-1: Communications for monitoring and control of wind power plants – Overall description of principles and models
    - 61400-25-2: Communications for monitoring and control of wind power plants – Information models
    - 61400-25-3: Communications for monitoring and control of wind power plants – Information exchange models
    - 61400-25-4: Communications for monitoring and control of wind power plants – Mapping to communication profile
    - 61400-25-5: Communications for monitoring and control of wind power plants – Conformance testing

IEC 61400-1 (Ed. 3) turbine classification scheme

Table 1 – Basic parameters for wind turbine classes[2]

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

Wind conditions in design load cases modelled by

V_{ref} hub-height fifty-year extreme wind

I_{ref} reference turbulence intensity in a 10-min period

z_{hub} hub-height

Differences in IEC 61400-1 (Ed. 2)

- extra wind turbine class IV with V_{ref}= 30 m/s
- no turbulence category C
- turbulence parameterized by I_{15} ($\mu+\sigma$) instead of I_{ref} (μ) …(see "CTI")

IEC 61400-1 Design Load cases

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

Turbine operation

- normal power production
- start up and shut down
- control failure or network failure
- parked or idling state
- yaw error

Wind conditions

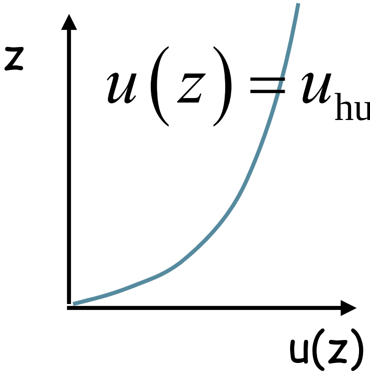
- Extreme wind
- Wind distribution
- Turbulence
- Wind shear
- Dynamic events

Load type

- Fatigue loads
- Ultimate load

IEC wind profile

Power law



$$u(z) = u_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha}$$

<u>Fitting power law to data</u>

$$\frac{d}{dz}\left[u_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha} \right] = u_{\text{hub}} \frac{\alpha}{z_{\text{hub}}} \left(z/z_{\text{hub}} \right)^{\alpha-1}$$

$$\Rightarrow \quad \alpha_{\text{fit}} = \frac{z_{\text{hub}}}{u_{\text{hub}}} \left. \frac{du}{dz} \right|_{\text{hub}}$$

$$\text{e.g.} \quad \alpha_{\text{fit}} = \frac{1}{\ln\left(z_{\text{hub}}/z_0 \right)} \quad \text{for logarithmic profile}$$

Shear parameter (α)

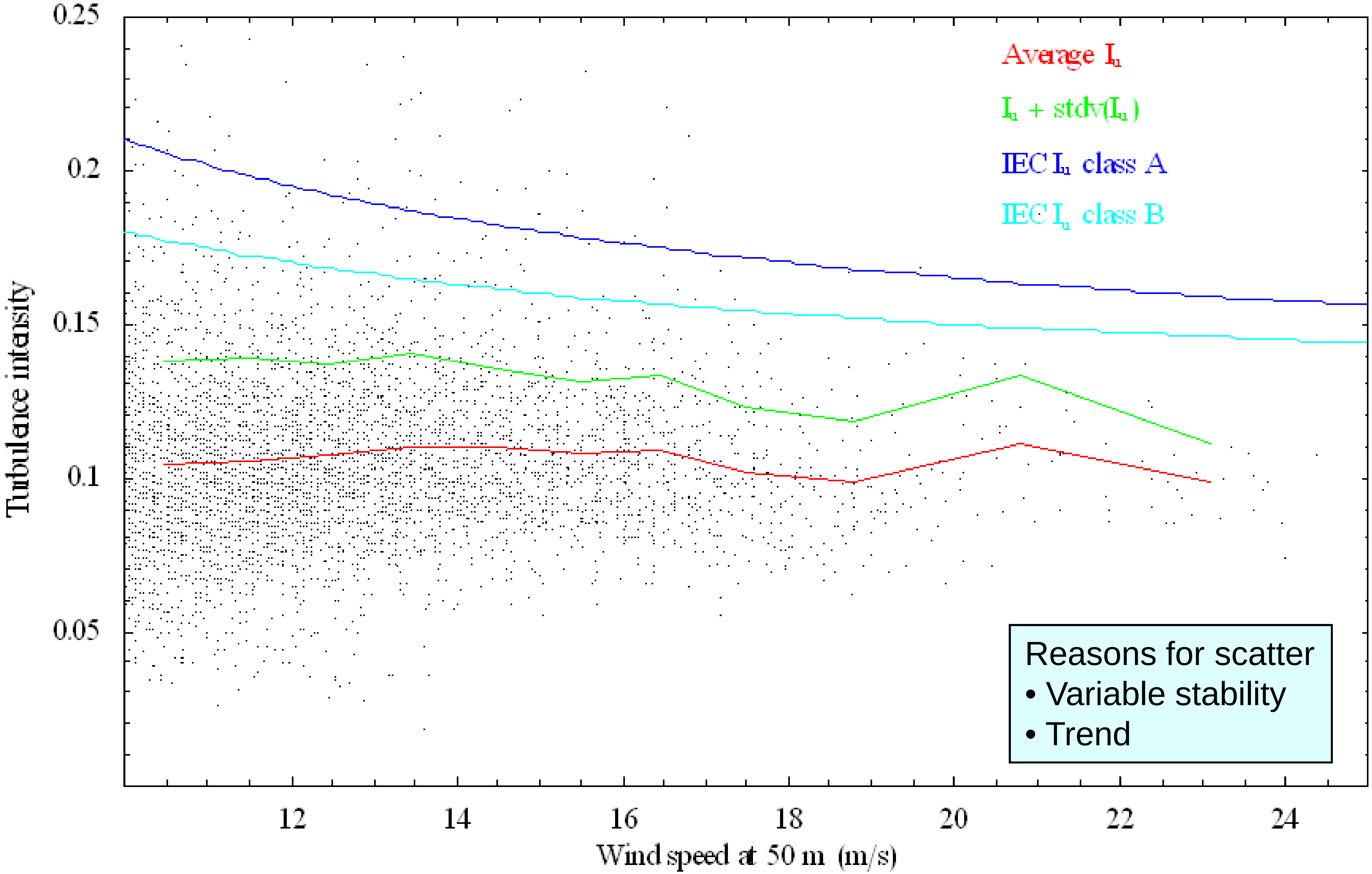
normal shear	$\alpha = 0.11$
enhanced shear	$\alpha = 0.2$

IEC Extreme-wind model

V_{hub}	Yaw error	Turbulence	Shear
$V_{50yr} = 1.4\ V_{ref}$	no	no	moderate[1]
$V_{1yr} = 1.12\ V_{ref}$	±15º	no	moderate
$V_{50yr} = 1.0\ V_{ref}$	no	$\sigma_1 = 0.11 V_{hub}$	moderate
$V_{1yr} = 0.8\ V_{ref}$	±15º	$\sigma_1 = 0.11 V_{hub}$	moderate

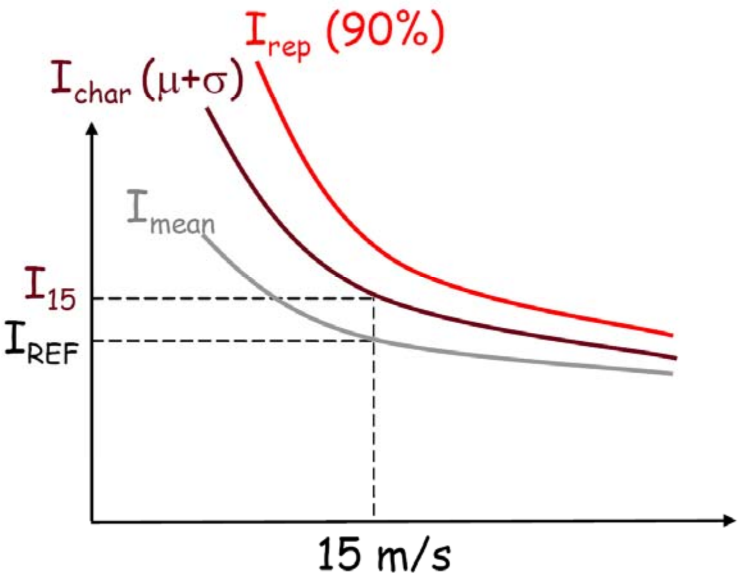
[1]the moderate (‘normal’) shear exponent is $\alpha = 0.11$

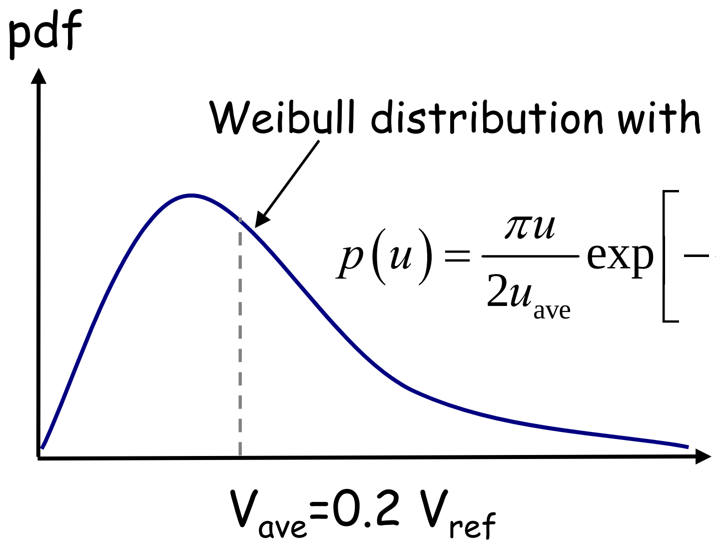
Observed 10-min turbulence intensities



.../A
sP

IEC normal-turbulence model





$$p(u) = \frac{\pi u}{2u_{\text{ave}}} \exp\left[-\frac{\pi u^2}{4u_{\text{ave}}^2}\right]$$

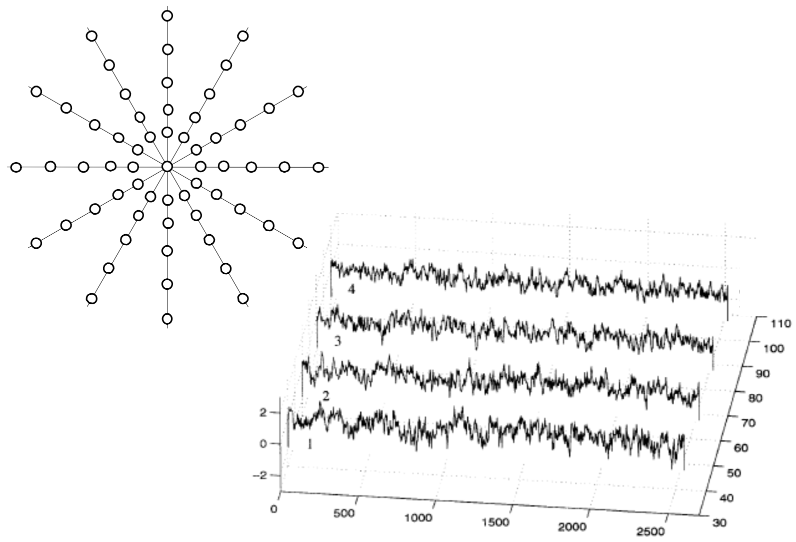
	Edition 2	Edition 3
Classification scheme	I_{15}	I_{ref} reference TI
Design rules	I_{char} characteristic TI	I_{rep} representative TI

$$\sigma_1 = I_{15}\left(15\text{m/s} + aV_{\text{hub}}\right) / \left(1 + a\right) \quad \text{Edition 2}$$

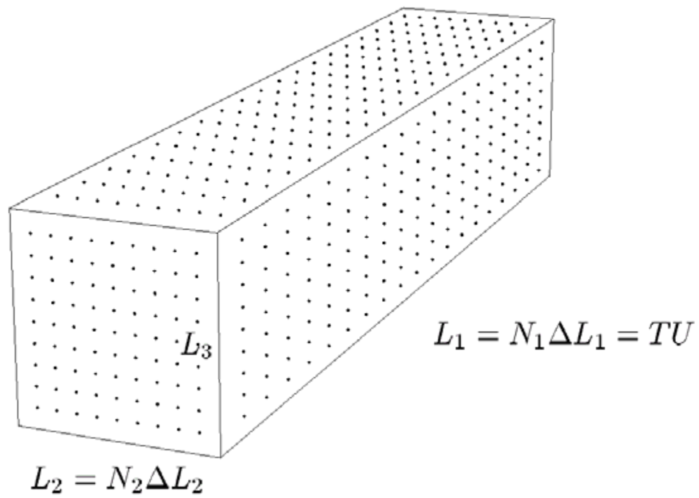
$$\sigma_1 = I_{\text{ref}}\left(0.75V_{\text{hub}} + 5.6\text{m/s}\right) \quad \text{Edition 3}$$

WA
sP

Turbulence simulation



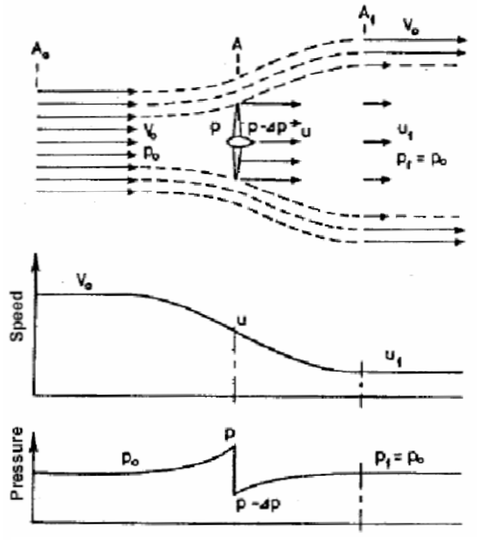
Multivariate Fourier simulation
Veers' method (1988)



3D Fourier simulation
WASP Engineering

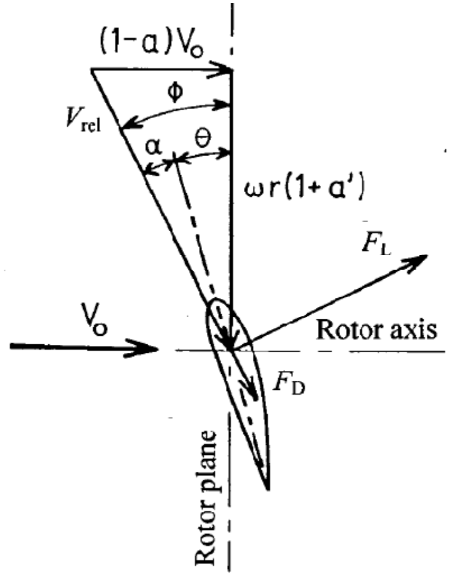
From wind to loads on turbines

Rotor aerodynamics



$$U = (1-a)U_0 = \sqrt{1 - C_T(U_0)}\,U_0$$

Loads on blade element



induction a, a'

inflow angle α

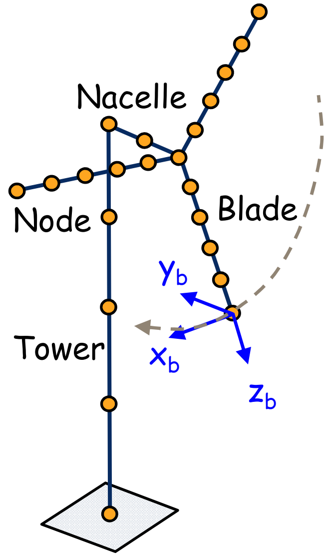
lift and drag $C_L(\alpha), C_D(\alpha)$

axial and tangential forces

$$C_N = \cos(\phi)C_L + \sin(\phi)C_D$$

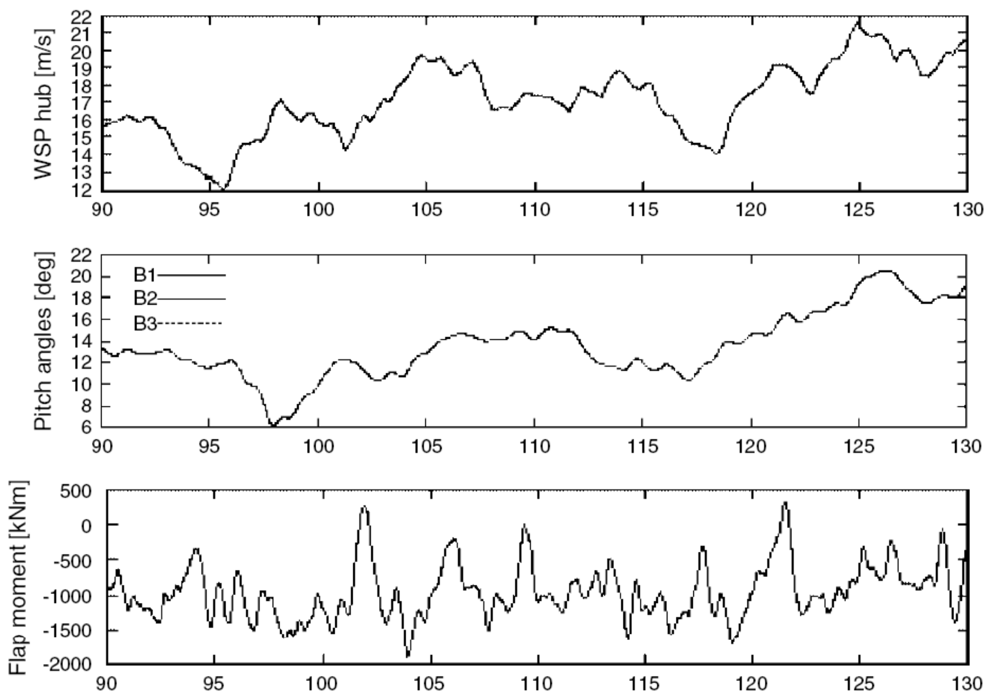
$$C_T = \sin(\phi)C_L - \cos(\phi)C_D$$

Structural dynamics



$$\mathbf{M}\,\ddot{\mathbf{x}}(t) + \mathbf{C}\,\dot{\mathbf{x}}(t) + \mathbf{K}\,\mathbf{x}(t) = \mathbf{F}(t)$$

Aeroelastic load simulations

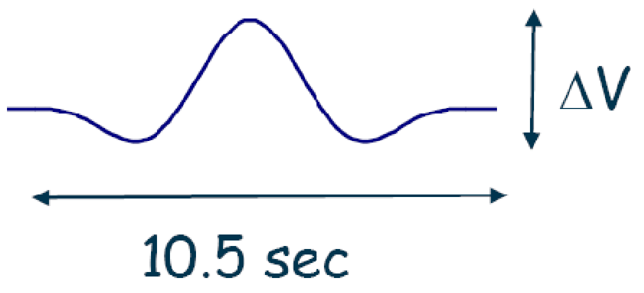


Fatigue load criteria

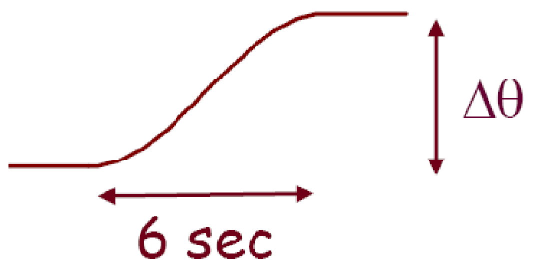
- safe after 20 years
- with standard Weibull distribution (k=2, V_{ave}=0.2V_{ref})
- and enhanced wind shear α=0.2
- and flow inclination angles of ±8º
- and a representative number of start/stop situations

Dynamic wind events for IEC load cases

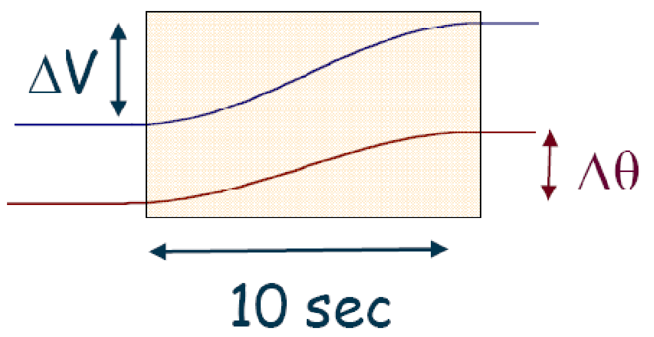
Extreme operating gust (EOG)



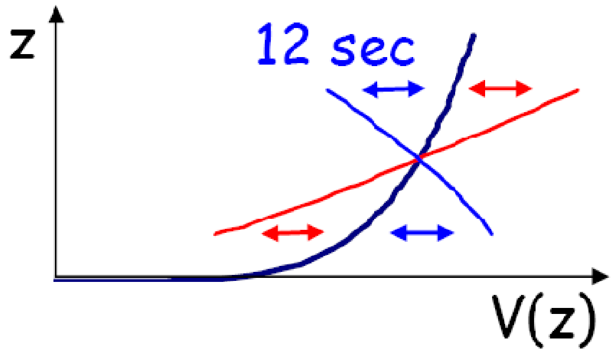
Extreme directional change (EDC)



Extreme coherent gust with directional change (ECD)

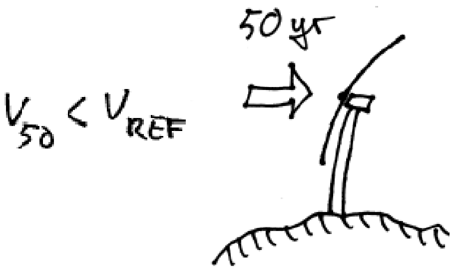


Extreme wind shear (EWS)



Amplitudes depend on turbine class and wind speed

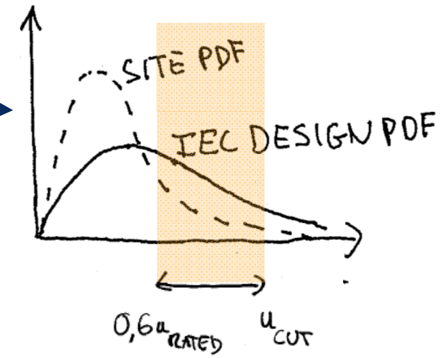
IEC 61400-1 site assessment rules

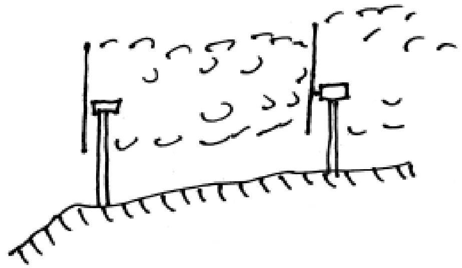


Class	V_{ref}
I	50 m/s
II	42.5 m/s
III	37.5 m/s
IV*	30 m/s
S	Designer specifies

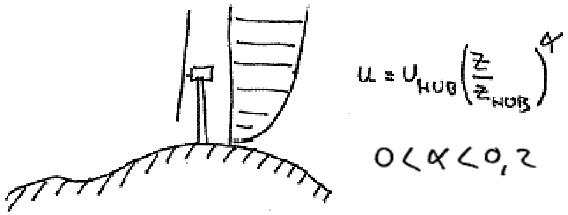
Checklist

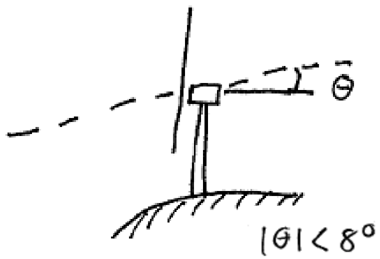
- Extreme winds
- Shear of vertical wind profile
- Flow inclination
- Background turbulence
- Wake turbulence
- Wind-speed distribution



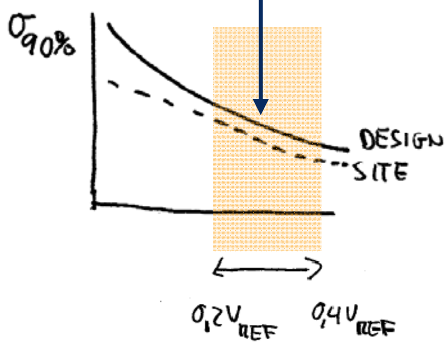


averaged over all directions



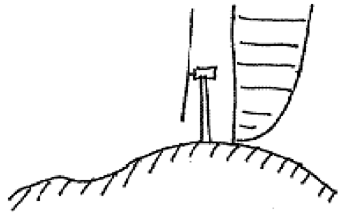


for any direction



Modeling by WASP Engineering

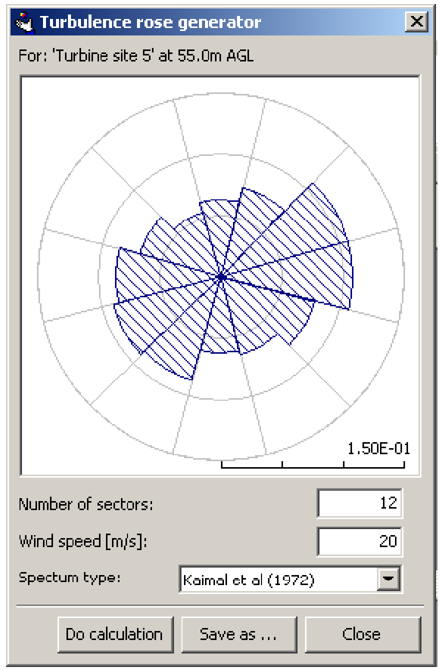
- Extreme winds
- Shear of vertical profiles
- Inclination of terrain and flow lines
- Turbulence intensity
- Wind-speed probability distribution
    - calling WASP from a script
- Effective turbulence intensity
    - IEC wake model with
    - Windfarm Assessment Tool (WAT)



$$u = U_{HUB}\left(\frac{z}{z_{HUB}}\right)^{\alpha}$$

$$0 < \alpha < 0,2$$

$$\alpha = \frac{z_{HUB}\left.\frac{du}{dz}\right|_{z_{HUB}}}{u_{HUB}}$$



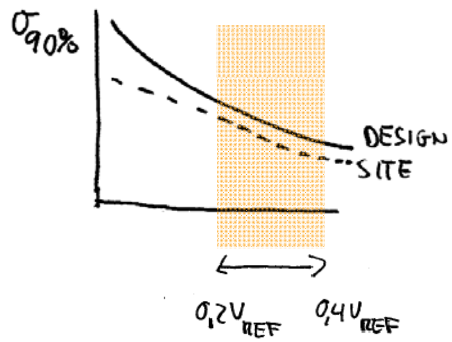
IEC turbulence model

Characteristic TI (IEC 61400-1 ed.2)

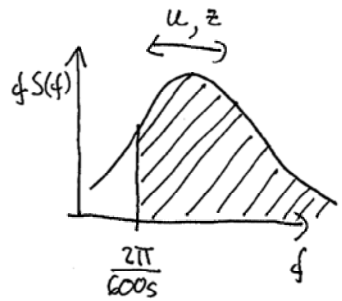
$$\sigma_1 = I_{15}\left(15\ \text{m/s} + a V_{\text{hub}}\right)/\left(1+a\right)$$

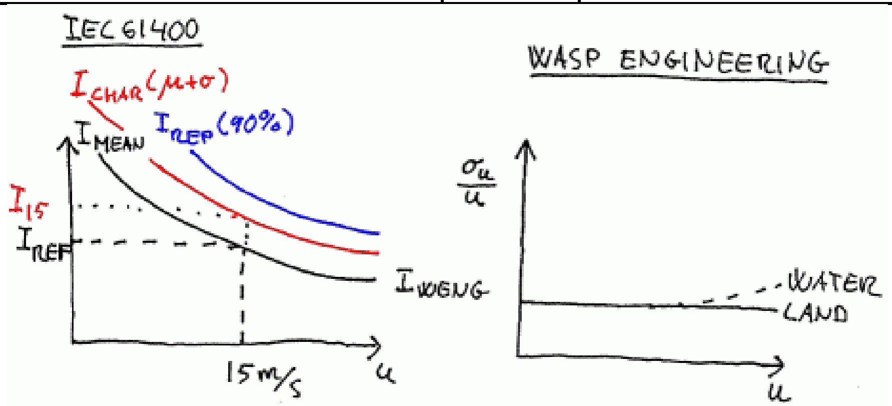
Representative TI (IEC 61400-1 ed.3)

$$\sigma_1 = I_{\text{ref}}\left[\left(15\ \text{m/s} + a V_{\text{hub}}\right)/\left(1+a\right) + 1.28 \times 1.44\ \text{m/s}\right]$$



IEC61400-1 edition 2			IEC61400-1 edition 3		
Class	I_{15}	a	Class	I_{ref}	a
A	0.18	2	A	0.16	3
B	0.16	3	B	0.14	3
S	Designer specifies		C	0.12	3
			S	Designer specifies	

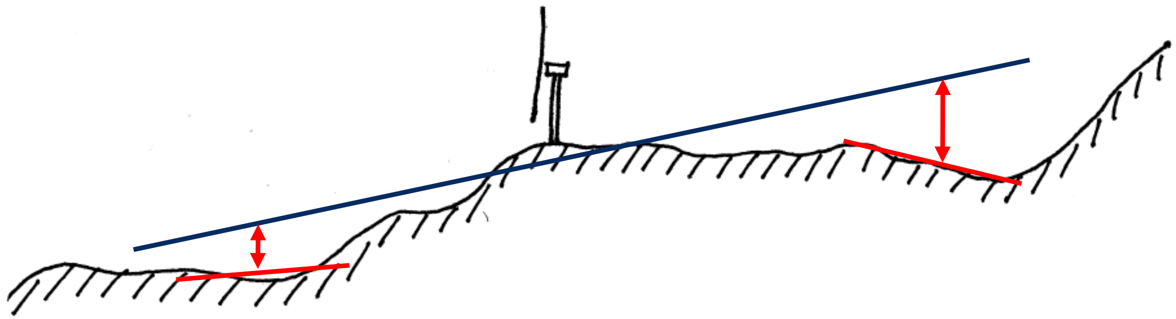




$$I_{\text{ref}} = I_{\text{WEng}} \cdot \left(\frac{1+a}{a}\right)$$

$$I_{15} = I_{\text{ref}}\left(1 + \frac{1.44\,\text{m/s}}{15\,\text{m/s}}\right)$$

IEC complex terrain indicator



1. fit big circle
2. check slope
3. fit small circles
4. check displacement

Table 4 – Terrain complexity indicators

Distance Range from Wind Turbine	Max slope of fitted plane	Maximum terrain variation from a disc with radius 1.3 z_{hub} fitted to the terrain
< 5 z_{hub}	< 10°	< 0.3 z_{hub}
< 10 z_{hub}		< 0.6 z_{hub}
< 20 z_{hub}		< 1.2 z_{hub}

enhanced TI in complex terrain!

$$C_{\text{complex}} = \frac{\sqrt{1+(\sigma_2/\sigma_1)^2+(\sigma_3/\sigma_1)^2}}{1.375}$$

Wake turbulence in the IEC 61400 standard

Annex D
(informative)

Wake and wind farm turbulence

Risø-R-1188(EN)

D.1 Wake effects

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity $I_{eff,}$, Frandsen (2003). The effective turbulence intensity – conditioned on hub height mean wind speed – may be defined as

$$I_{eff}(V_{hub}) = \left\{ \int_0^{2\pi} p(\theta | V_{hub}) I^m(\theta | V_{hub}) d\theta \right\}^{\frac{1}{m}} \qquad (D.1)$$

where

p is the probability density function of wind direction;

I is the turbulence intensity combined of ambient and wake flow from wind direction θ, and

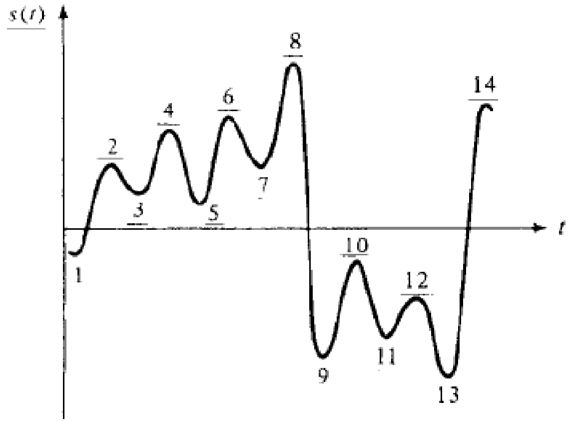
m is the Wöhler (SN-curve) exponent for the considered material.

IEC effective turbulence

Small *m*	ductile material	e.g. steel
Large *m*	brittle material	e.g. glass fiber

Traditional fatigue-load calculus

$$n_{\text{eqivalent}} S_{\text{ref}}^{\text{m}} = \sum n_i S_i^m$$



- Effective turbulence is a weighted average depending on Wöhler coefficient *m*

$$I_{\text{eff}}(u) = \left[\int_0^{2\pi} I_{\text{actual}}^m (\theta \mid u) \, p(\theta \mid u) \, d\theta \right]^{m^{-1}}$$

Optional whether to apply a uniform or actual wind distribution

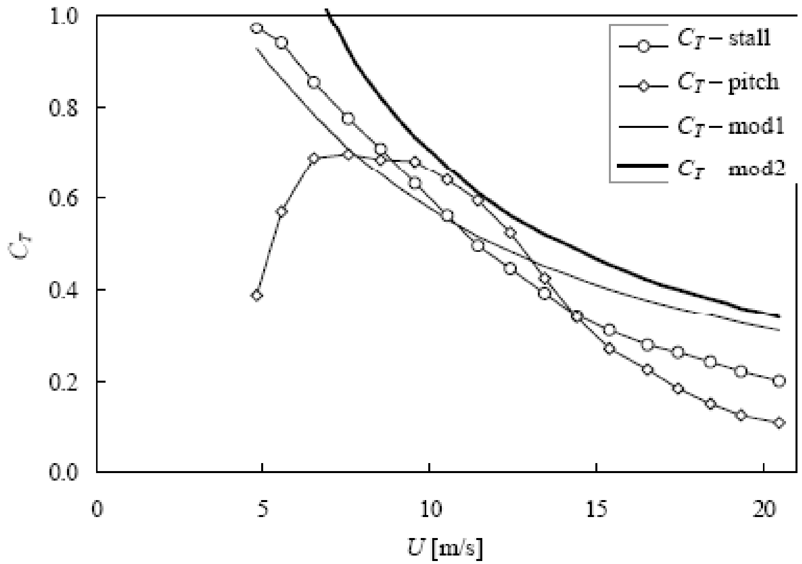
IEC effective turbulence (2)

IEC model for wake turbulence $I_{\text{wake}} = \sqrt{I_{\text{added}}^2 + I_{\text{ambient}}^2}$

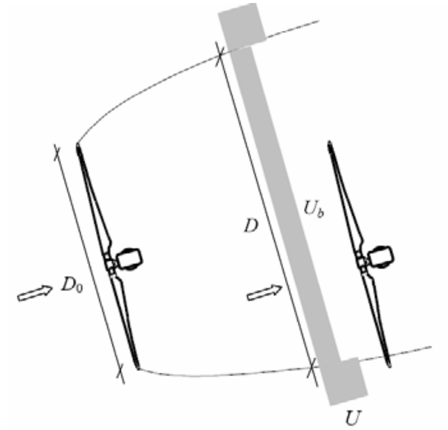
with $$I_{\text{added}}^2 = \frac{0.9}{\left(1.5 + 0.3d\sqrt{u}\right)^2}$$

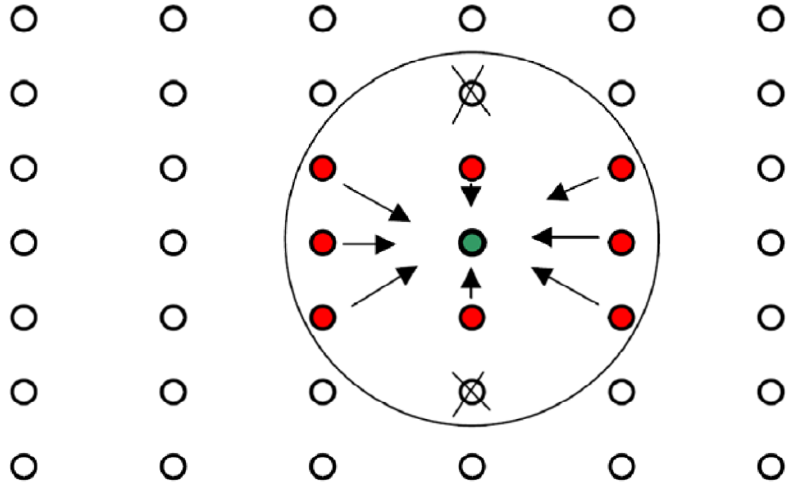
Basic Frandsen formula

$$I_{\text{added}}^2 = \frac{1}{\left(1.5 + 0.8\,d/\sqrt{C_{\text{T}}}\right)^2}$$



IEC effective turbulence (3)





•exposure angle is fixed to 21.6 deg

•ignore distant turbines $\Delta x > 10\ d_{rotor}$

•no wake superposition

•enhance background turbulence in *large dense wind farms*, i.e. farms with more than five rows of turbines in the predominant wind direction and column separation less than three rotor diameters

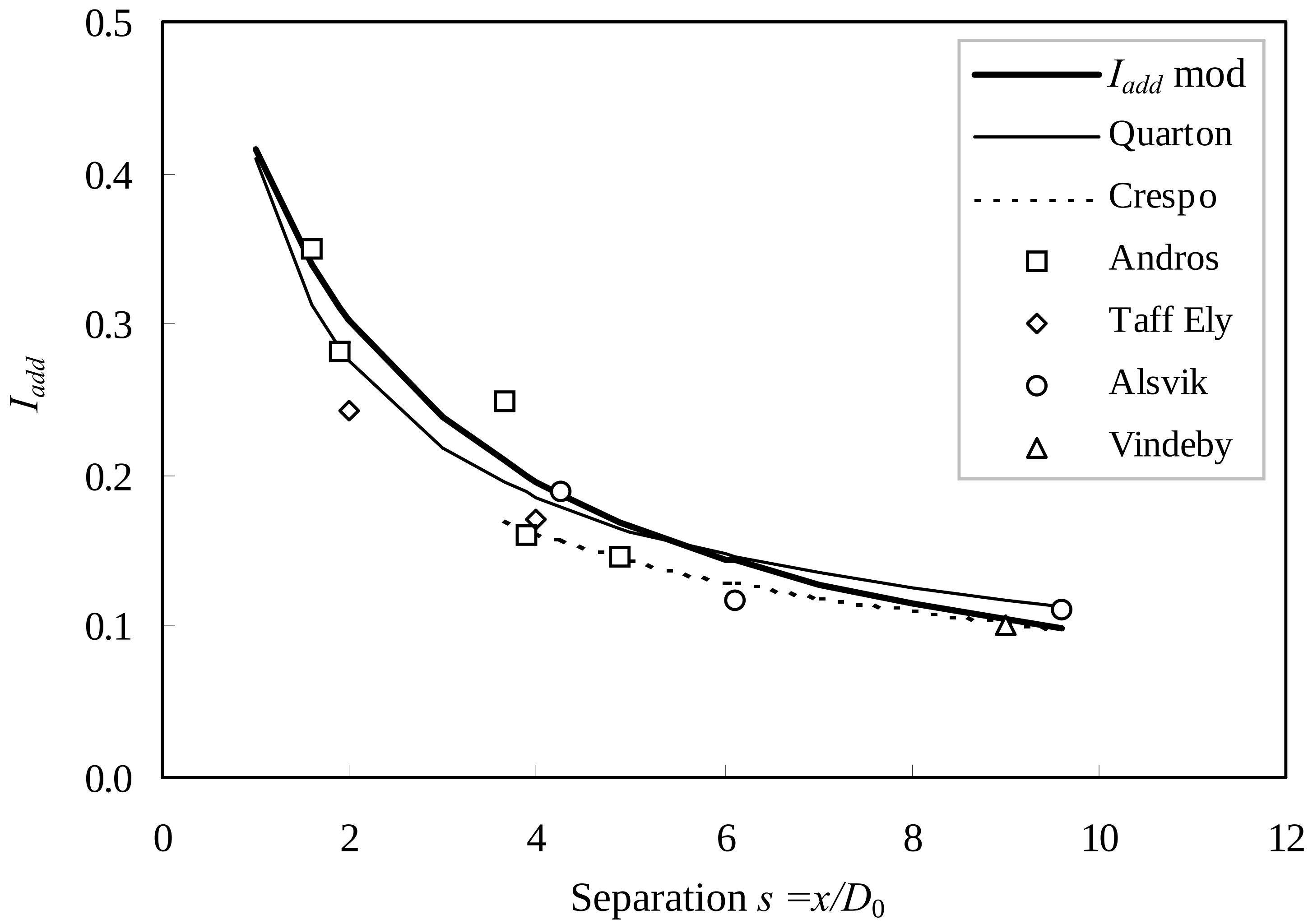
$$I' = \tfrac{1}{2}\left(\sqrt{I_w^2 + I^2} + I\right)$$

$$I_w = \frac{0.36}{1 + 0.2\sqrt{d_1 d_2 / C_T}}$$

Approximation for irregular layout

$$I_w = \frac{0.36}{1 + 0.2\sqrt{\Delta\theta_{sec}\,\tfrac{1}{2}\,d_{max}^2 / \left(N_{sec} C_T\right)}}$$

Verification of wake model



Conditional wind-direction distribution

$$I_{\text{eff}}(u) = \left[\int_0^{2\pi} I^m_{\text{actual}}(\theta \mid u)\, p(\theta \mid u)\, d\theta \right]^{m^{-1}}$$

$$p(\theta|u) = \frac{p(u|\theta)\,p(\theta)}{p(u)} = \frac{p(u|A_j,k_j)\,f_j}{\sum_{i=0}^{N-1} p(u|A_i,k_i)\,f_i}$$

using WASP sector-wise wind climates

1. Frequency, f
2. Weibull scale parameter, A
3. Weibull shape parameter, k

$$p(u|A_j,k_j) = \frac{k_j}{A_j}\left(\frac{u}{A_j}\right)^{k_j-1} \exp\left[-\left(u/A_j\right)^{k_j}\right]$$

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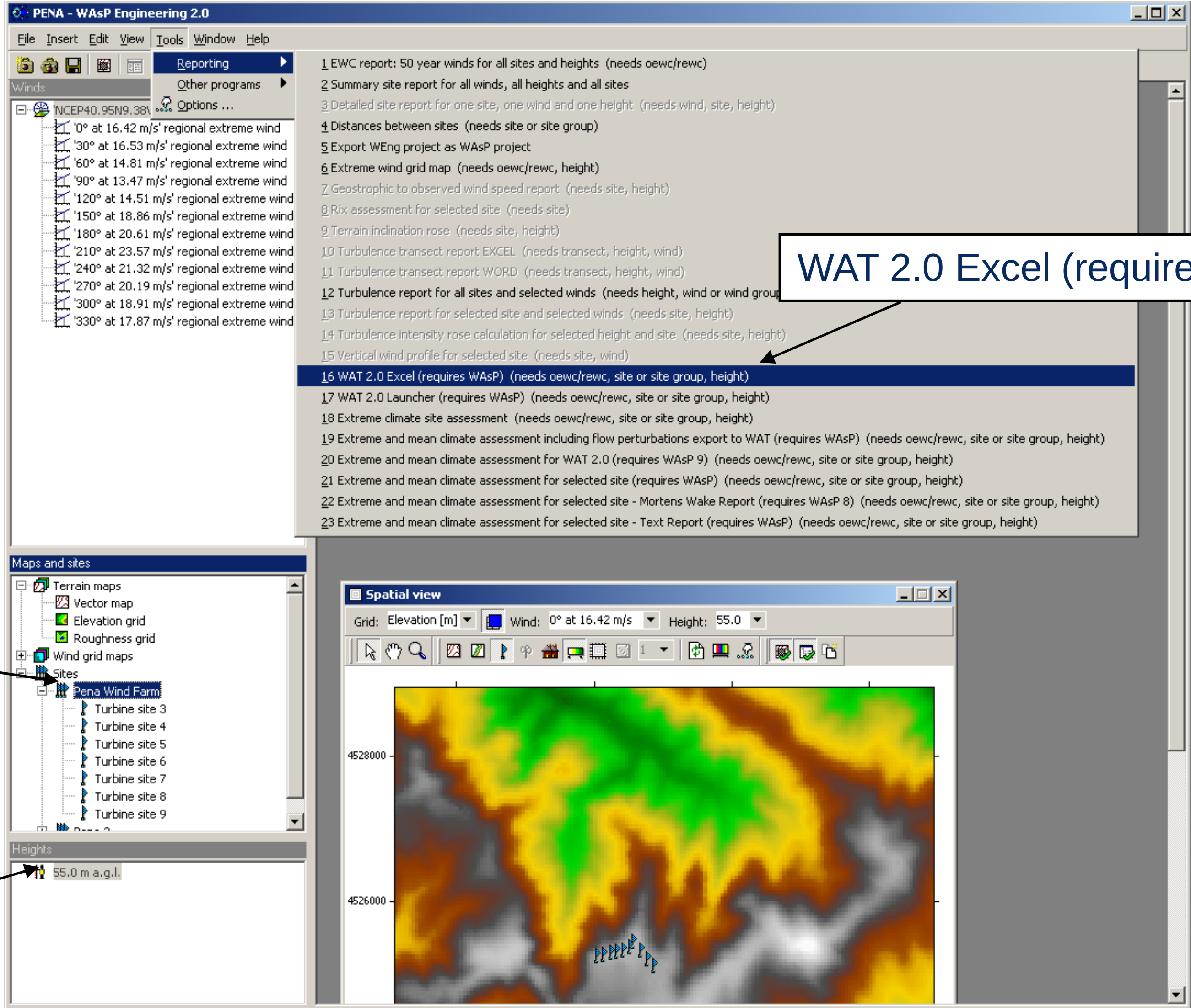
Site assessment with WEng + WAT

wind

sites

height



WAT 2.0 Excel (requires WAsP)

Script output

Microsoft Excel - Book1

File Edit View Insert Format Tools Data Window Help Adobe PDF

O38

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Site assessment report for sites from 'Pena Wind Farm', in project: 'PENA'														
2	Using regional extreme wind climate 'NCEP40.95N9.38W' and regional mean wind climate 'Port06'														
3															
4															
5	Site: Turbine site 3 (576573.6,4525371) at 55m a.g.l.														
6	Direction	alpha	TI	Sigma-U	Flow angle	Terrain inclination	V-ref (50 yrs)	Frequency	Weibull-A	Weibull-k	Speedup facto	Deflection	TI2	TI3	
7	[°]	[ ]	[%]	[m/s]	[°]	[°]	[m/s]	[%]	[m/s]	[ ]	[ ]	[°]	[%]	[%]	
8	0	0.036	6.935	2.09	3.162	-1.502	30.11	8.459	5.586	1.936	1.553	-5.825	5.77	5.24	
9	30	0.069	7.194	2.03	2.83	-1.167	28.26	5.31	5.606	1.947	1.407	-4.028	5.56	5.54	
10	60	0.082	8.378	2.09	1.569	-0.519	24.98	4.734	7.156	2.291	1.339	2.66	6.72	6.48	
11	90	0.056	7.883	1.94	-0.177	0.267	24.63	6.42	8.417	2.338	1.527	6.193	7.28	6.34	
12	120	0.027	6.546	1.9	-1.534	0.982	29.02	10.146	8.944	2.572	1.62	3.244	6.29	5.45	
13	150	0.029	6.537	2.5	-2.454	1.435	38.21	11.105	8.856	2.311	1.62	-2.144	5.77	5.06	
14	180	0.058	7.468	2.82	-3.014	1.502	37.82	7.843	8.636	1.959	1.479	-5.805	6.18	5.36	
15	210	0.067	8.215	3.29	-2.666	1.167	40.03	4.453	8.244	2.146	1.421	-4.031	5.75	4.98	
16	240	0.062	7.372	2.7	-1.355	0.519	36.58	4.227	6.826	2.068	1.34	2.636	6.03	5.73	
17	270	0.038	6.542	2.43	0.278	-0.267	37.18	5.868	6.274	2.01	1.485	6.021	6.32	5.94	
18	300	0.023	6.109	2.33	1.641	-0.982	38.22	14.645	7.059	2.072	1.596	3.265	6.01	5.33	
19	330	0.008	5.309	1.88	2.7	-1.435	35.44	16.79	7.182	2.279	1.679	-1.979	4.95	4.94	
20	All						42.01								
21															
22	Site: Turbine site 4 (576512.8,4525302) at 55m a.g.l.														
23	Direction	alpha	TI	Sigma-U	Flow angle	Terrain inclination	V-ref (50 yrs)	Frequency	Weibull-A	Weibull-k	Speedup facto	Deflection	TI2	TI3	
24	[°]	[ ]	[%]	[m/s]	[°]	[°]	[m/s]	[%]	[m/s]	[ ]	[ ]	[°]	[%]	[%]	
25	0	0.026	6.5	2.02	2.125	-0.515	31.13	9.094	5.844	1.955	1.59	-5.686	5.57	5.1	
26	30	0.06	7.185	2.05	1.398	-0.208	28.59	5.463	5.832	1.982	1.409	-6.682	5.63	5.29	
27	60	0.103	9.405	2.23	0.126	0.155	23.67	4.527	6.81	2.291	1.276	-0.166	7.18	6.67	
28	90	0.085	Calculating...												
29	120														
30	150														
31	180														
32	210														
33	240														
34	270														
35	300														

- be patient
- export results to ASCII file

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Windfarm Assessment Tool (WAT)

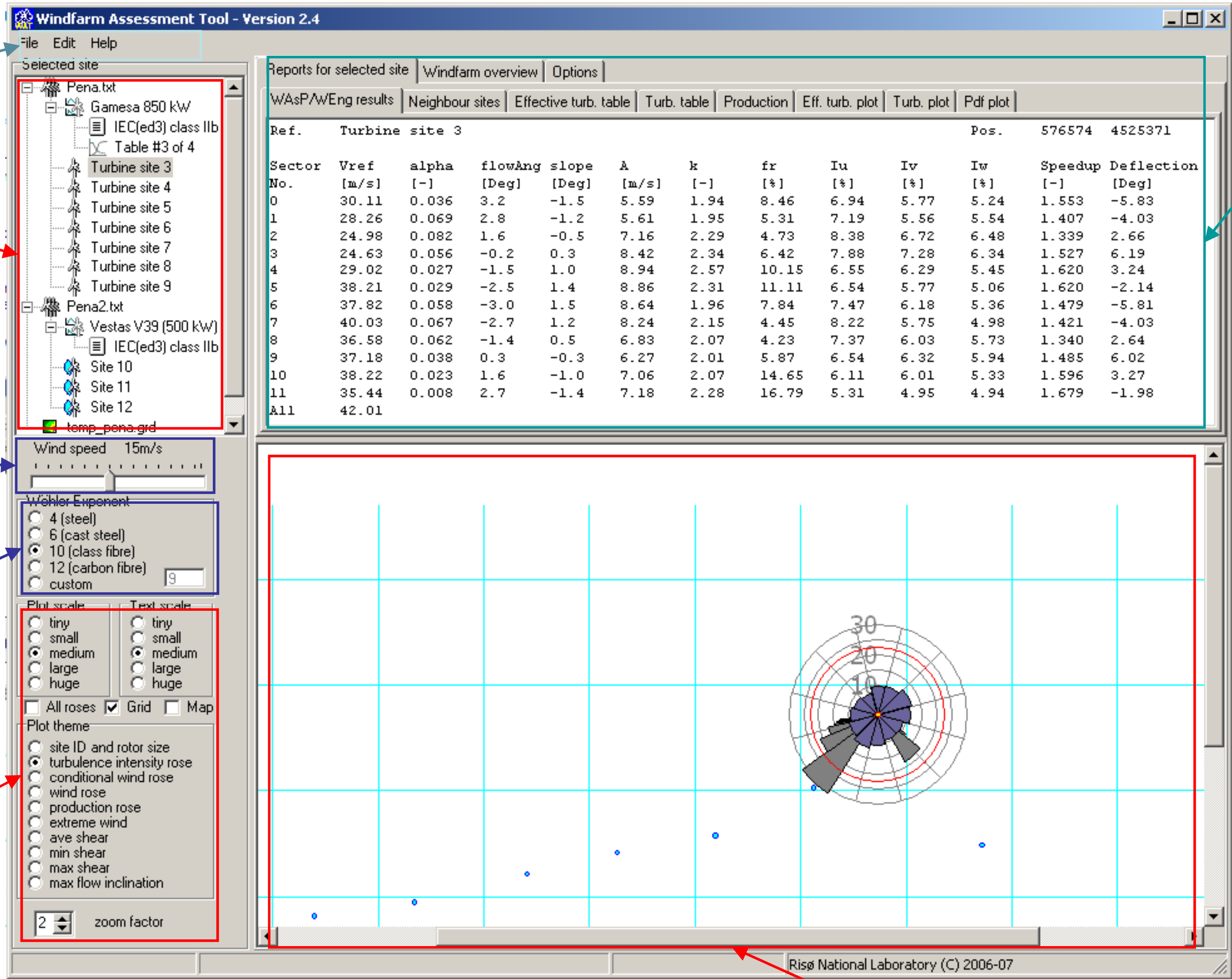
input, export & help

site list

speed

material

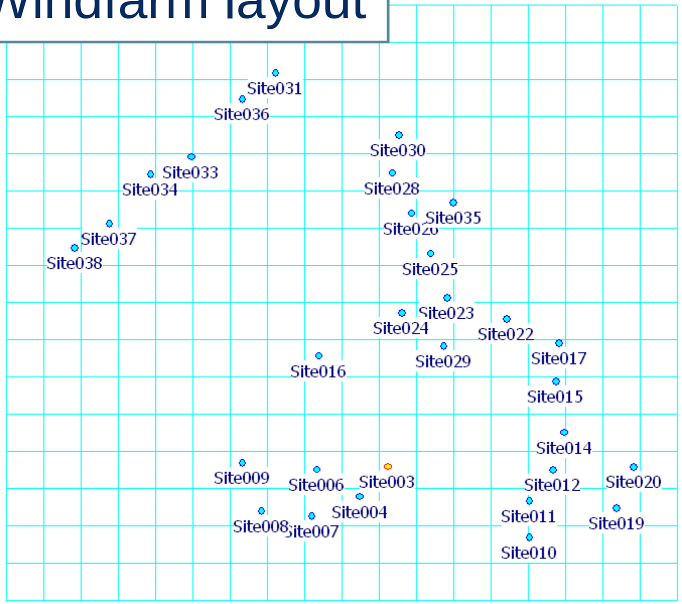
plot options



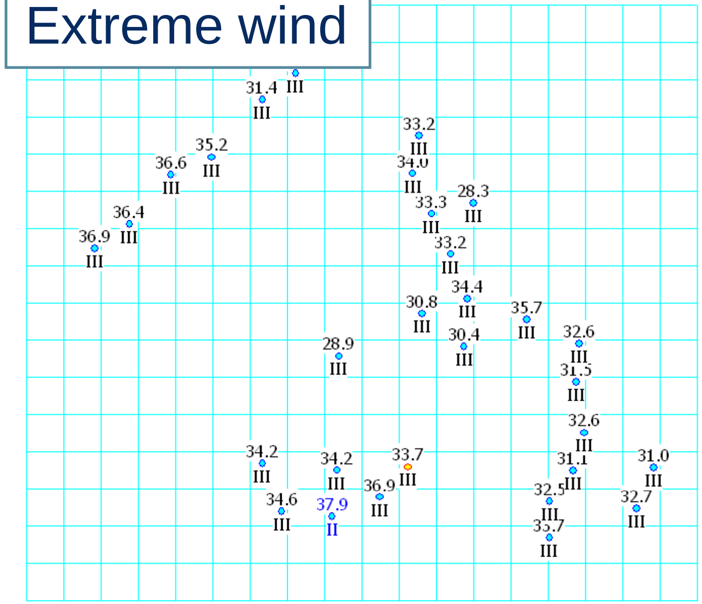
results plots & options

windfarm plot

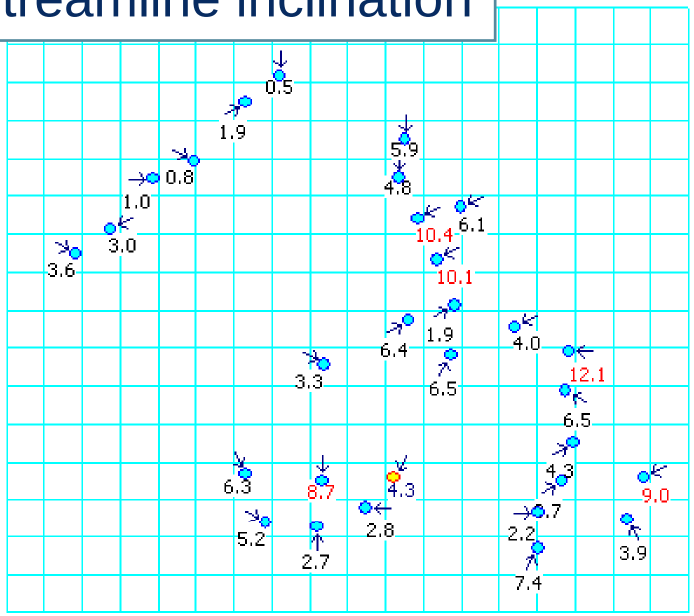
Windfarm layout



Extreme wind

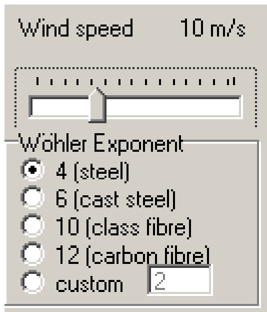


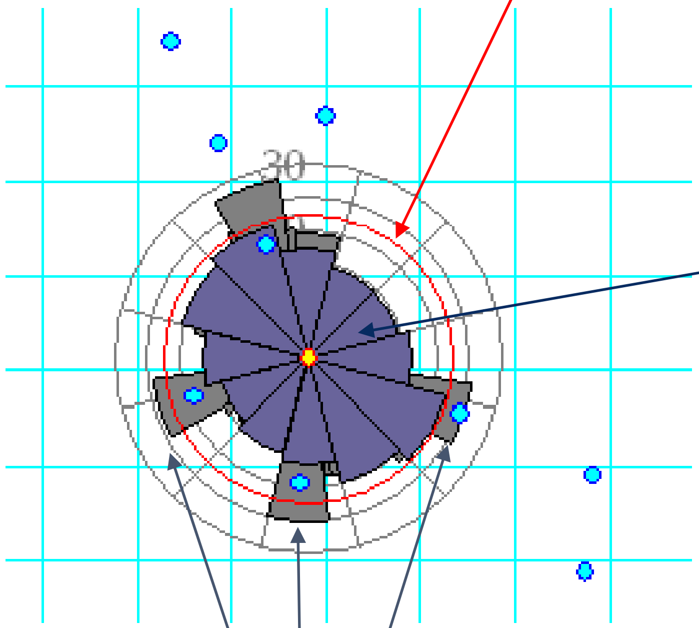
Streamline inclination



Turbulence plot

NB: Effects of wind and material constant affects turbulence!





Effective turbulence (2)

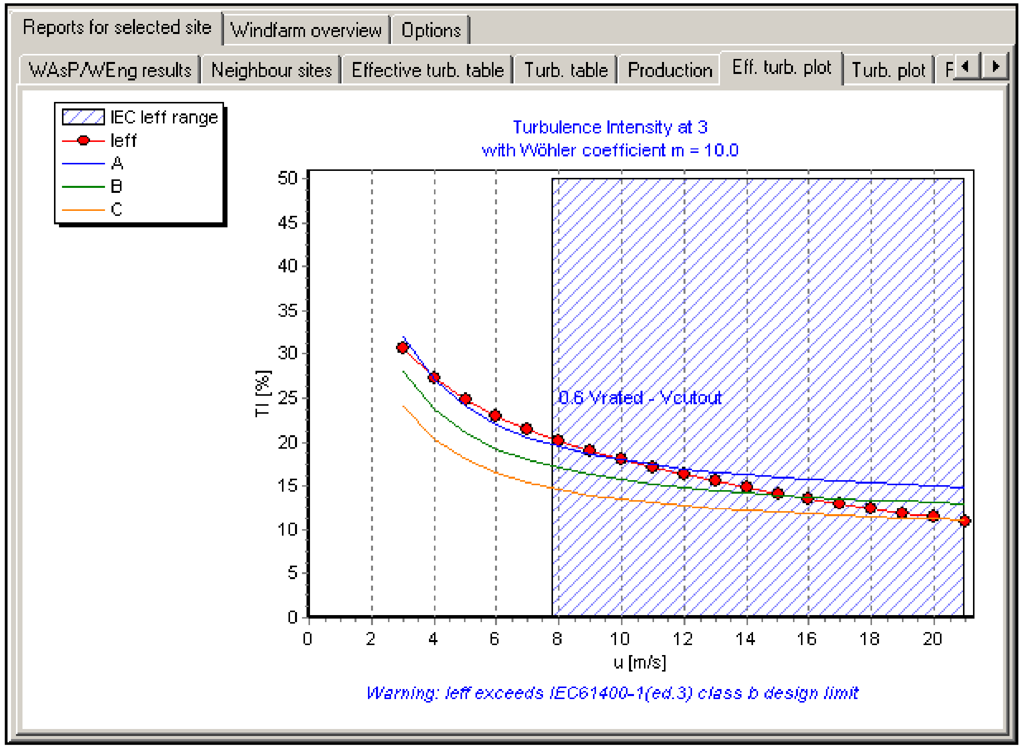
Reports for selected site | Windfarm overview | Options

WAsP/WEng results | Neighbour sites | Effective turb. table | Turb. table | Production | Eff. turb. plot

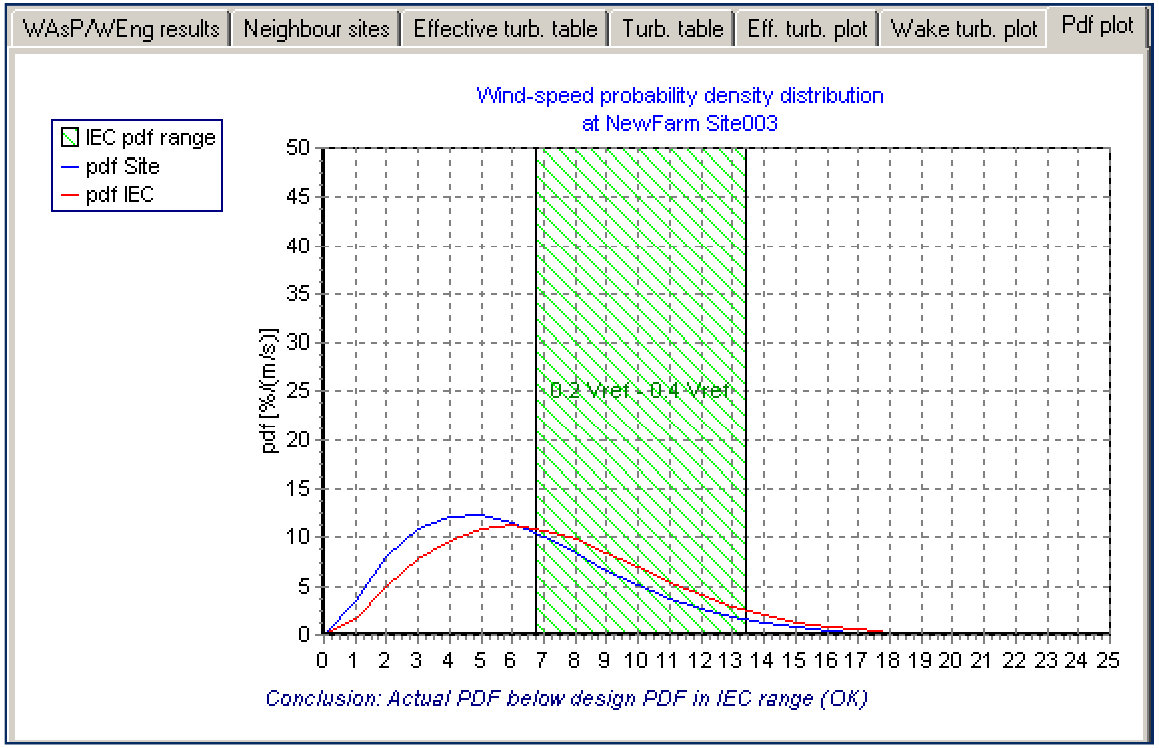
Ref. Turbine site 3

m=10.00

uHi	p(u)	Imax	Ieff	Idesign	Pdesign
1	1.51	24.3	20.6	72.0	1.56
2	4.72	16.5	14.0	42.0	3.04
3	7.69	43.4	30.7	32.0	4.39
4	9.98	40.8	28.8	27.0	5.54
5	11.35	38.8	27.5	24.0	6.45
6	11.76	37.2	26.3	22.0	7.10
7	11.28	35.8	25.4	20.6	7.48
(60% of rated wind)					
8	10.14	34.7	24.6	19.5	7.60
9	8.59	33.7	23.9	18.7	7.48
(20% of reference wind)					
10	6.89	32.8	23.3	18.0	7.16
11	5.25	32.0	22.8	17.5	6.68
12	3.81	31.3	22.3	17.0	6.08
13	2.63	30.6	21.9	16.6	5.42
14	1.74	30.0	21.5	16.3	4.72
15	1.10	29.4	21.2	16.0	4.02
16	0.67	28.9	20.9	15.7	3.37
17	0.39	28.4	20.5	15.5	2.76
18	0.22	28.0	20.2	15.3	2.22
19	0.12	27.6	19.9	15.2	1.75
(40% of reference wind)					
20	0.07	27.2	19.6	15.0	1.36
21	0.04	26.8	19.2	14.9	1.03
(cut-out wind)					
22	0.02	14.4	11.6	14.7	0.77
23	0.01	14.2	11.3	14.6	0.57
24	0.01	14.0	10.8	14.5	0.41
25	0.00	13.8	10.4	14.4	0.29
26	0.00	7.2	6.5	14.3	0.20
27	0.00	7.2	6.4	14.2	0.14
28	0.00	7.2	6.4	14.1	0.09
29	0.00	7.1	6.4	14.1	0.06
30	0.00	7.1	6.4	14.0	0.04
(50yr extreme wind)					
42.01		8.4	7.5	13.4	0.00



Comparison of actual and design PDFs



IEC rules:

- design PDF is Rayleigh distribution with V_{ave}=0.2V_{ref}
- actual PDF must be less than design PDF in speed range [0.2V_{ref}..0.4V_{ref}]

Summary

- Modern site assessment for a wind farm involves both estimates of resources and external design conditions, they even sometimes go hand in hand – e.g. high resources in complex terrain => large loads
- Proper estimates of external conditions optimizes the material use in wind turbines => increase the competitiveness of wind energy compared to conventional energy types