The wind

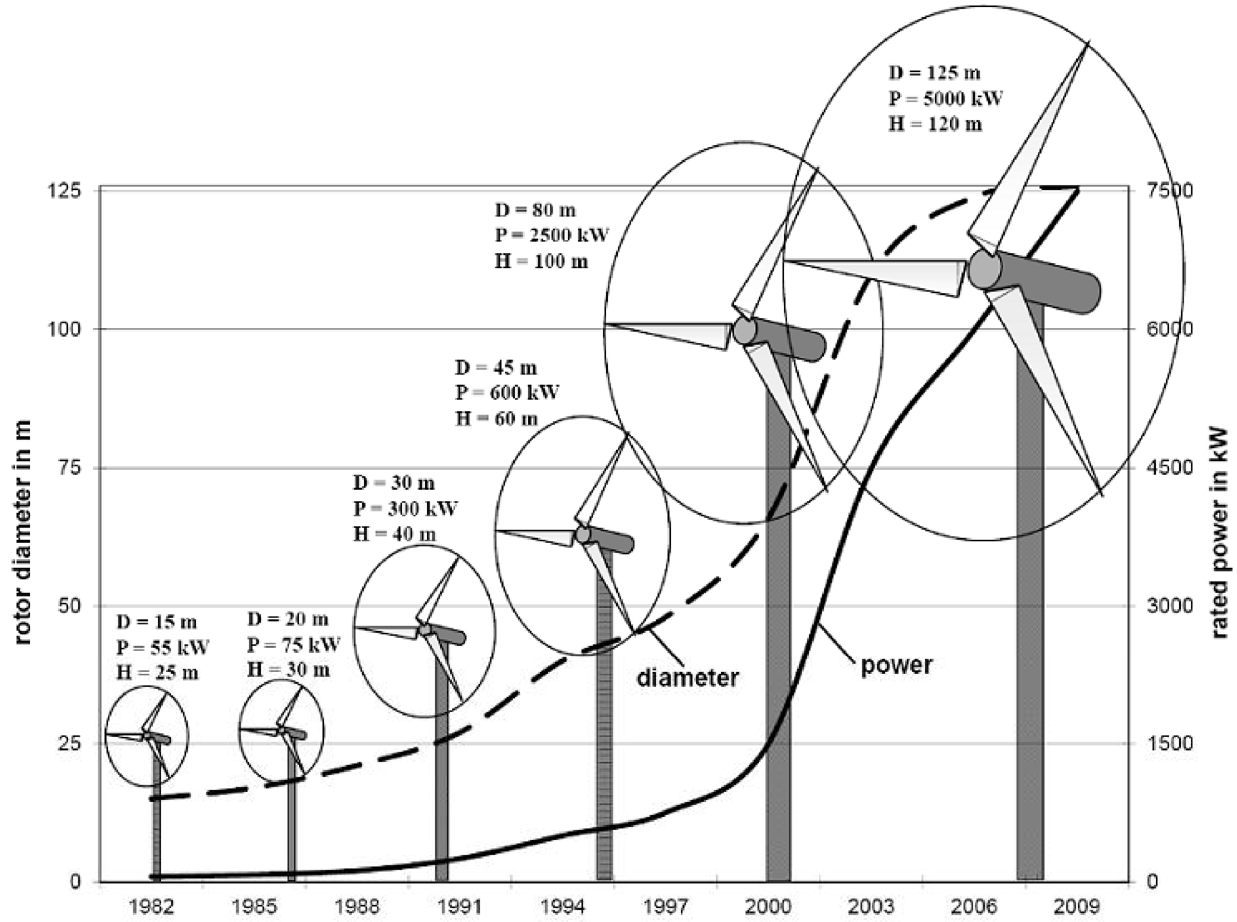


Fig 1-1 Size and power increases of commercially produced wind turbines over time

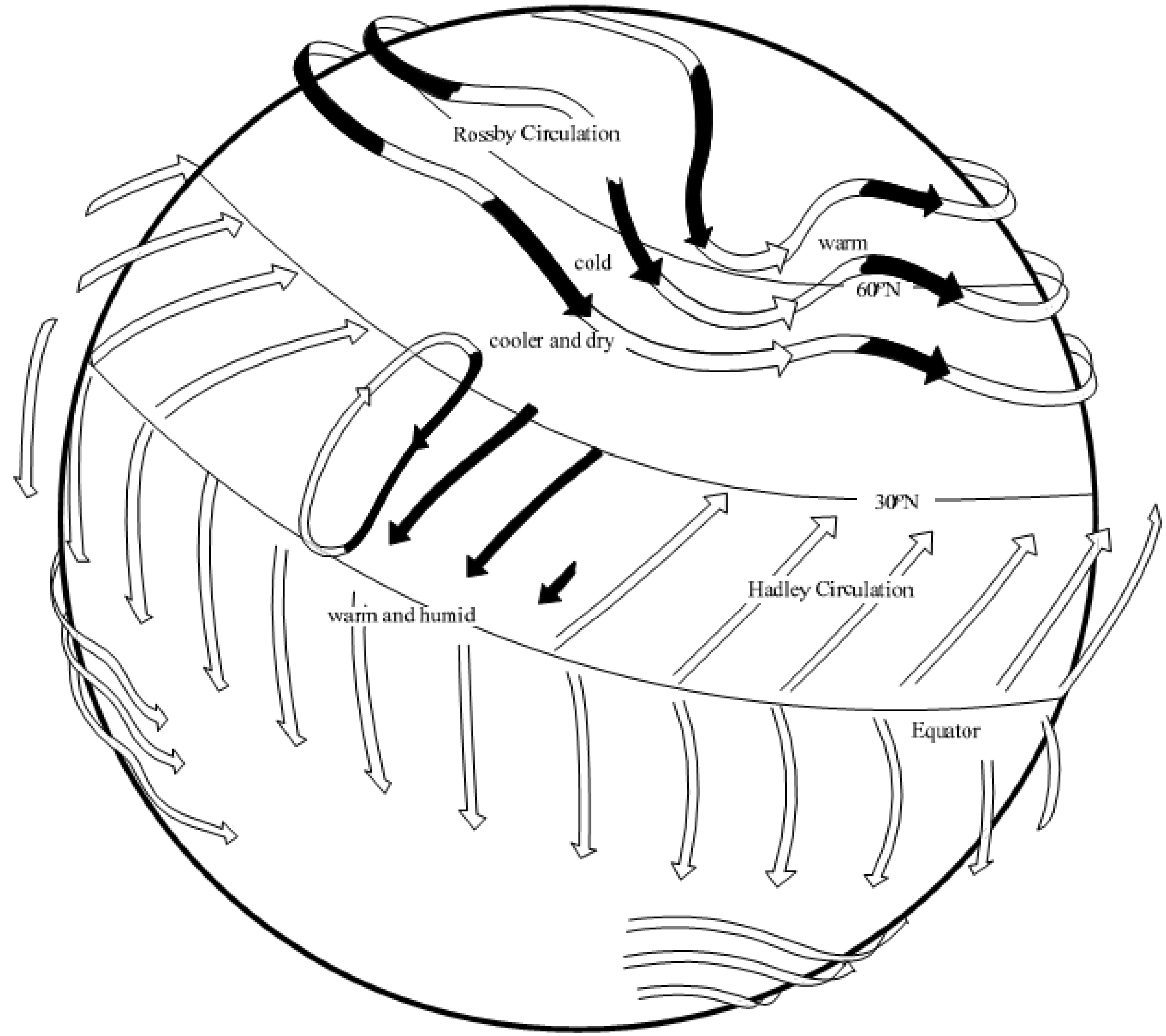
$$P_{\text{wind}} = \dot{E} = \frac{1}{2}\,\dot{m}\,v^2 = \frac{1}{2}\,\rho\;A\,v^3$$

Global wind systems

- The global atmosphere can be considered as a thermal engine powered by the sun

- Water is the most important energy carrier in the atmosphere since it exists in the atmosphere in all the three states: vapour, droplets and ice

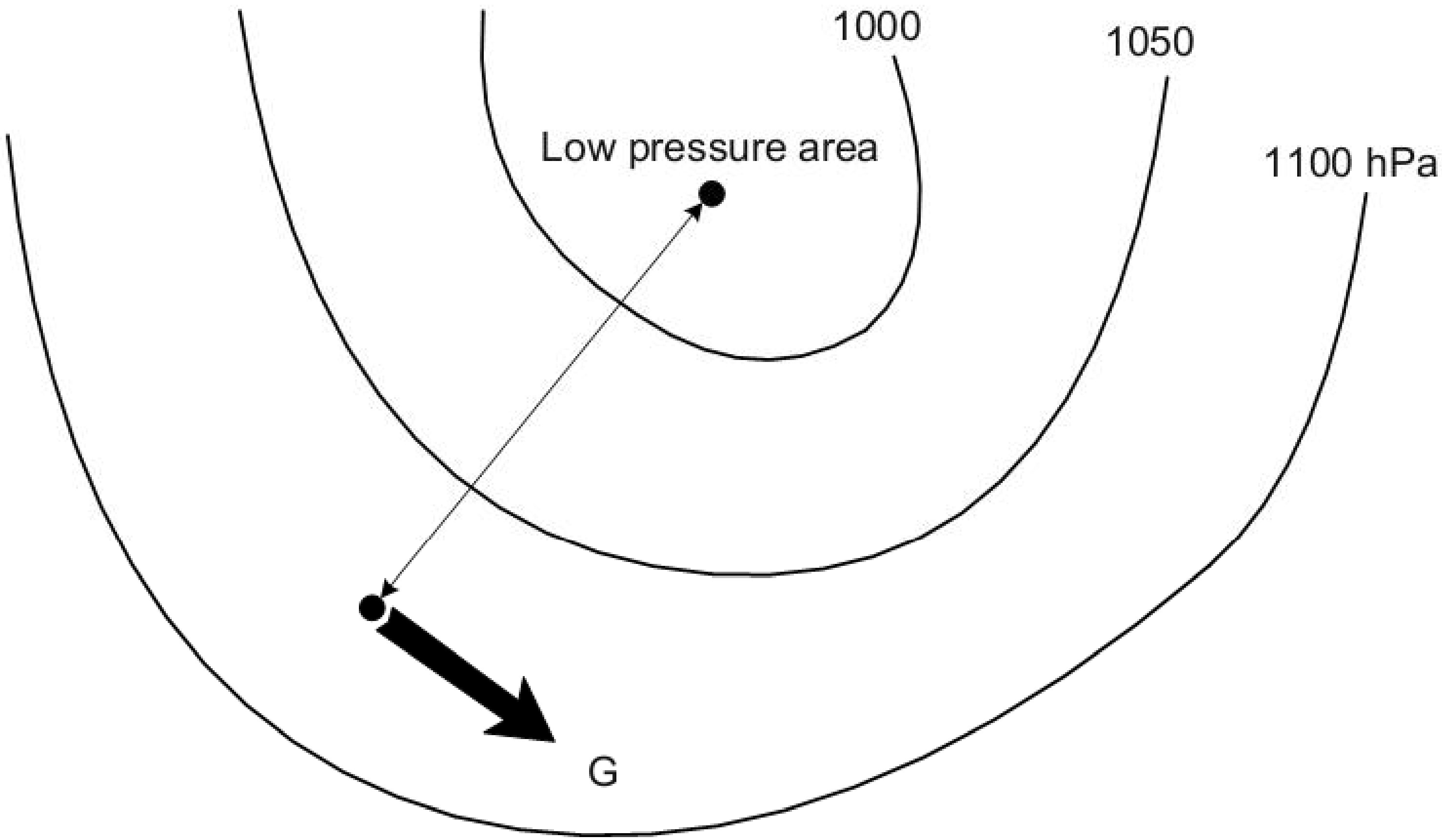
- there is excess energy in the atmosphere in the equatorial zones and a deficit in the area of the poles



Global wind circulation, black arrows: flow near the ground

Geostrophic Wind

- High above the ground, the friction of the ground has no influence on the air flow
- This undisturbed flow is called the geostrophic wind; the pressure gradient force and the Coriolis force are in balance
- The gradient force results from the air pressure differences and points always towards the low-pressure region



Geostrophic wind G and isobars (on northern hemisphere)

Local wind systems

- Apart from the global winds there are also local wind systems which origin from potential differences

- temperature differences are the driving cause

- The most important of these local wind systems are the sea-land breeze and the moun-tain-valley breeze

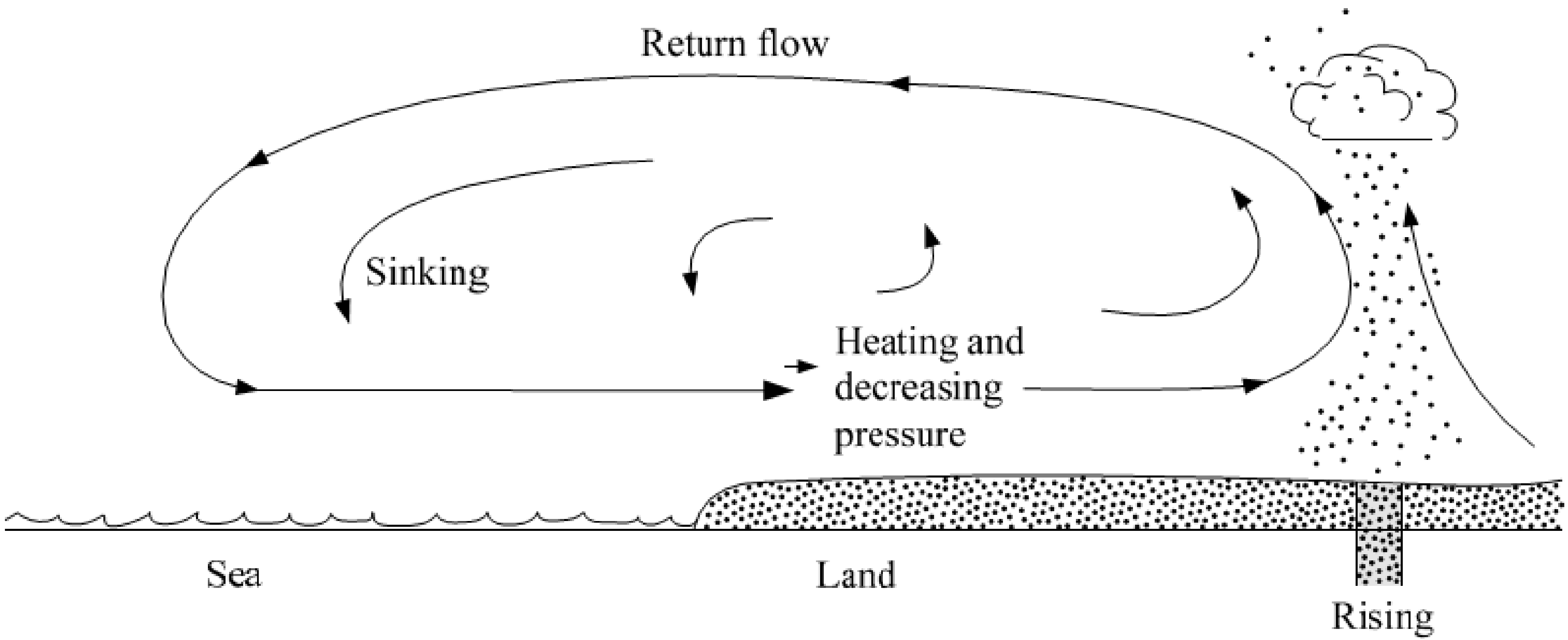
Sea-land circulation

- The sea-land breeze is a diurnal wind system at the sea shore emerging under sunny weather conditions with a high temperature difference between the land and the water

- The resulting “sea breeze” is the flow of cool, humid air to the shore

- In the late afternoon, the land is cooling down faster than the sea, so the flow conditions reverse

- Due to the friction at the ground it is weaker than the sea breeze

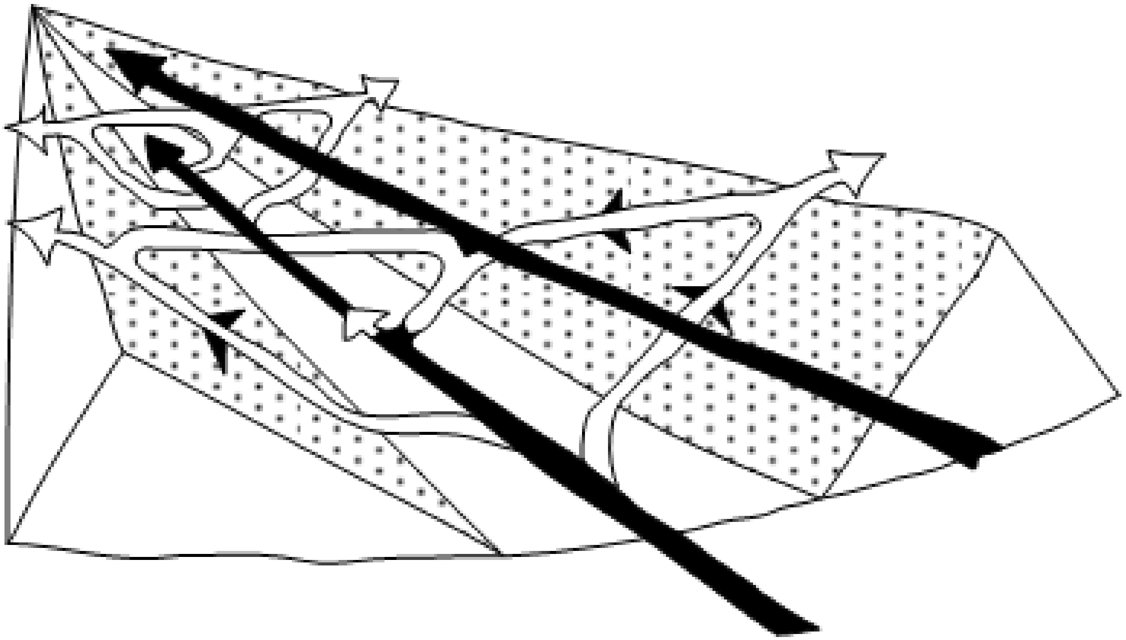


Scheme of the sea-land breeze, example: day

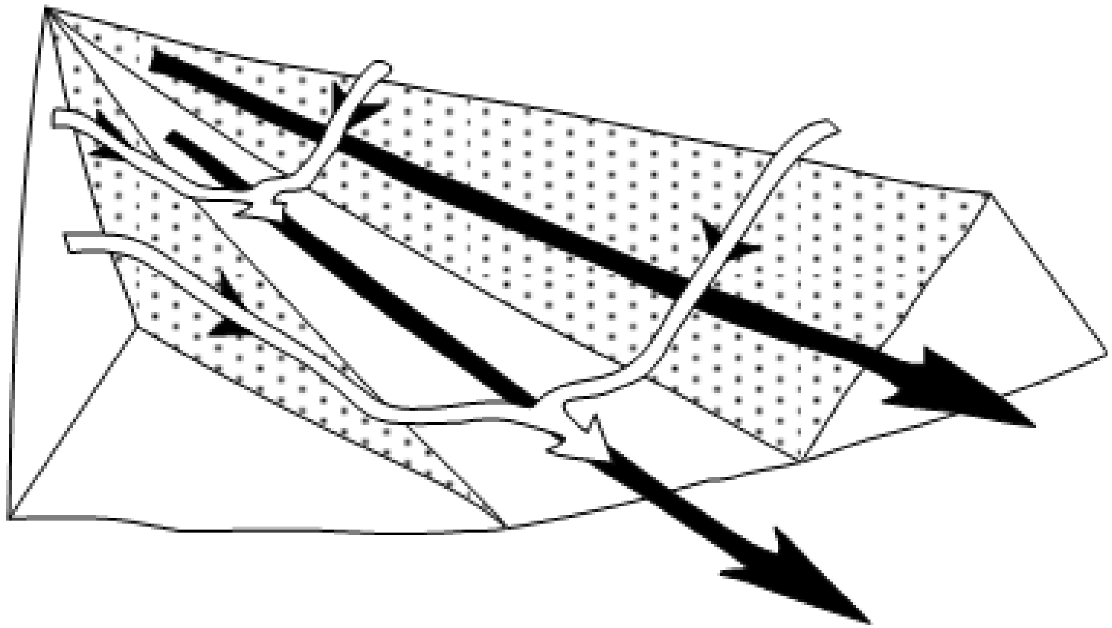
Mountain-valley circulation

- In the mountains, there are also thermal circulations from the superposition of two flow systems: the slope winds and the mountain-valley winds
- After sunrise the slopes of the mountain are strongly heated by the sun, so are the air masses closely above it
- At night it is the other way round

Mountain-valley breeze (white: slope winds, black: valley wind)



valley wind at noon



valley wind at noon

Atmospheric boundary layer

- The lowest layer of the atmosphere is a turbulent layer called the atmospheric boundary layer

- The air flow in this layer is influenced by the friction at the ground, the orography, the topography and as well by the vertical distribution of temperature and pressure

- layer where the wind speed is varying strongly with the height above ground

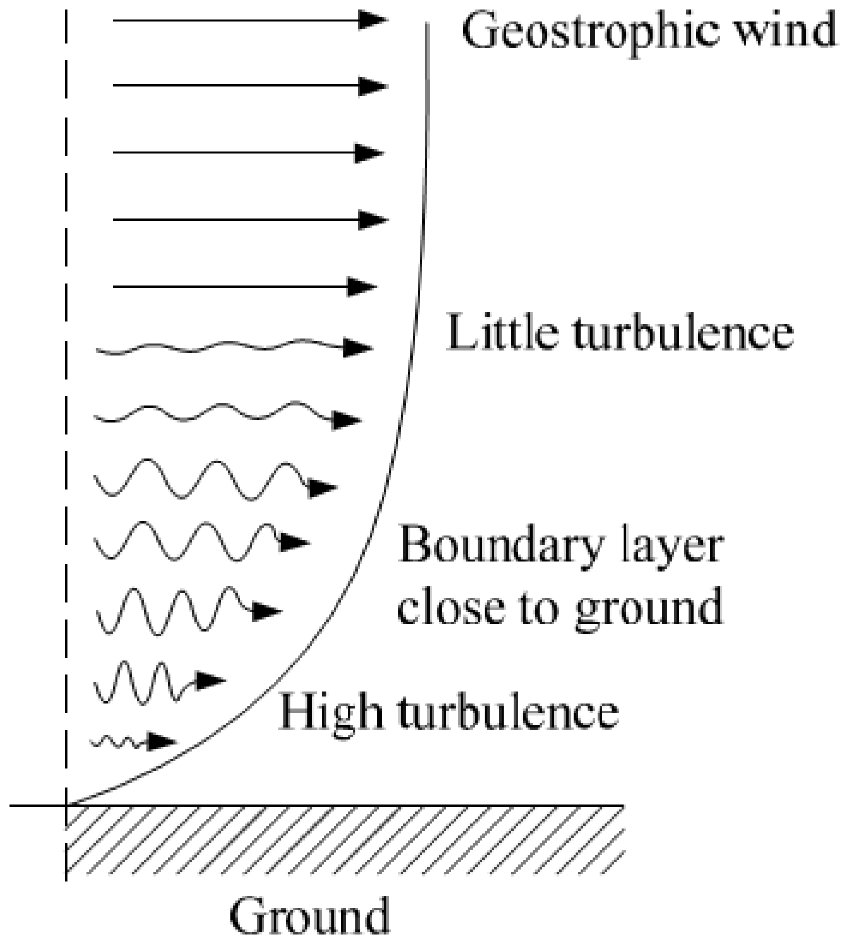
- The friction at the surface roughness takes energy from the air flow causing a vertical gradient of the wind speed

Scheme of the atmospheric boundary layer

- Wind turbines have to operate within this atmospheric boundary layer

- The height of the atmospheric boundary layer varies depending on the roughness of the ground, the vertical temperature profile and wind speed

- 100 m – 2000m



Surface boundary layer

- The air mass flowing directly above the ground is called surface boundary layer
- Its height is often given as a fixed value of approx. 10% of the atmospheric boundary layer's height
- In reality, it varies e.g. depending on the vertical temperature profile

Vertical wind profile

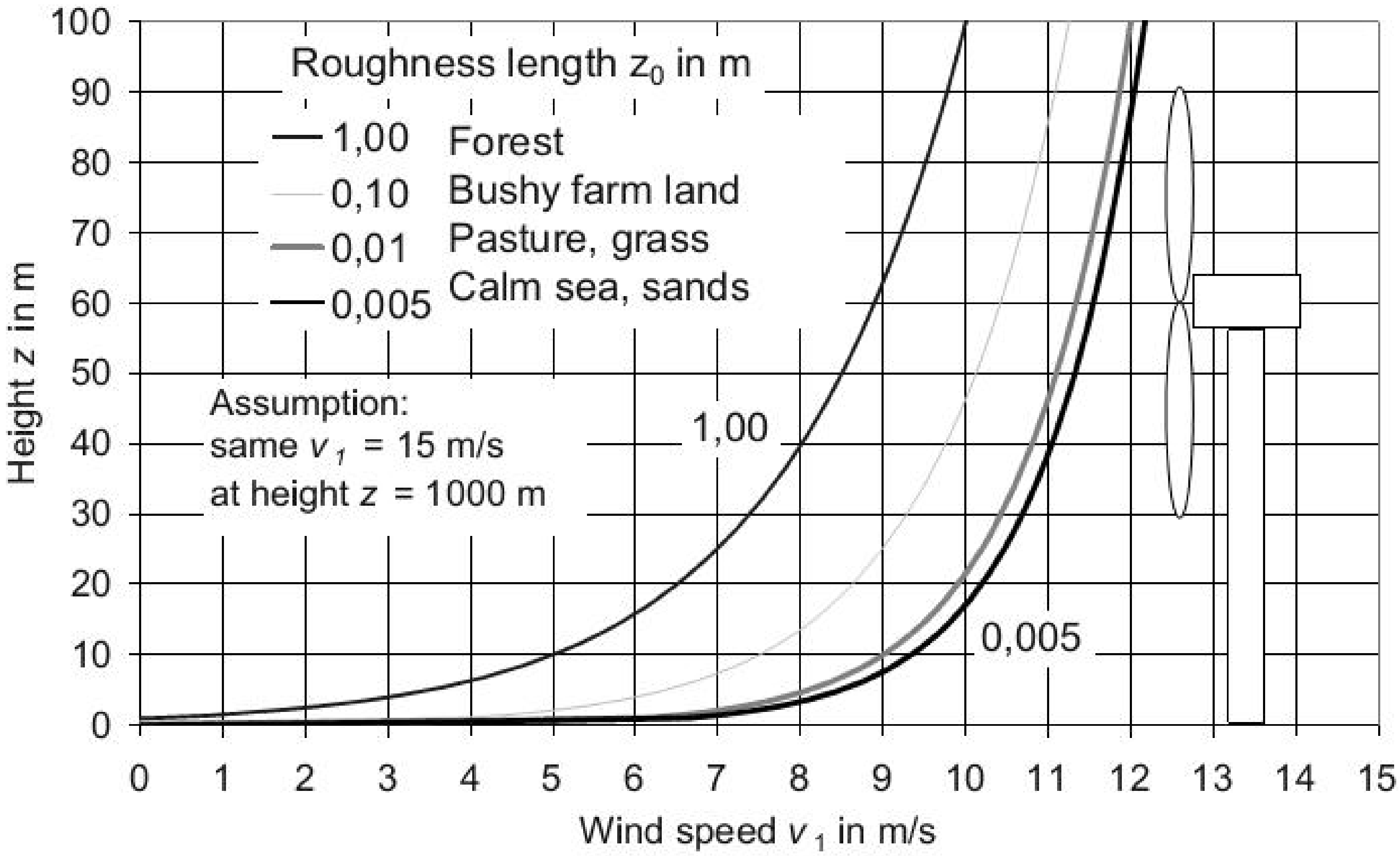
- Having measured a wind speed v1in the height z1(measuring mast) this equation allows to calculate the wind speed v2in the height z2(e.g. hub height) if the roughness length z0 is given.

$$v_2(z_2) = v_1(z_1) \cdot \frac{\ln\left(\frac{z_2}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)}$$

Roughness length z0 for different types of terrain

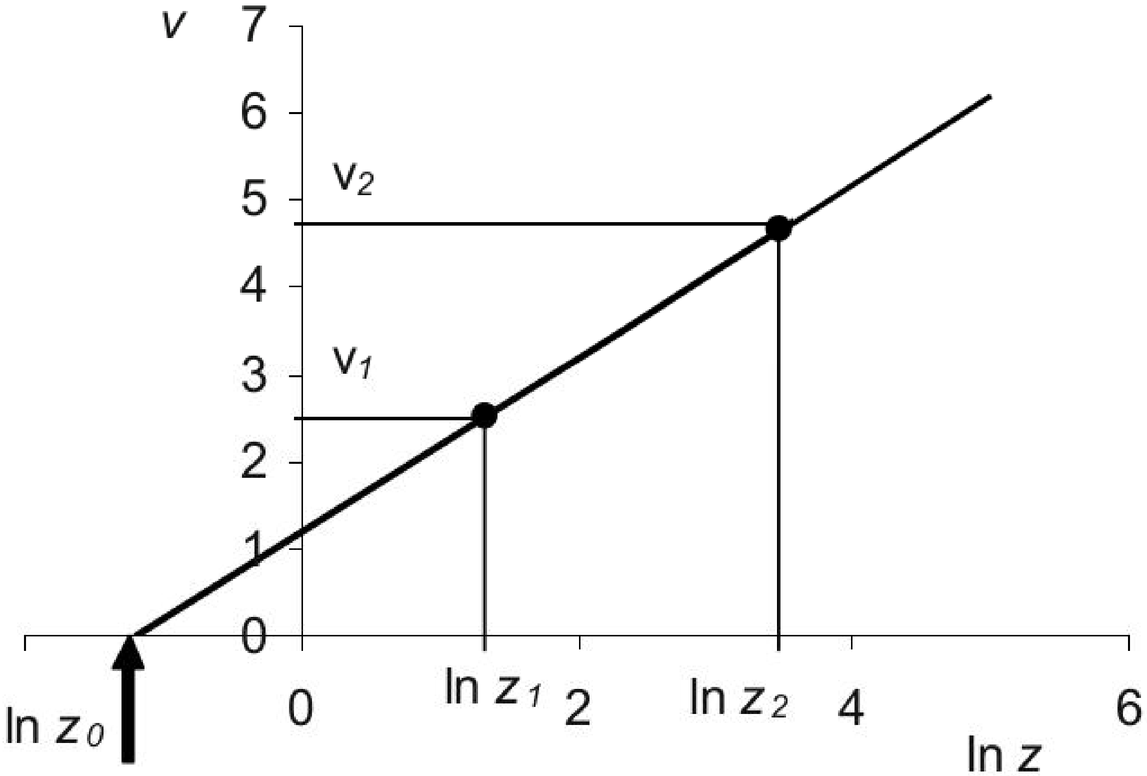
Type of terrain	z_0 in m
Calm water	0.0001 – 0.001
Farm land	0.03
Heather with few bushes and trees	0.1
forest	0.3 – 1.6
suburb, flat building	1.5
City centers	2.0

- Having erected a measuring mast which records the wind speed at several heights of the wind profile, the roughness length z0 may be determined for the close area around it



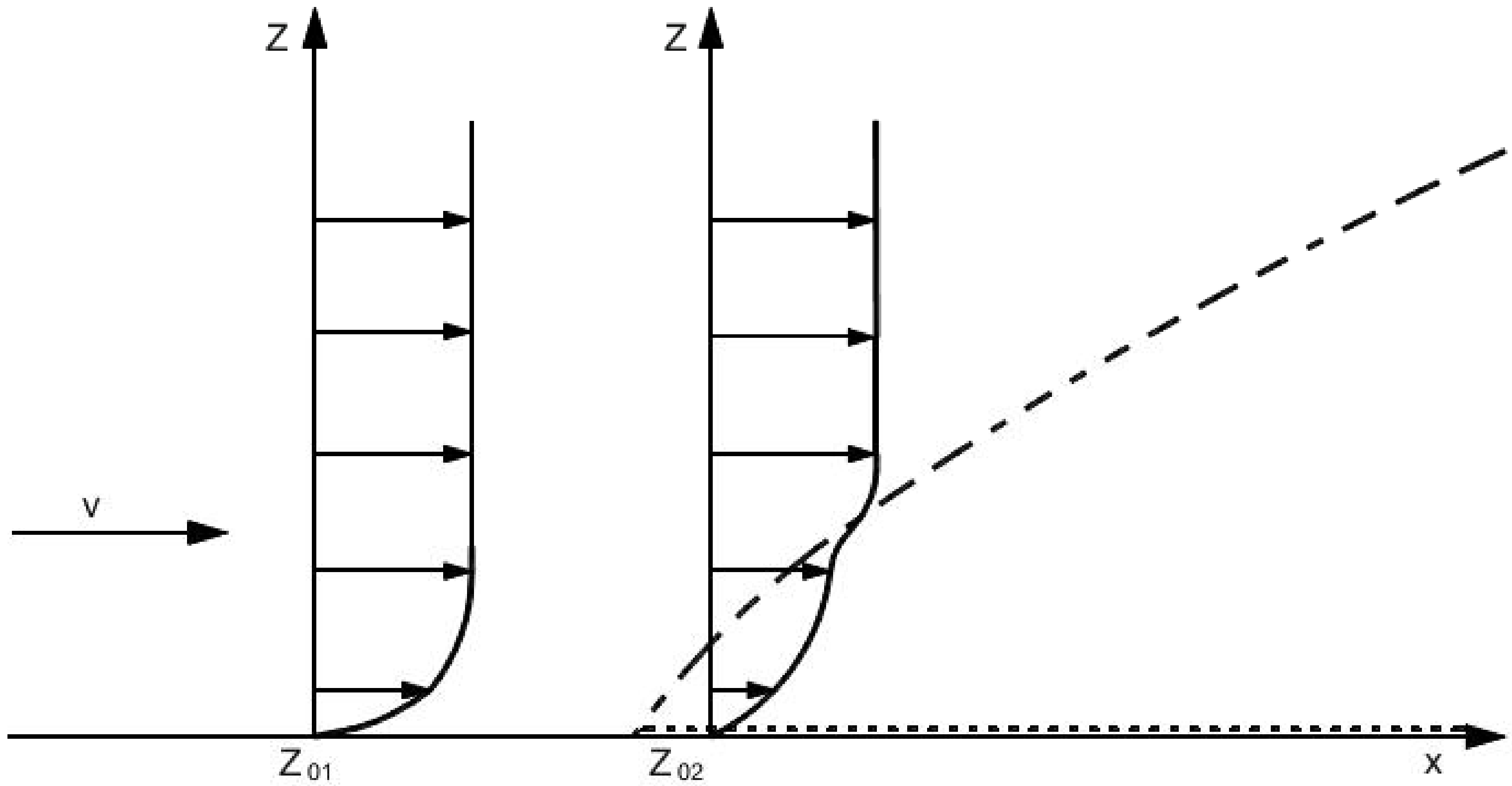
Vertical wind profile for different roughness lengths z0, assumed “geostrophic wind” of 15 m/s

Physical meaning of the roughness length

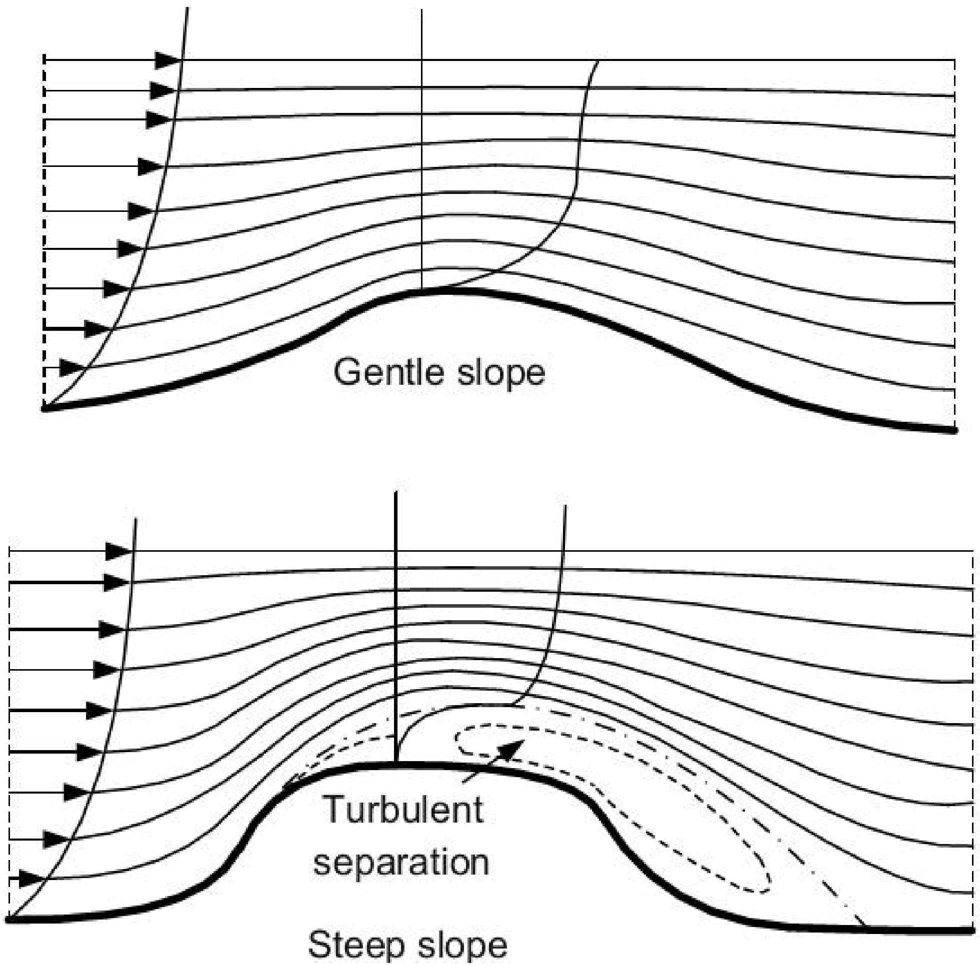


it is the height above ground where in the mean the wind speed is zero

Influence of roughness change on the vertical wind profile – transition zone



Influence of topography and roughness on the vertical wind profile



Turbulence intensity

- The knowledge about turbulence and gustiness is required first of all for the load calculation of the wind turbine

The mean wind speed in the measuring period T is:

$$\bar{v} = \frac{1}{T}\int_0^T v(t)dt$$

variance, a measure for the "irregularity" of the wind

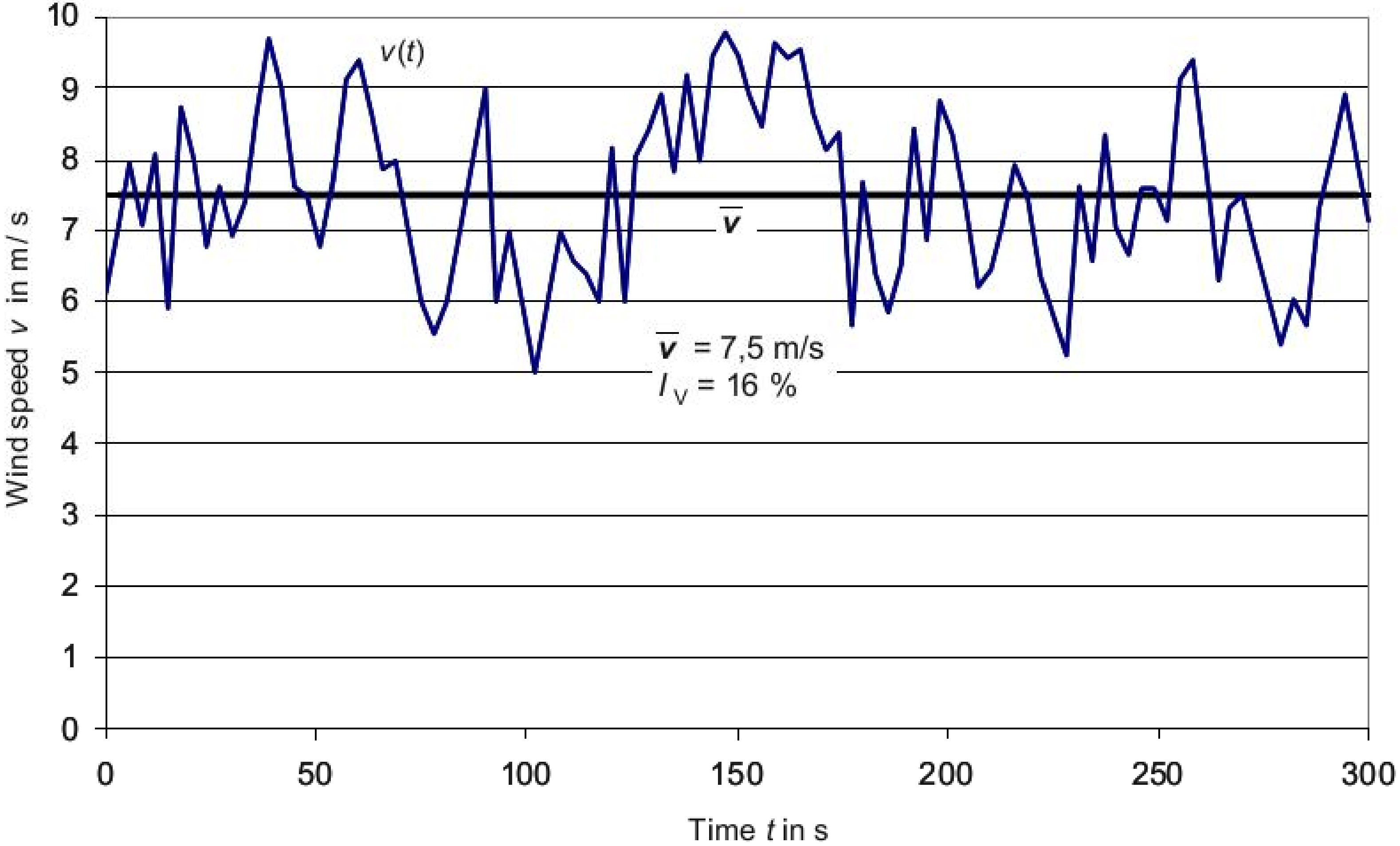
$$\overline{v^2} = \frac{1}{T}\int_0^T \left(v(t) - \bar{v}\right)^2 dt$$

The square root of the variance is the standard deviation

$$\sigma_v = \sqrt{\overline{v^2}}$$

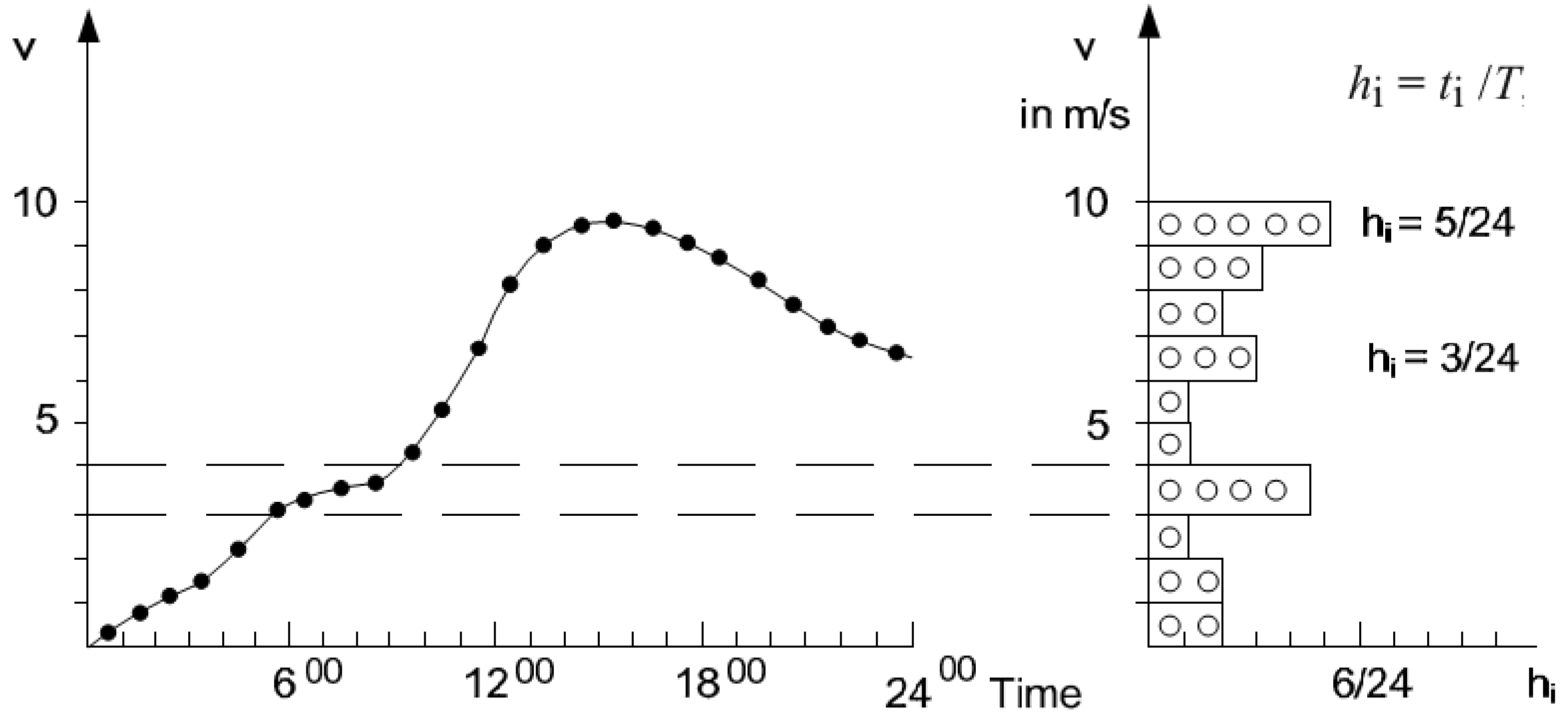
The ratio of standard deviation to the mean wind speed gives the turbulence intensity Iv

$$I_V = \frac{\sigma_v}{\bar{v}} = \frac{\sqrt{\overline{v^2}}}{\bar{v}}$$



Turbulent wind and mean wind speed $\overline{v}$

Frequency distribution – Histogram of wind speeds



Left: Diurnal time series of hourly averaged values; right: corresponding histogram of the relative frequency h_i of the respective day

Wind speed distribution function

The measured frequency distribution is mostly “compressed” into a mathematical description using the Weibull distribution function which is quite flexible due to its two parameters

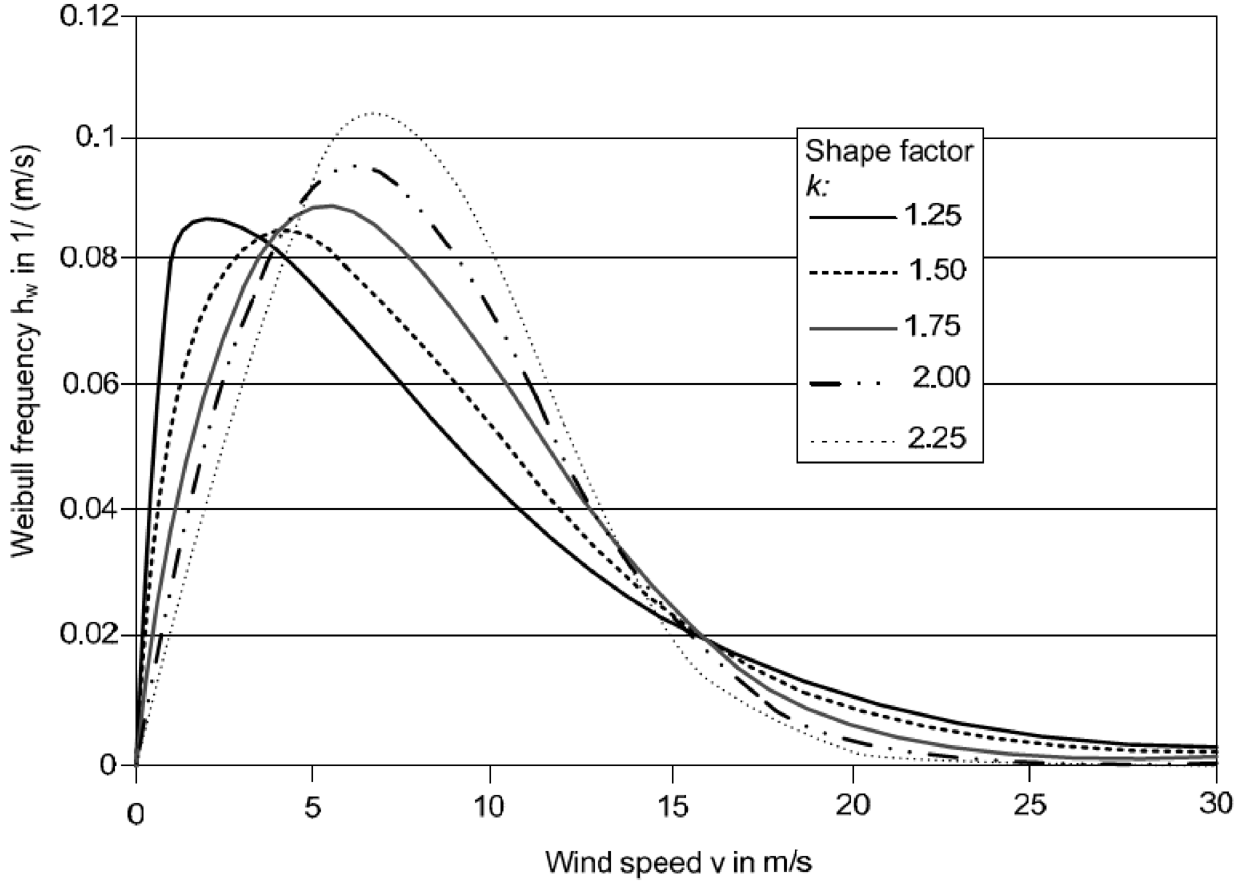
$$h_W(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^{k}\right)$$

Given Weibull factors allow an estimation of the mean wind speed $\bar{v}$

$$\bar{v} \approx A\left(0{,}568 + \frac{0{,}434}{k}\right)^{1/k}$$

The scaling factor A is a measure for the characteristic wind speed of the considered time series. The shape factor k describes the curve shape. It is in the range between 1 and 4, and the value is roughly characteristic for certain wind climate:

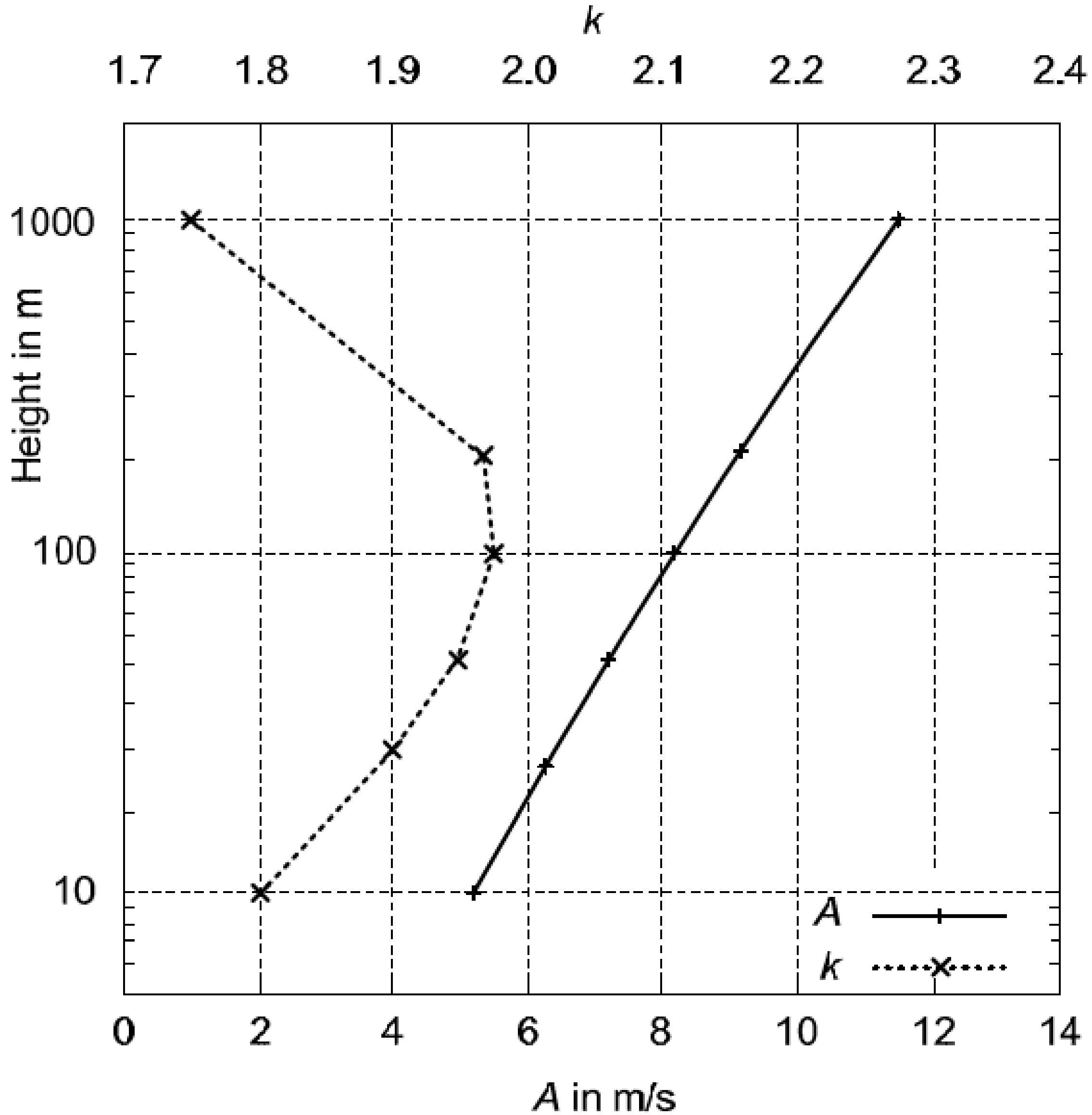
$k \approx 1$: Arctic regions
$k \approx 2$: Regions in Central Europe
$k \approx 3$ to 4: Trade wind regions



Example of Weibull distributions for a mean wind speed $v = 8$ m/s and different shape factors k

Table 4.2 Weibull factors for different sites in Germany, measuring height 10 m, from [36]

Site	***k***	***A* in m/s**	$\bar{v}$ **in m/s**
Helgoland	2,13	8,0	7,1
Hamburg	1,87	4,6	4,1
Hannover	1,78	4,1	3,7
Wasserkuppe	1,98	6,8	6,0

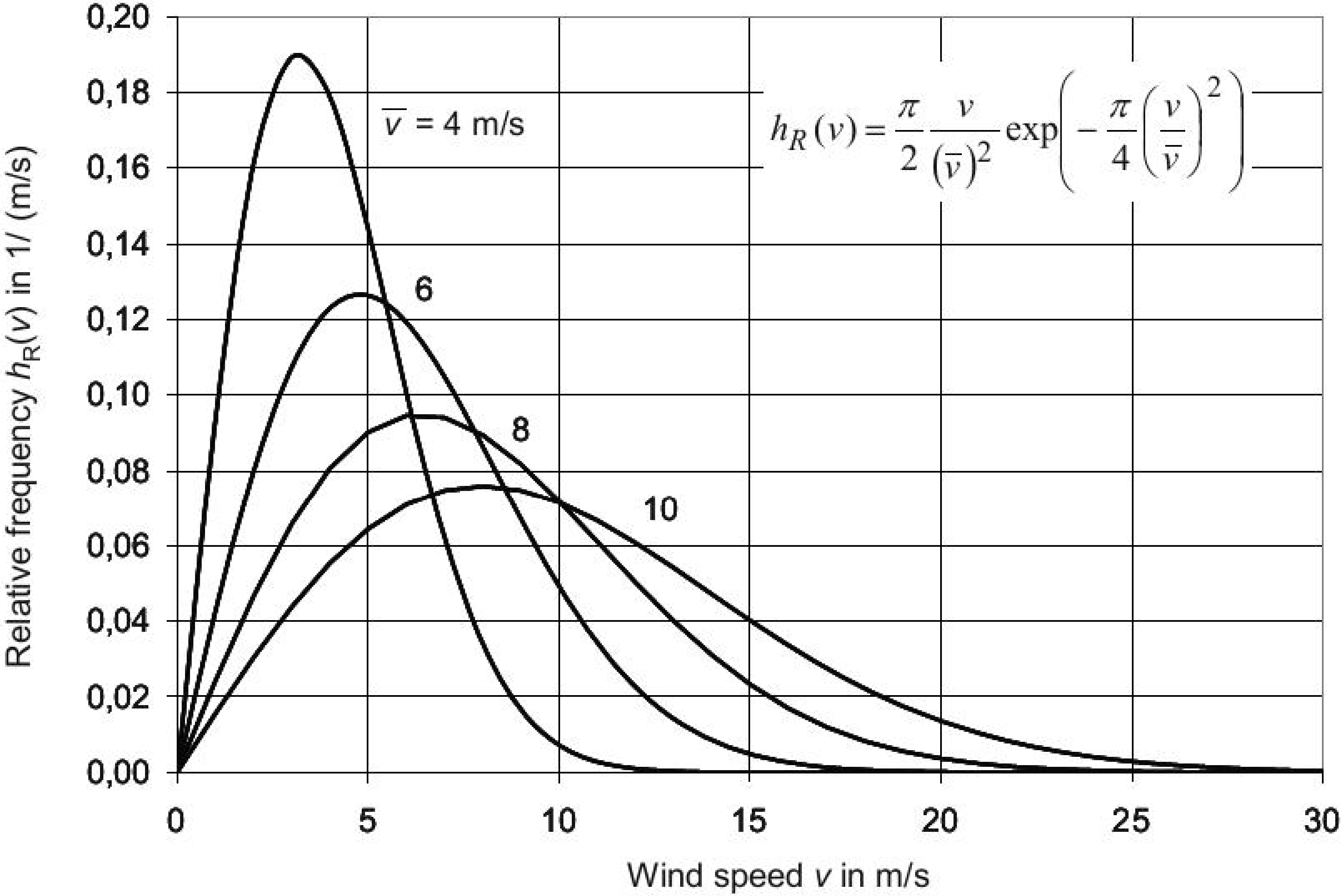


Change of Weibull factors with height

Rayleigh distribution function

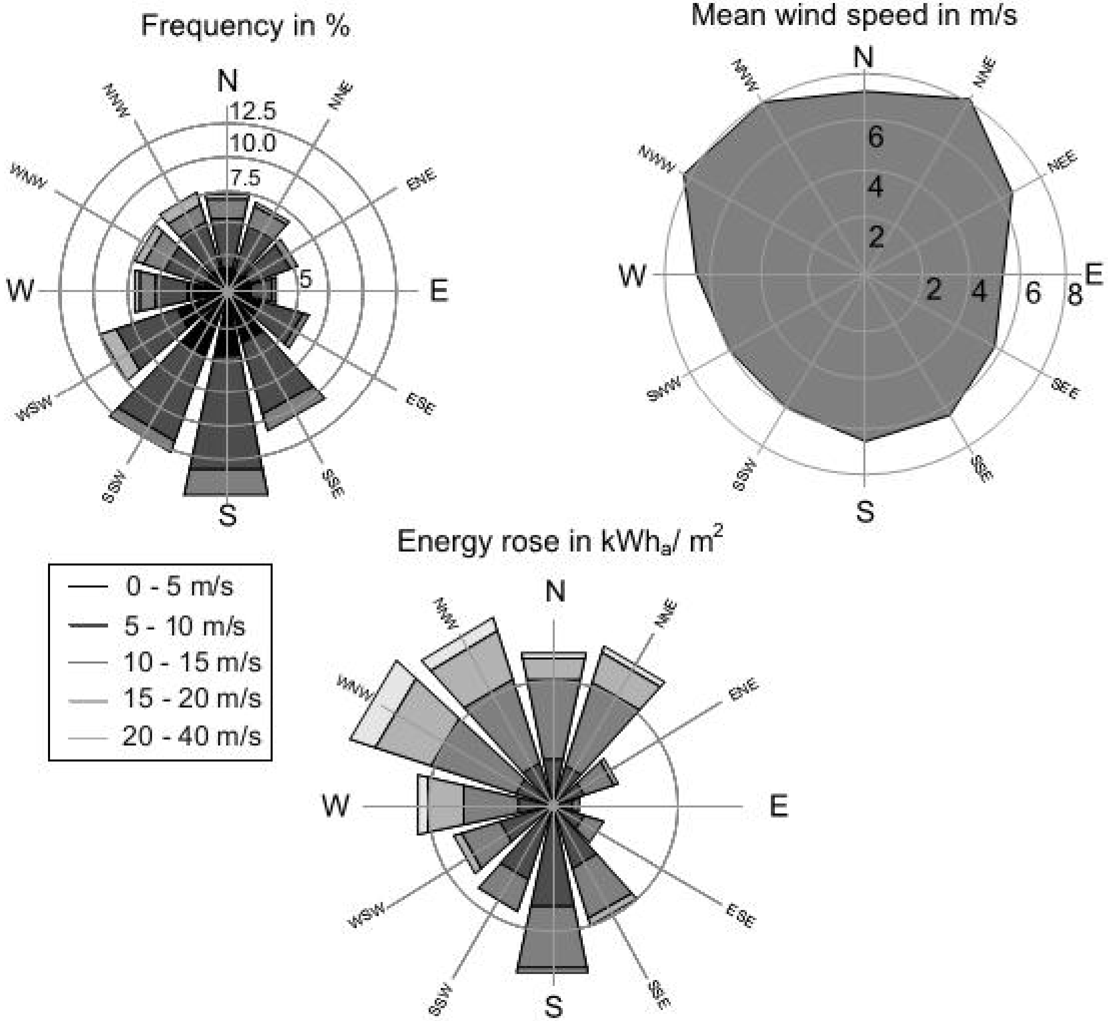
The Rayleigh distribution function, Fig. 4-21 (a), is a special, simplified case of the Weibull distribution function for the shape factor k= 2

$$h_R(v) = \frac{\pi}{2} \frac{v}{(\bar{v})^2} \exp\left(-\frac{\pi}{4} \left(\frac{v}{\bar{v}} \right)^2 \right)$$



0,20
0,18
0,16
0,14
0,12
0,10
0,08
0,06
0,04
0,02
0,00
Relative frequency $h_R(v)$ in 1/ (m/s)
$\overline{v}$ = 4 m/s
6
8
10
$h_R(v) = \frac{\pi}{2}\frac{v}{(\overline{v})^2}\exp\left(-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^2\right)$
0
5
10
15
20
25
30
Wind speed v in m/s

Wind roses



Frequency in %
N
NNE
ENE
E
ESE
SSE
S
SSW
WSW
W
WNW
NNW
12.5
10.0
7.5
5
Mean wind speed in m/s
N
NNE
NEE
E
SEE
SSE
S
SSW
SWW
W
NWW
NNW
2
4
6
8
Energy rose in kWh$_a$/ m^2
N
NNE
ENE
E
ESE
SSE
S
SSW
WSW
W
WNW
NNW
0 - 5 m/s
5 - 10 m/s
10 - 15 m/s
15 - 20 m/s
20 - 40 m/s

Power curve measurement

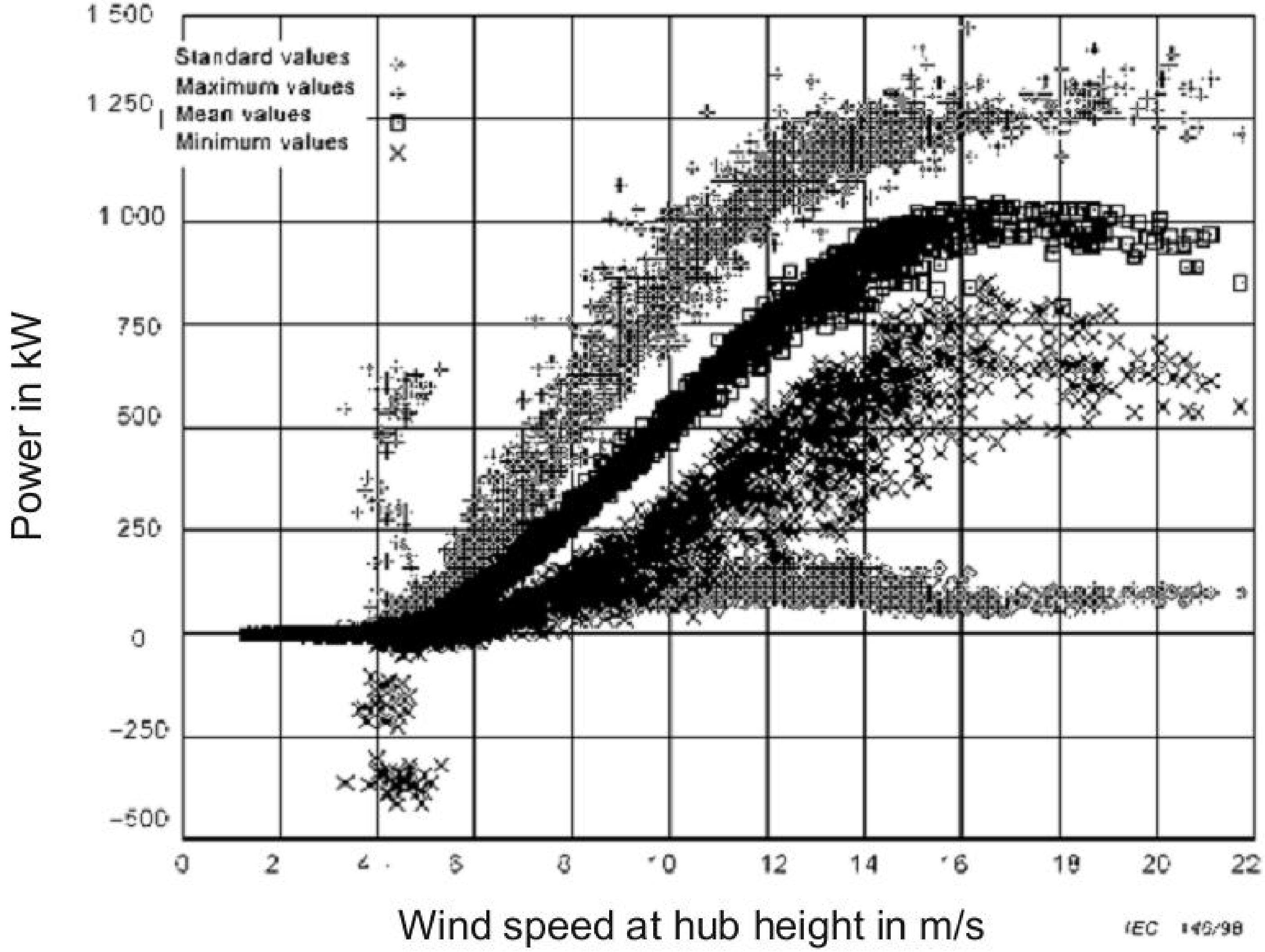
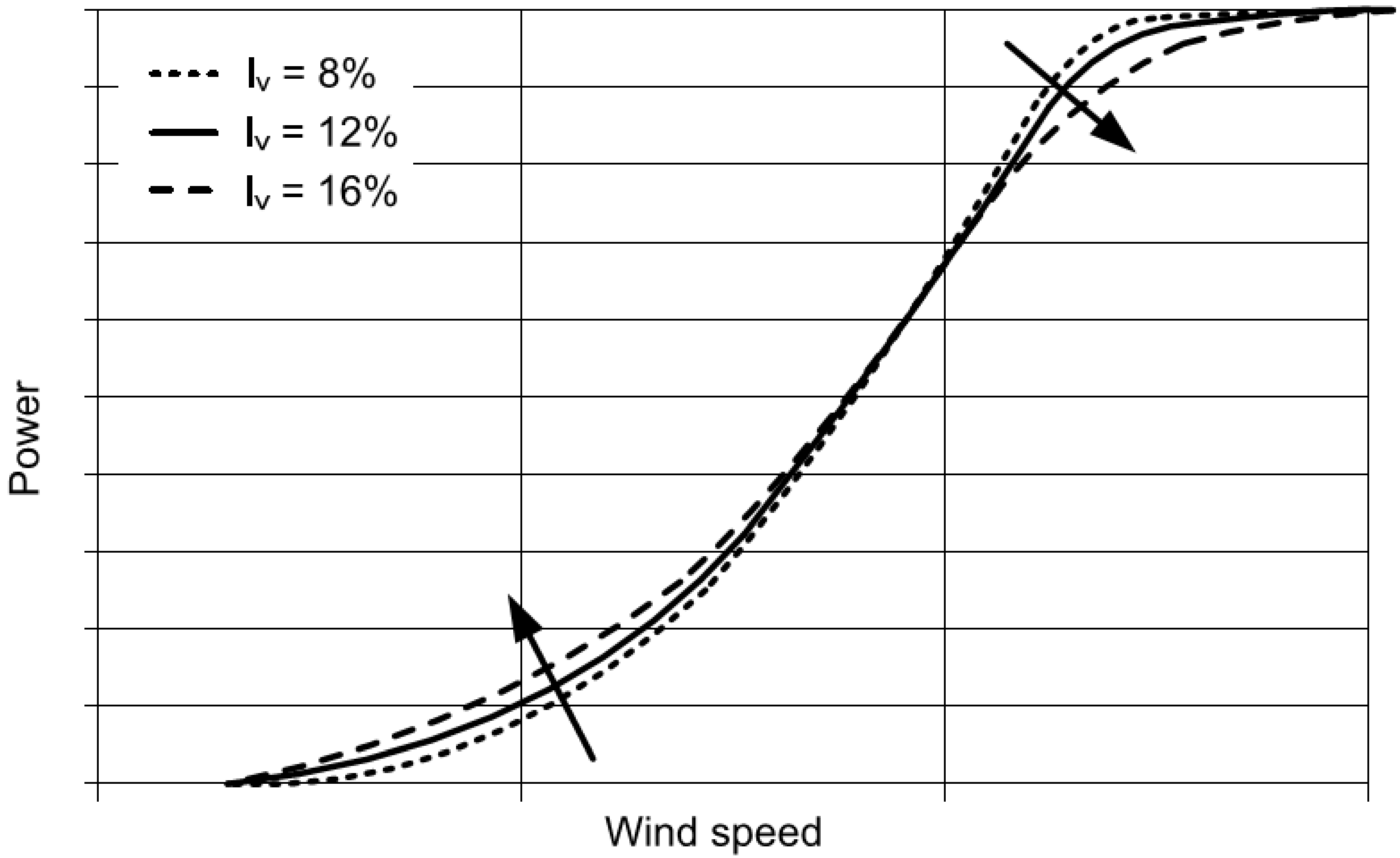
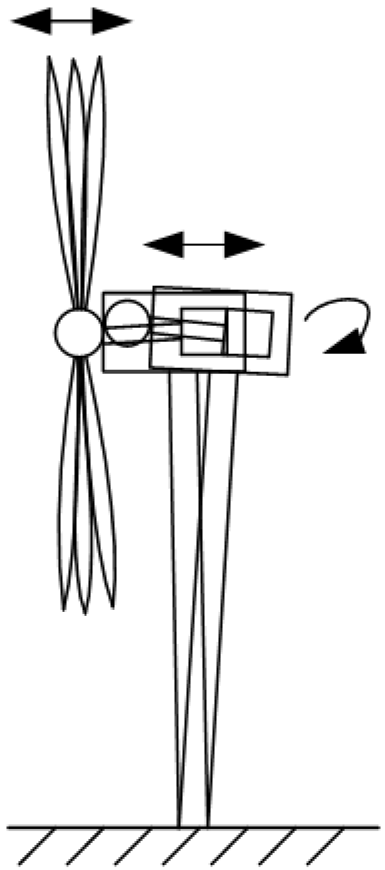


Fig. 4-26 Example of a measured power curve; 10-minute mean values, standard deviation and 1-second minimum and maximum values [4]



I_v = 8%
I_v = 12%
I_v = 16%
Power
Wind speed

Consequences of the turbulence



Turbulences provoking dynamic loads and vibrations

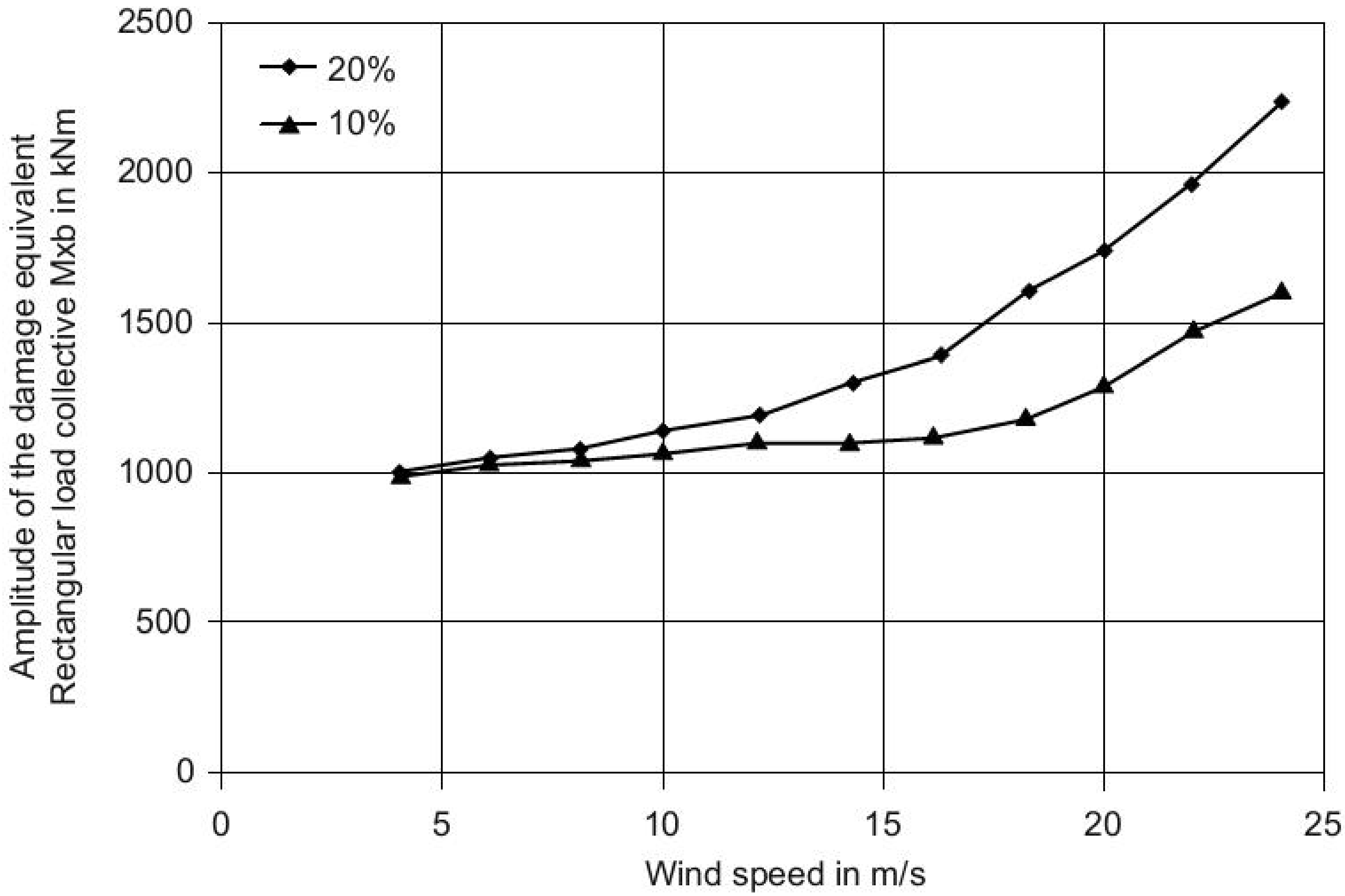
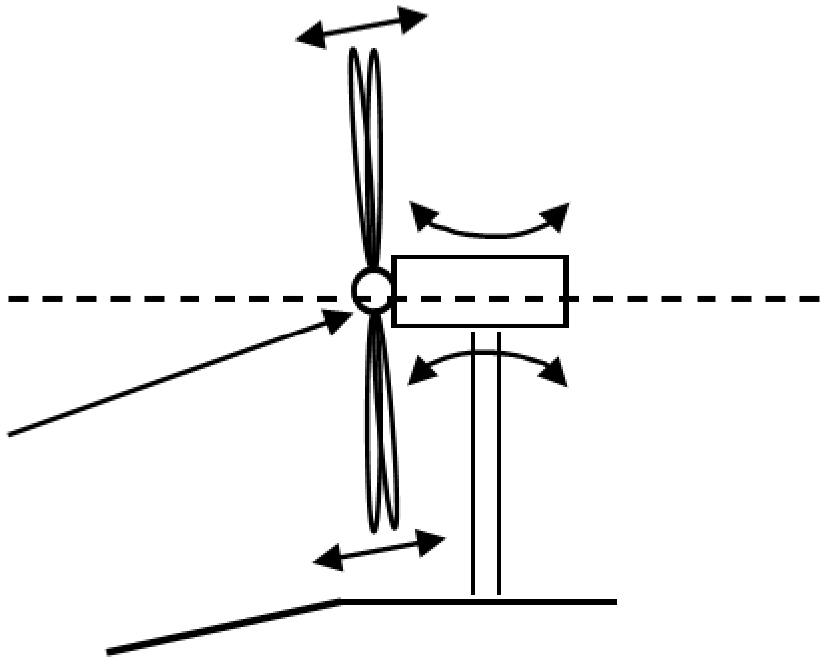


Fig. 4-32 Operational loads at the blade root of a 1,25 MW wind turbine for two different turbulence intensities [22]

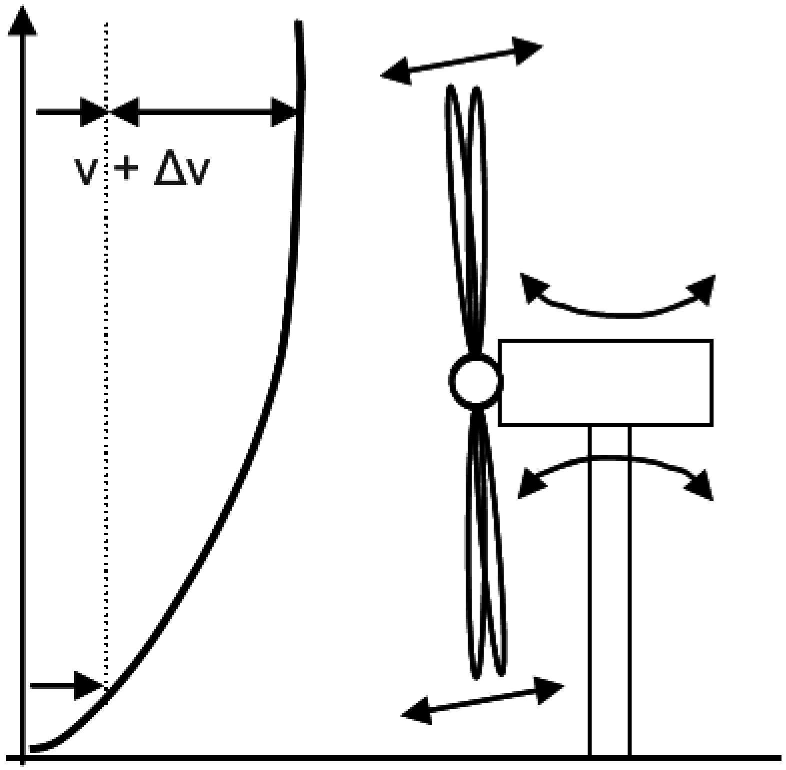
Consequences of oblique inflow



Loads due to vertical oblique flow

Influence of wind shear

The wind shear is defined as difference of the horizontal wind speed at the top and bottom of the rotor



Loads due to the wind profile (wind shear)

Wind farm design

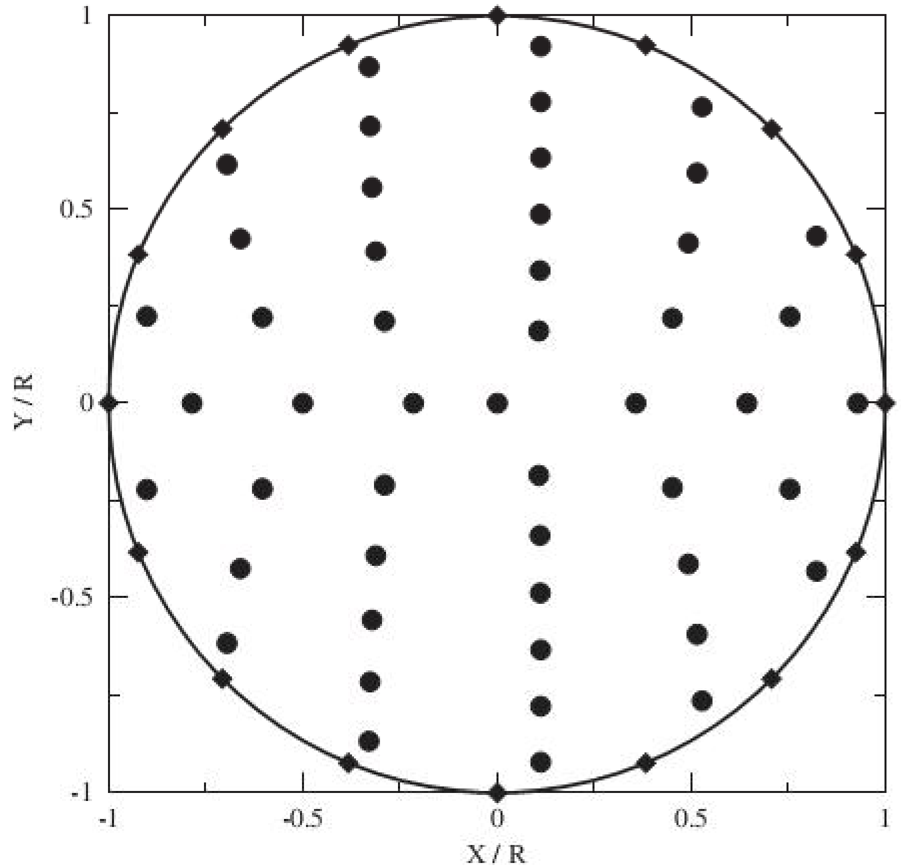
- Nominal power (maximum or allowed)

- Characteristics of turbines
  - Number
  - Power curve
  - Hub height
  - Rotor diameter
  - …….

- Farm layout

Farm layout design

- Maximum power extraction
- Economic power extraction



Wake effect

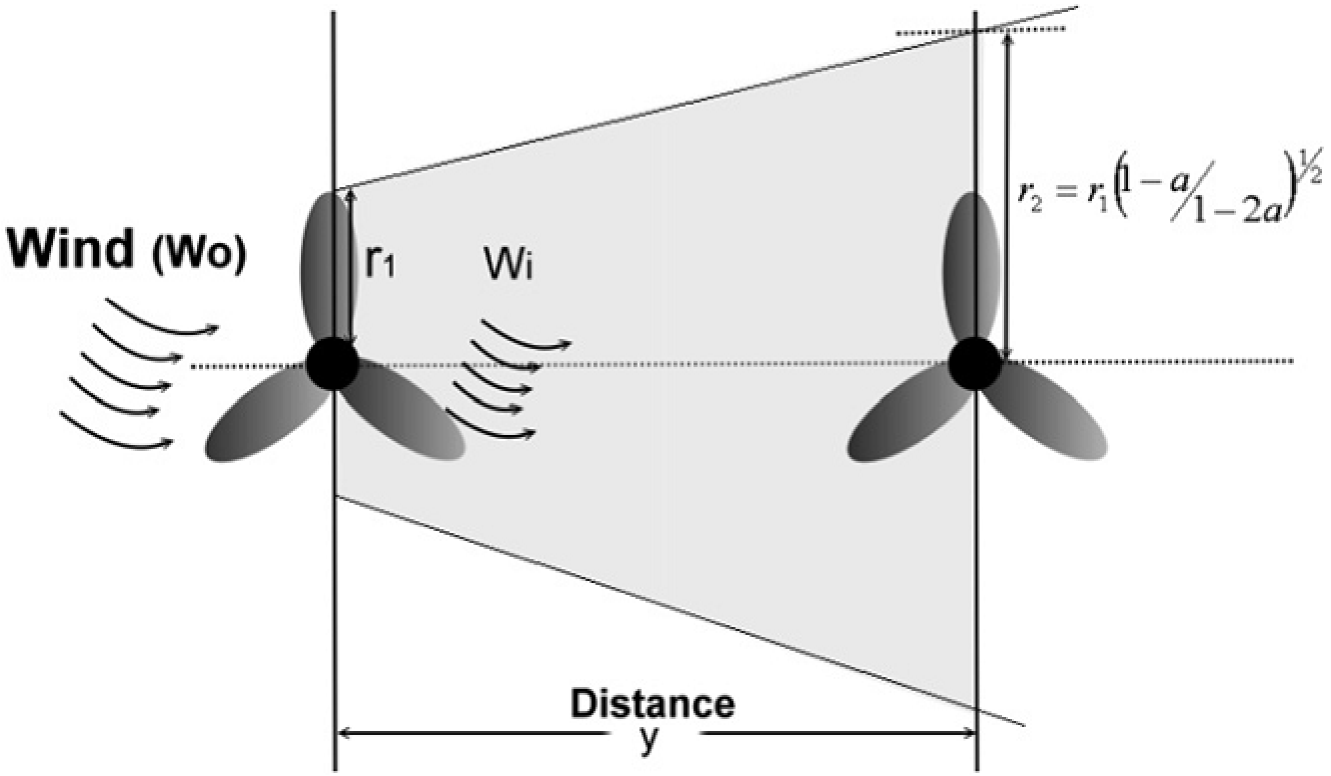


Fig. 3. Wind wake model.

Yield prediction of a wind farm

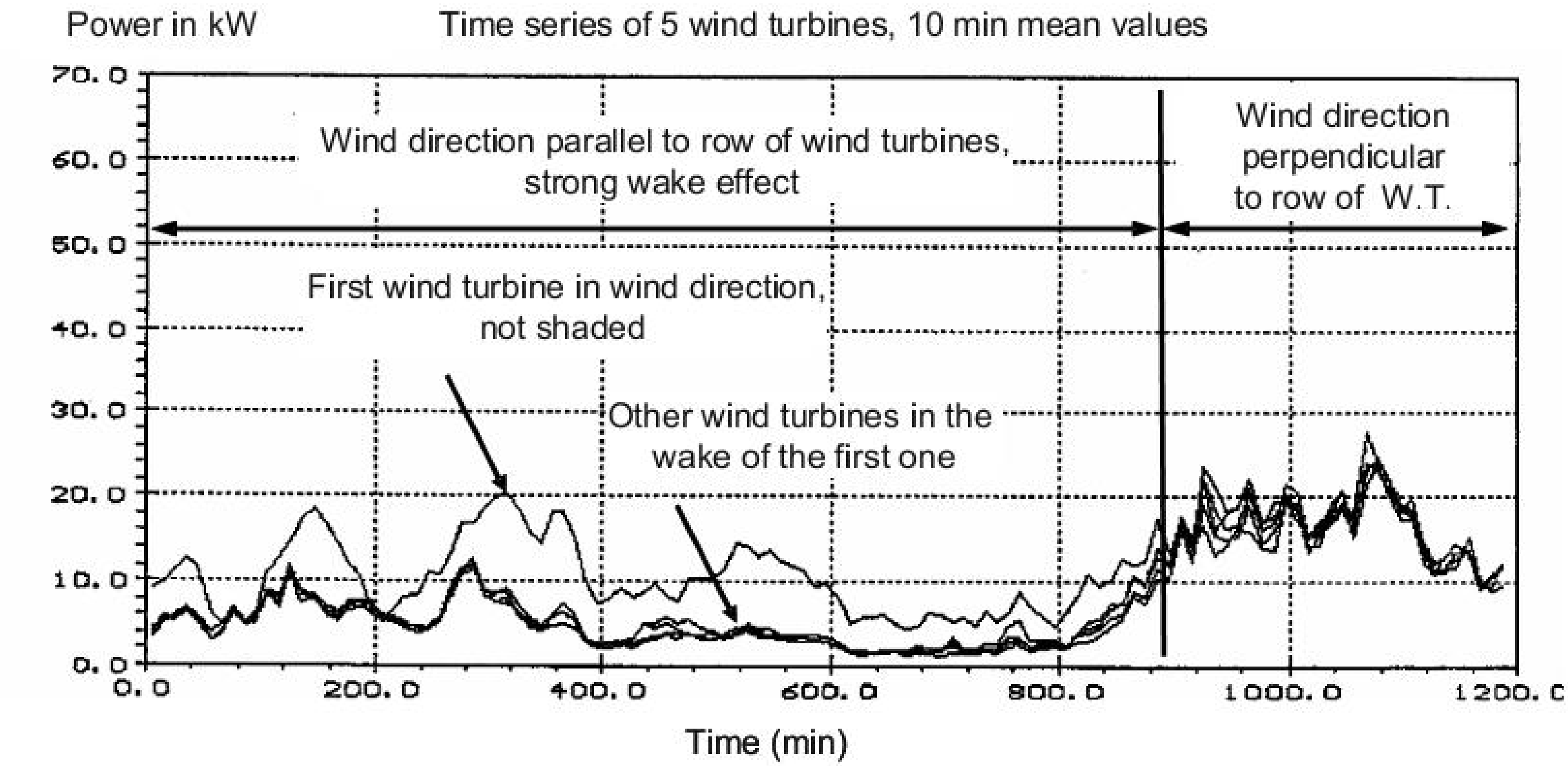


Fig. 4-28 Power reduction due to the wake effect in a wind farm with 5 wind turbines, left: wind direction in parallel to the lined-up wind turbines, right: wind direction perpendicular to the lined-up wind turbines [University Oldenburg, Germany]