Wind power meteorology

PHYS-E6572 Advanced Wind Power Technology

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based on material in Dipoli course by VTT Petteri Antikainen and Andrea Vignaroli

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Wind Energy: why do we need to know about the wind?

- MAXIMIZE WIND POWER PRODUCTION

Estimating average wind power production for life time
Forecasting next day production for markets

- MINIMIZE TURBINE LOADS

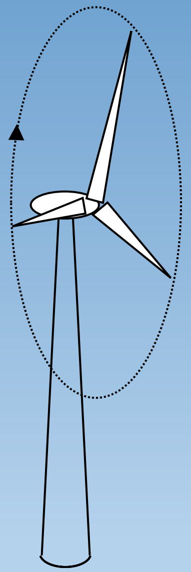
Power in the Wind – from kinetic energy

$$= \frac{1}{2} * \rho * A * V^3$$

Density = P/(R*T)

P - pressure (Pa)
R - specific gas constant (287 J/kgK)
T - air temperature (K)

kg/m^3



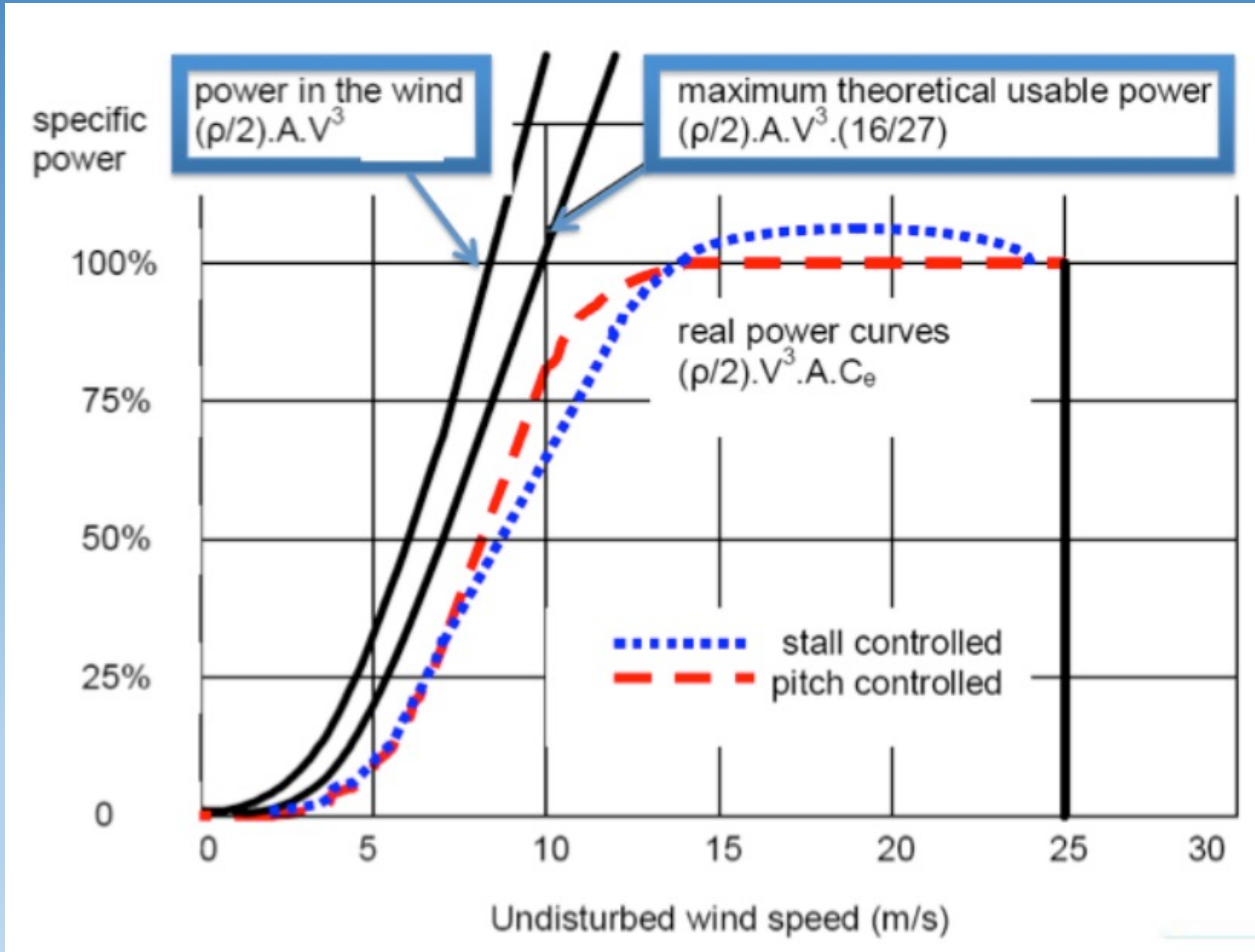
Area = πr^2

m^2

Instantaneous speed

m/s

Power curves – not quite V^3

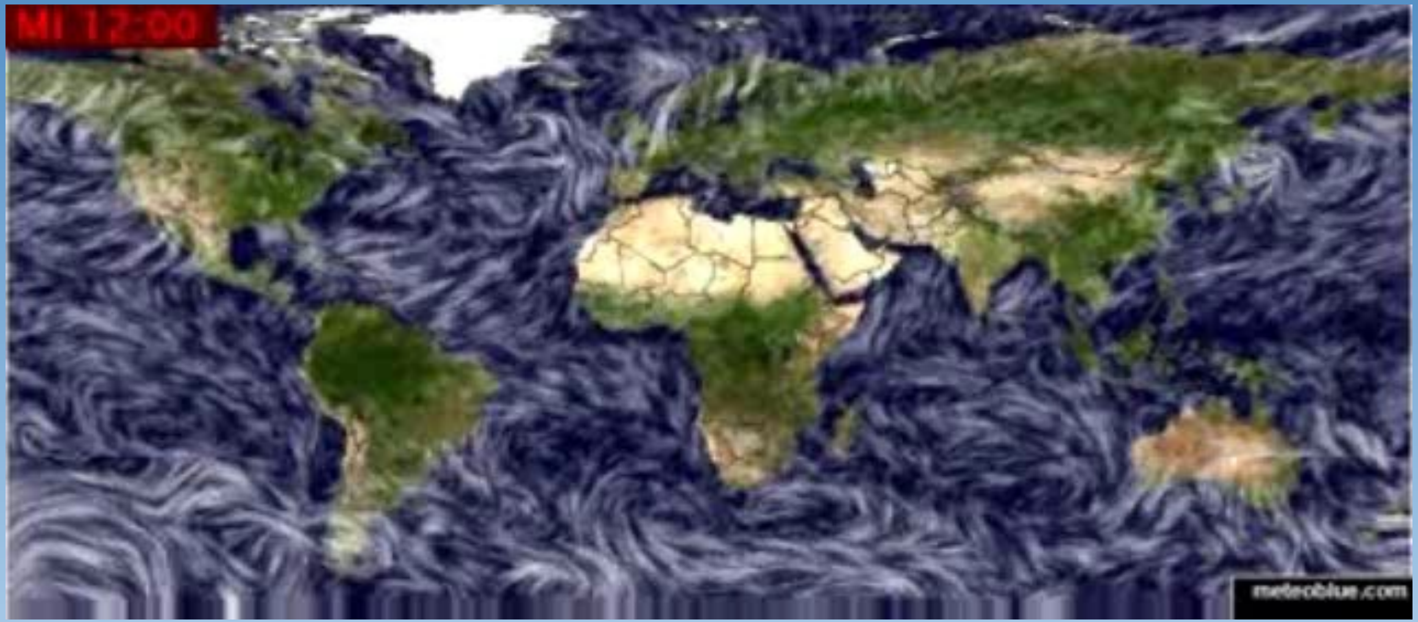


Note: stall controlled turbines old technology

What is wind

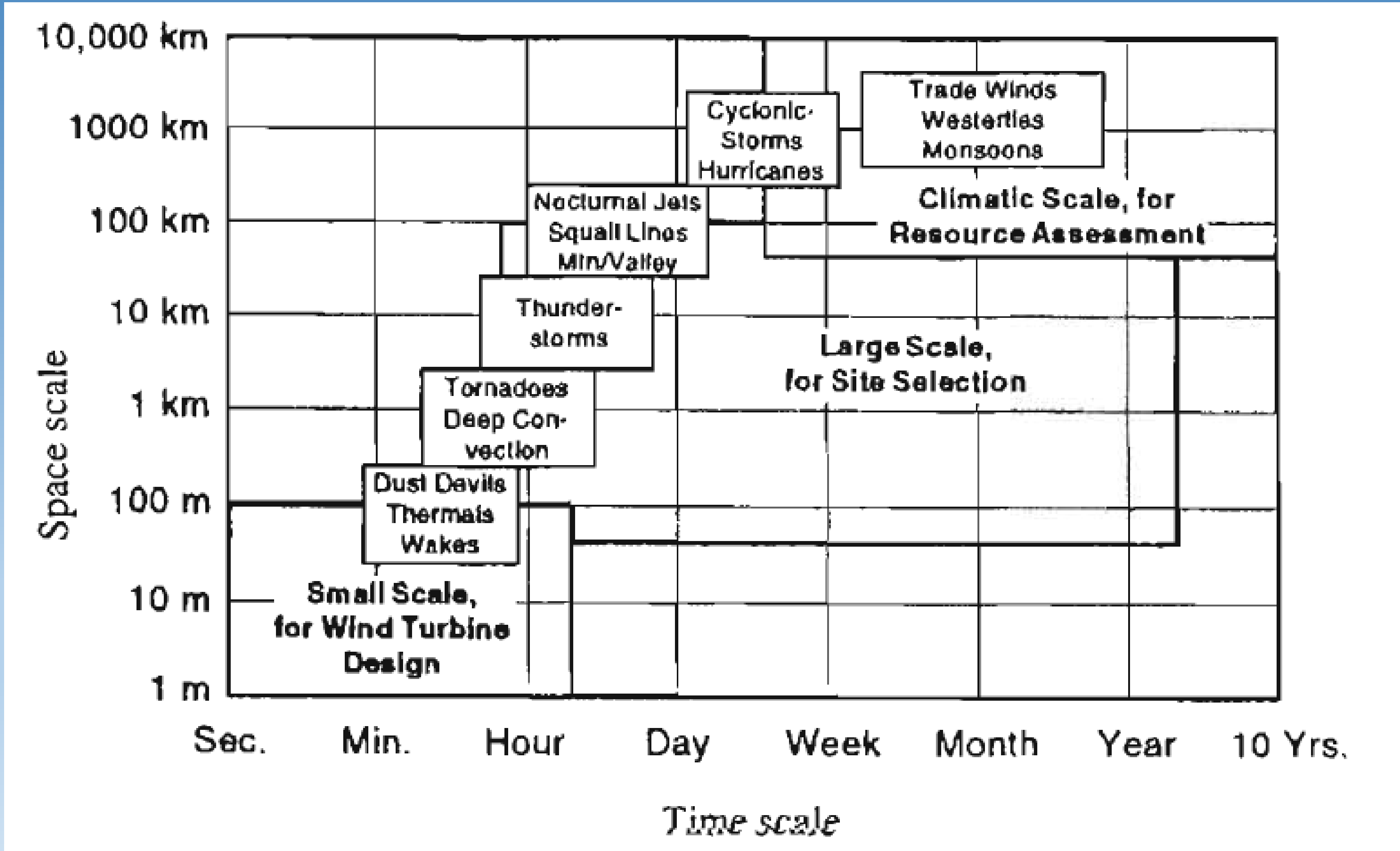
Average/max wind speeds, turbulence, gusts, extremes
Wind directions/wind rose, wind shear /profile, distributions

Where does wind come from?



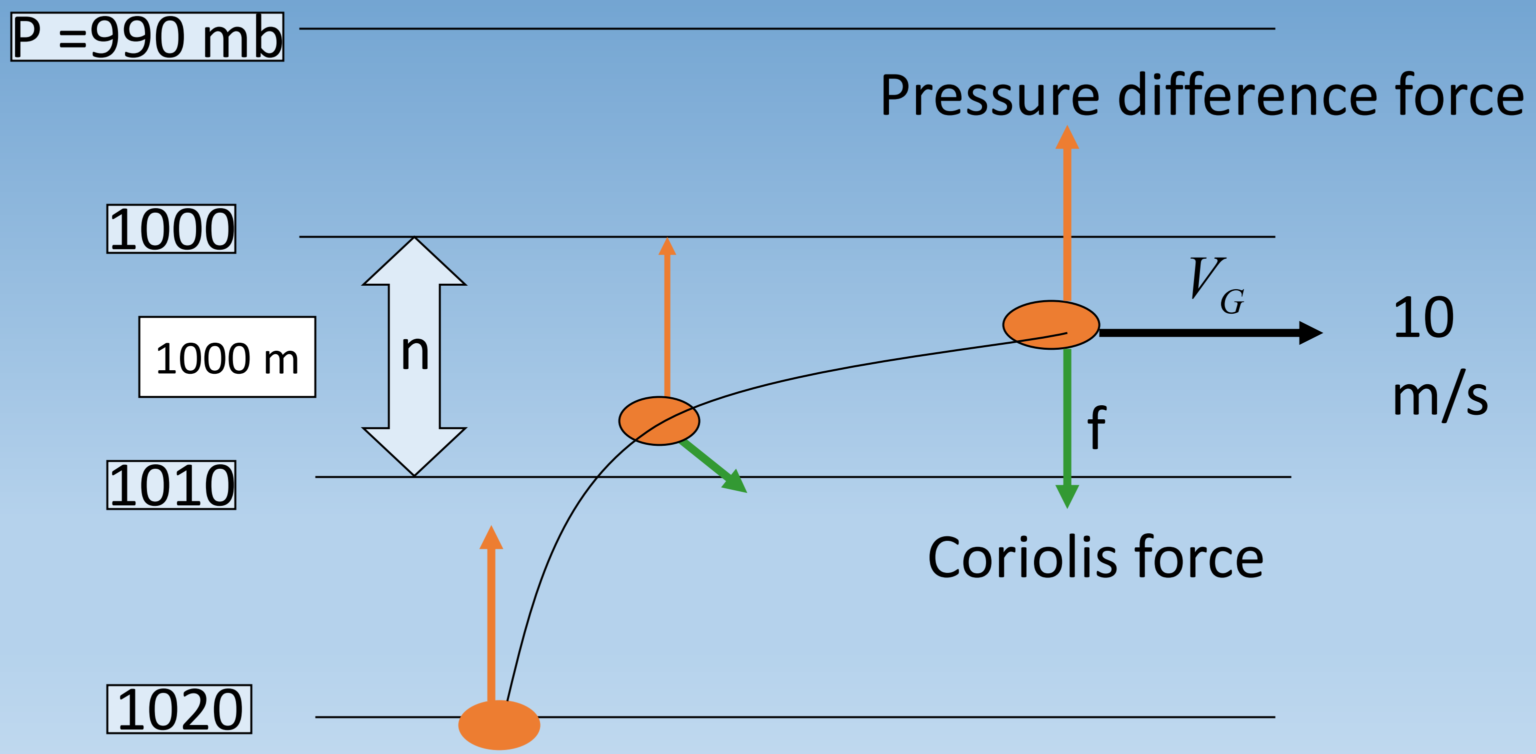
- <u>Uneven heating of the earth's surface</u>
- Earth's rotation
- Daily heating and cooling cycles
- Weather systems – track and intensity
- Position of jet stream

Wind Variation in Space and Time

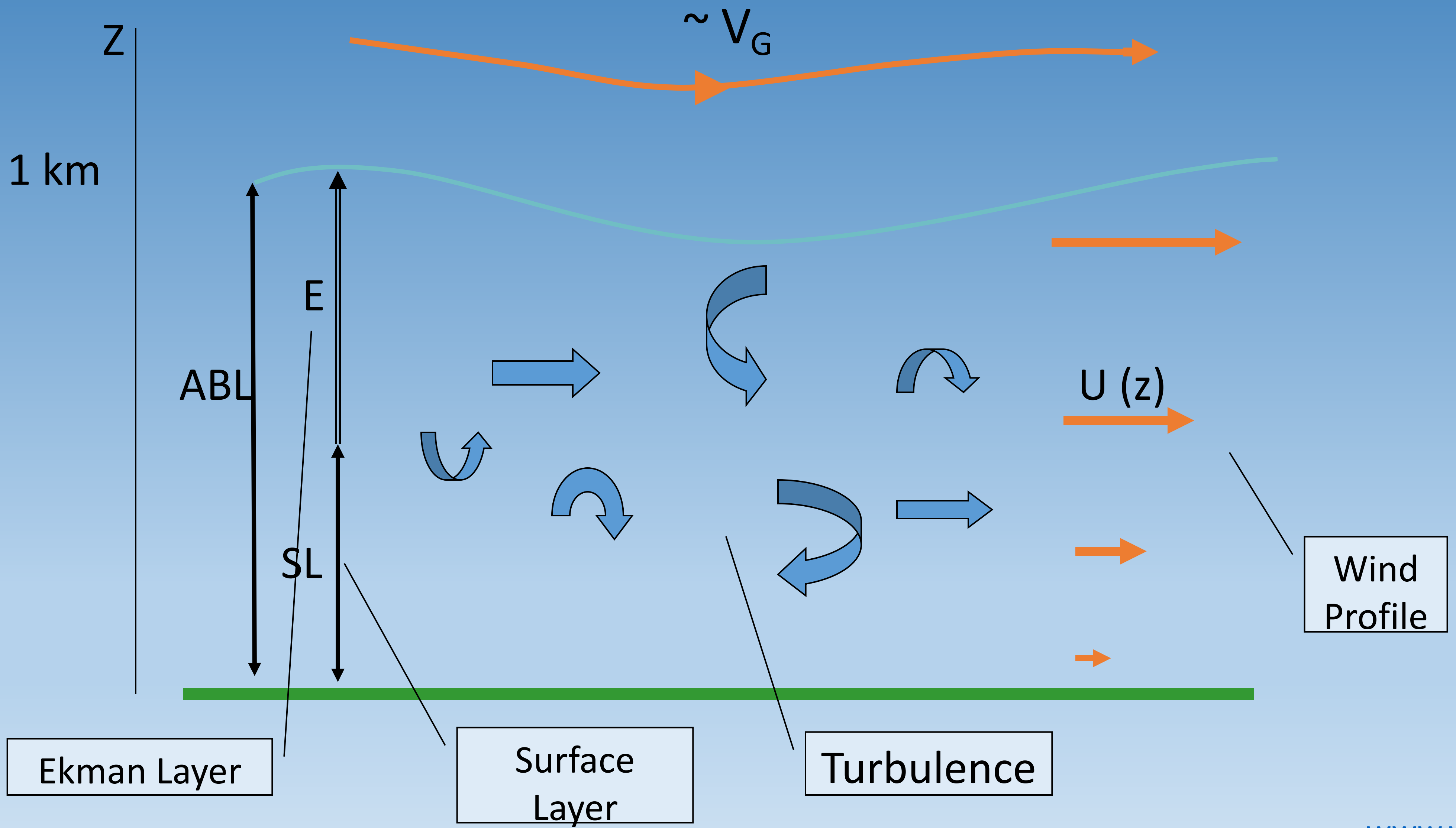


The Geostrophic Wind – from pressure differences

$$V_G = \frac{1}{f\rho}\frac{\partial P}{\partial n}$$

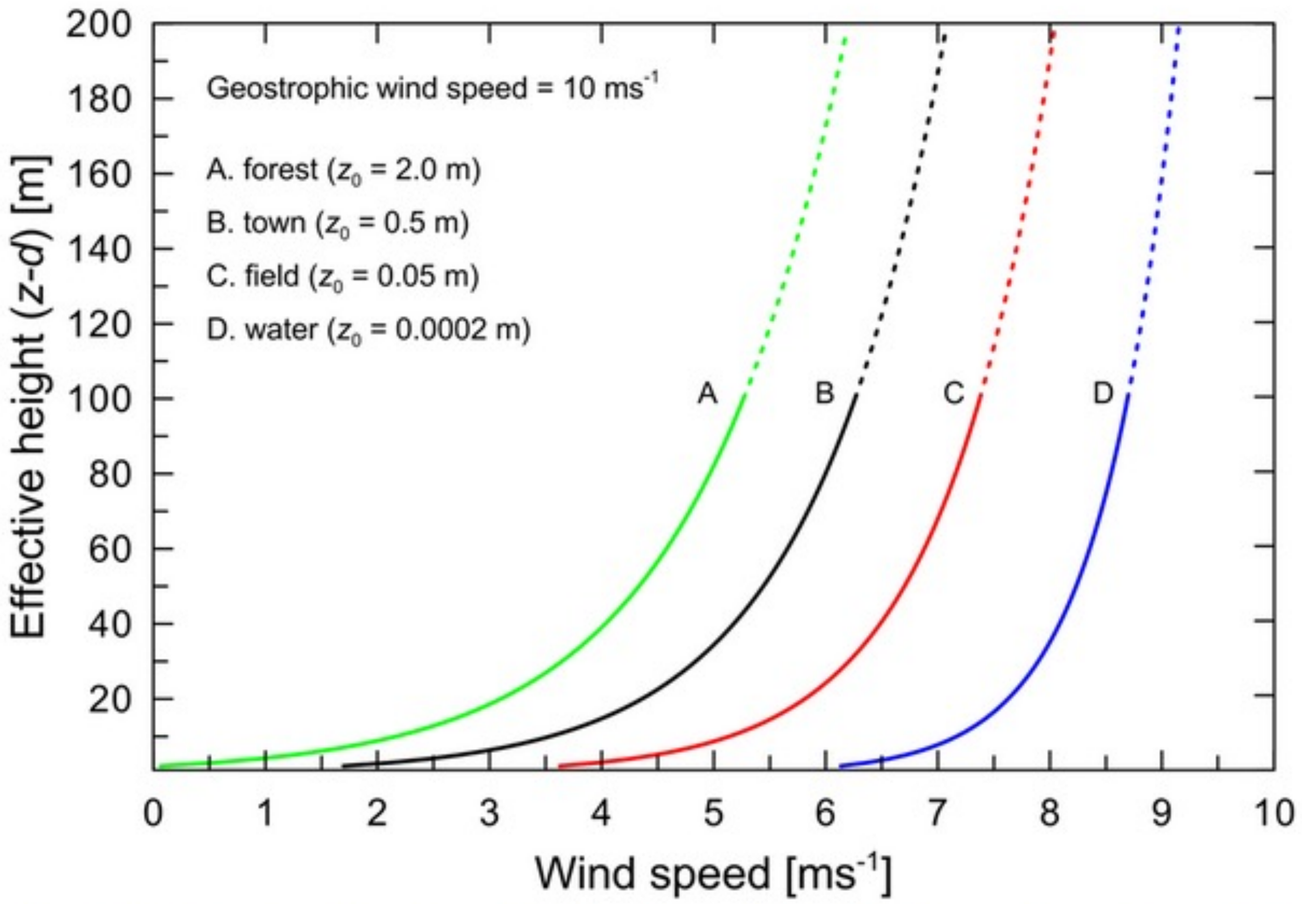


The Atmospheric Boundary Layer (ABL)



Wind profile – roughness effect

- Roughness of the terrain (z_0)
- For large roughness z_0 the wind speeds higher will be much larger than lower

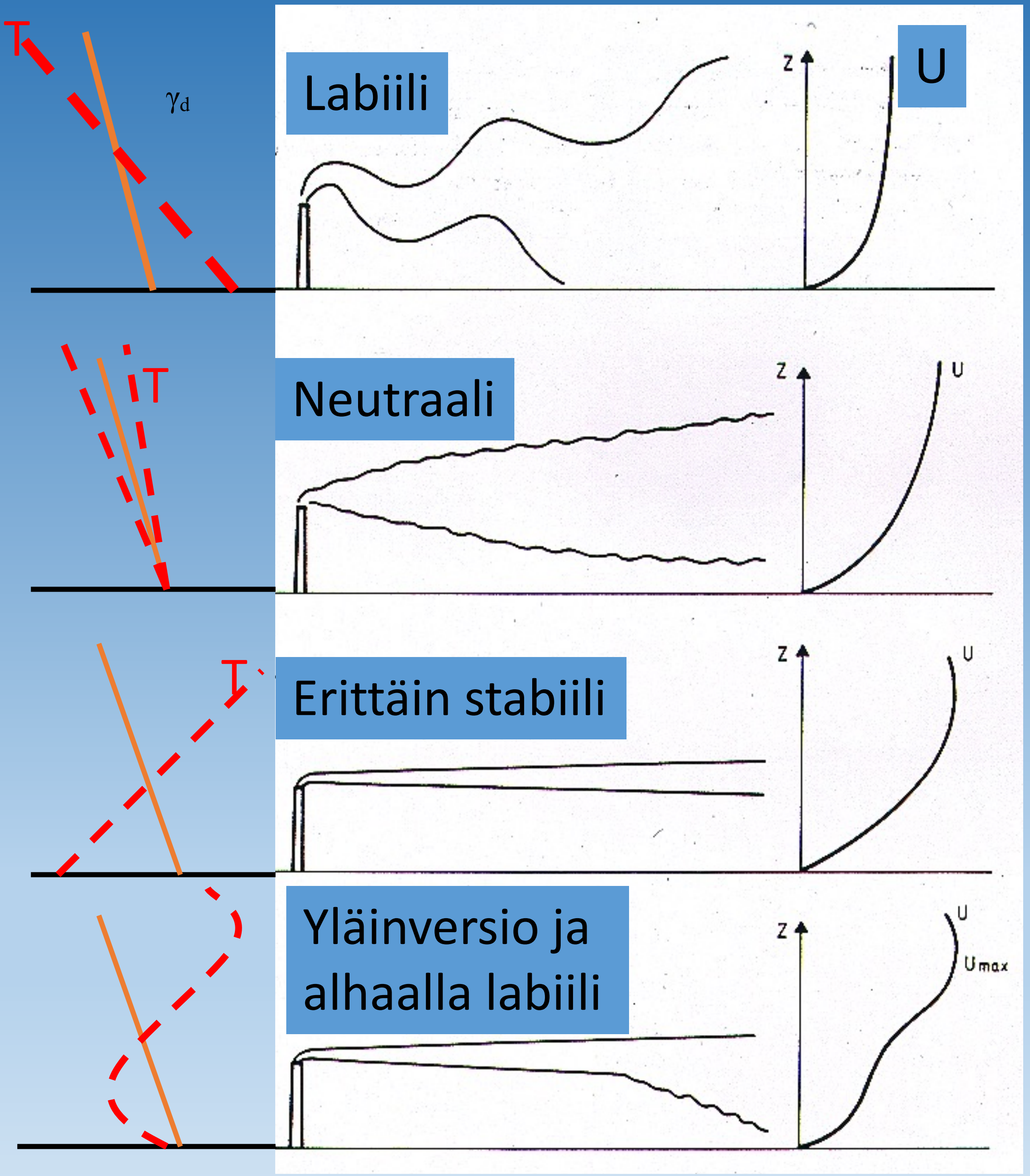


Different surface roughness lengths result in different vertical profiles of wind speed. The y-axis is height above surface and the x-axis is wind speed. For a range of surface roughness lengths, the curves show the wind speed profile for neutral conditions and a geostrophic wind of 10 m/s.

Wind shear – vertical, how much more wind at higher altitude

Source: https://globalwindatlas.info/about/method

Wind Profile – stability effect



www.windatlas.fi

Wind profile on flat terrain

$$u(z) = \frac{u_*}{k}[\ln(z/z_0) - \Psi(z/L)]$$

u(z) =horizontal wind speed in function of the height z
u*= friction velocity
κ = Von Karman constant ~ 0.4
z0 = Roughness height
ψ = function which depends on atmospheric stability
L= Monin Obukhov length

Wind profile on flat terrain

For neutral conditions…

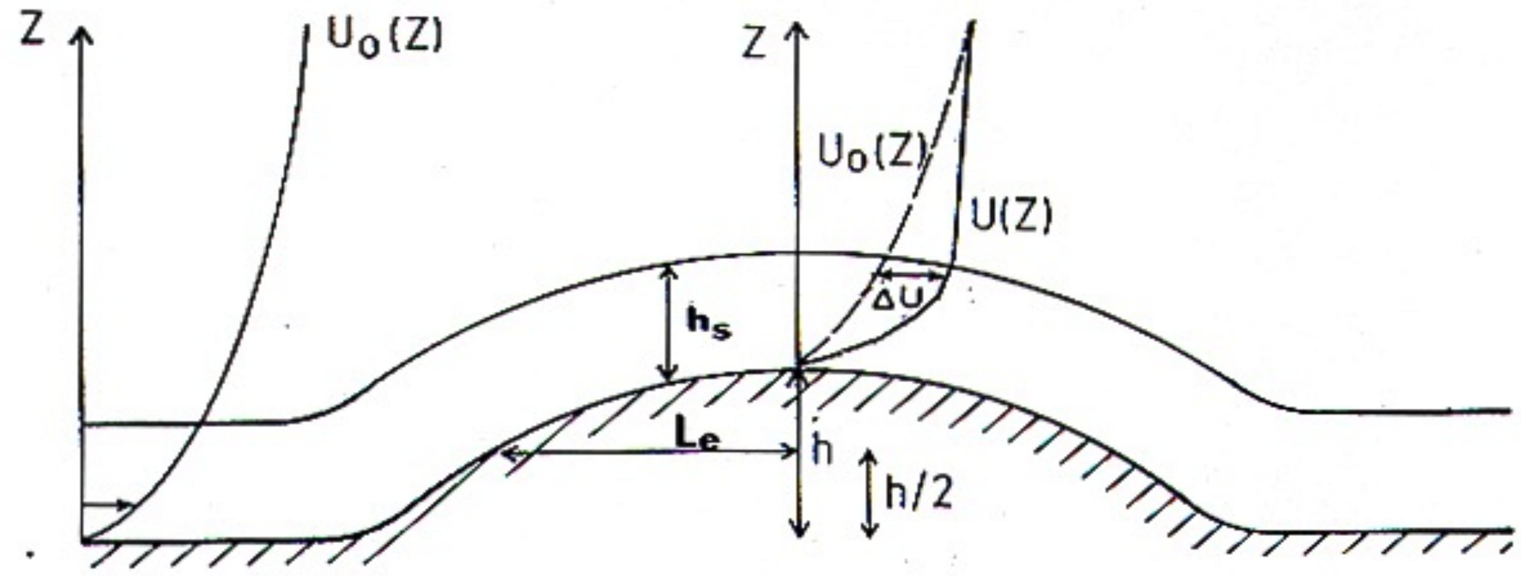
Logarithmic profile $$V(z) = V(z_r).\frac{\ln(z/z_0)}{\ln(z_r/z_0)}$$

or

Power law $$V(z) = V(z_r).\left(\frac{z}{z_r}\right)^{\alpha}$$

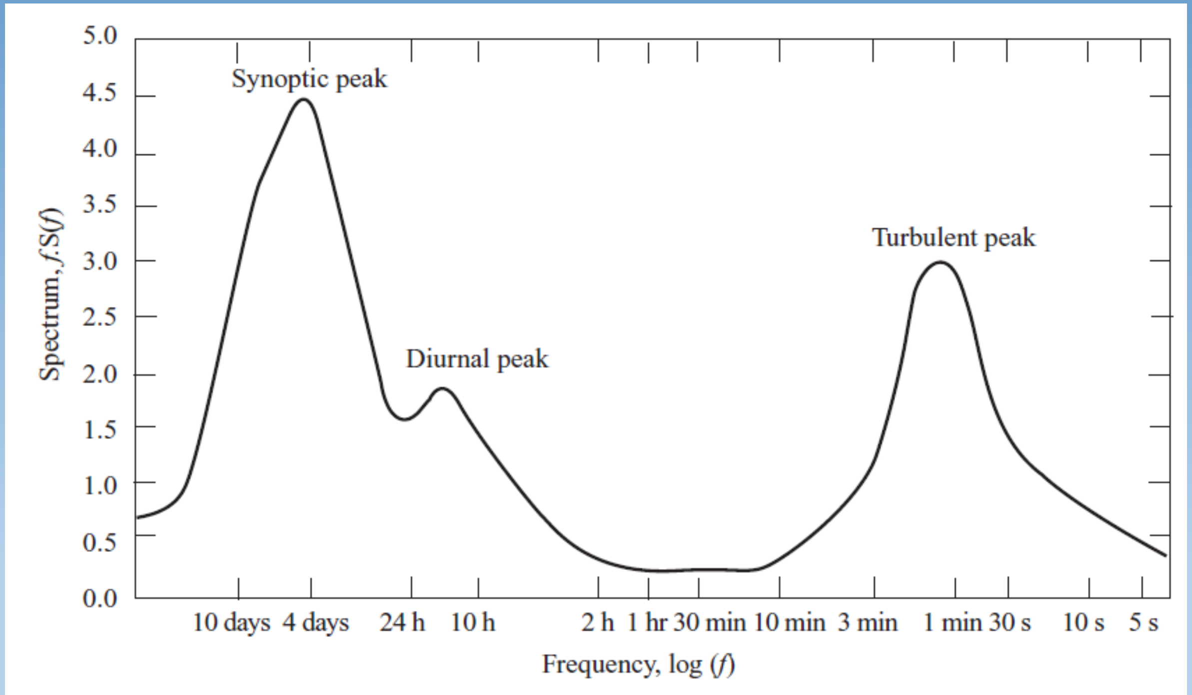
$V(z)$	is the wind speed at height z;
z	is the height above ground;
z_r	is a reference height above ground used for fitting the profile;
z_0	is the roughness length;
α	is the wind shear (or power law) exponent

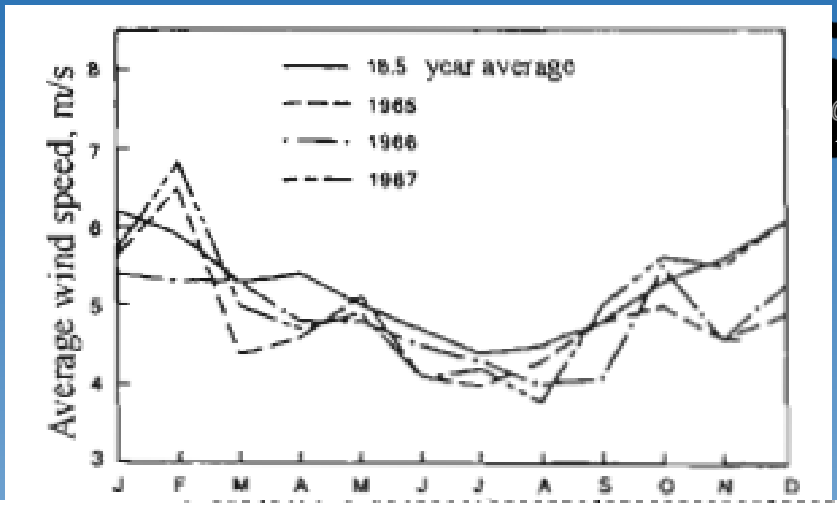
Wind profile: Speed-up effect due to a hill

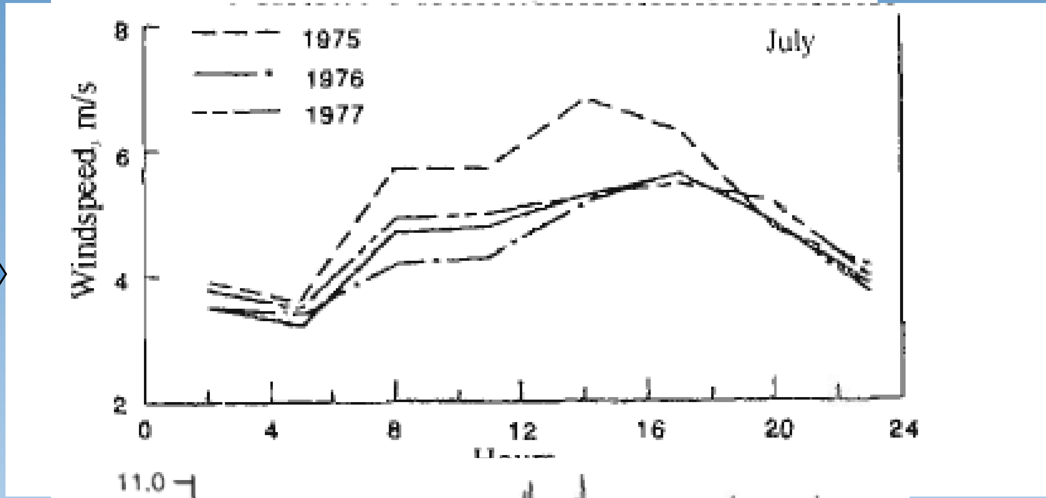


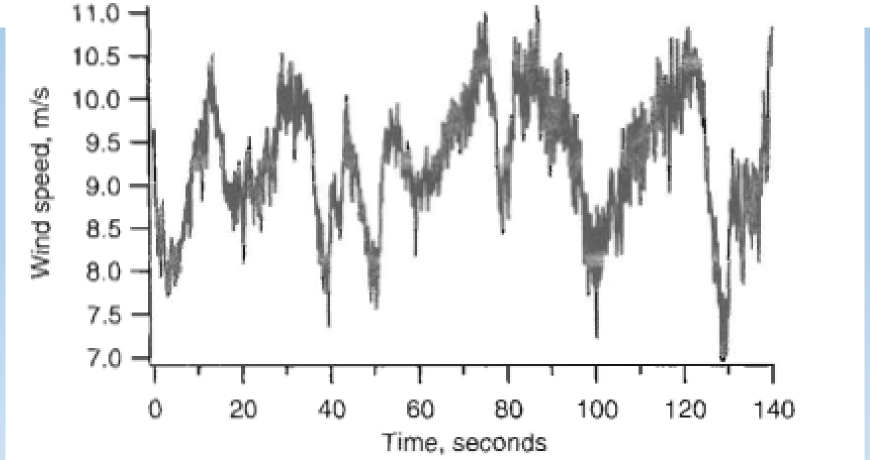
Kuva 25. Periaatekuva mäen aiheuttamasta tuulen nopeuden lisäyk-sestä.

Wind Variation in Time





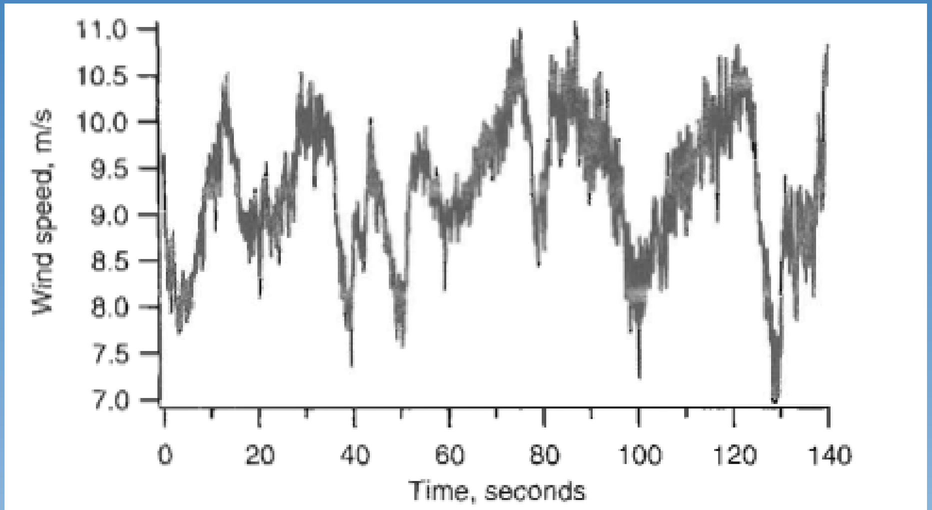




Turbulence

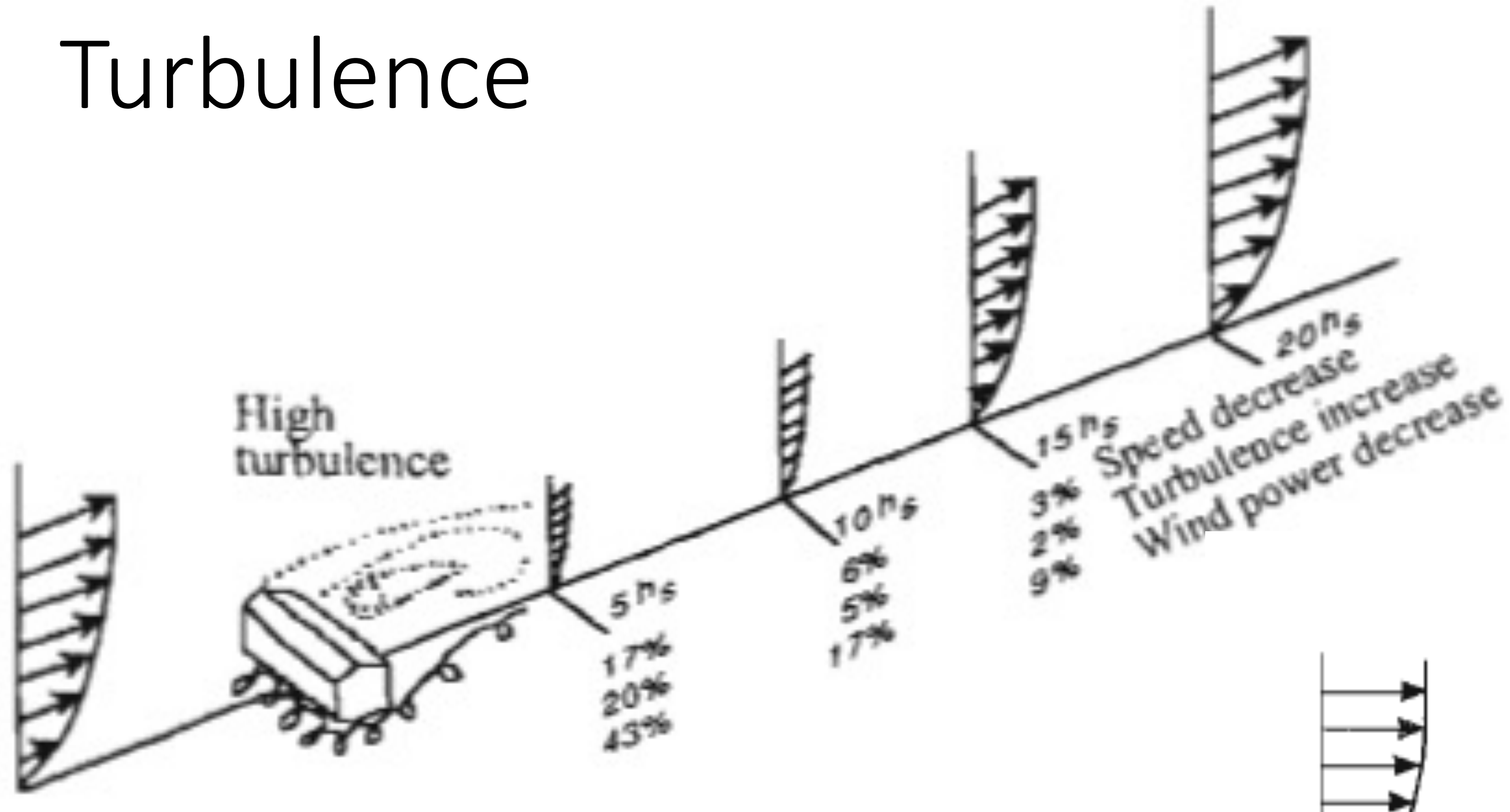
Friction and thermal effects generate turbulence

$$T.I. = \sigma / U$$

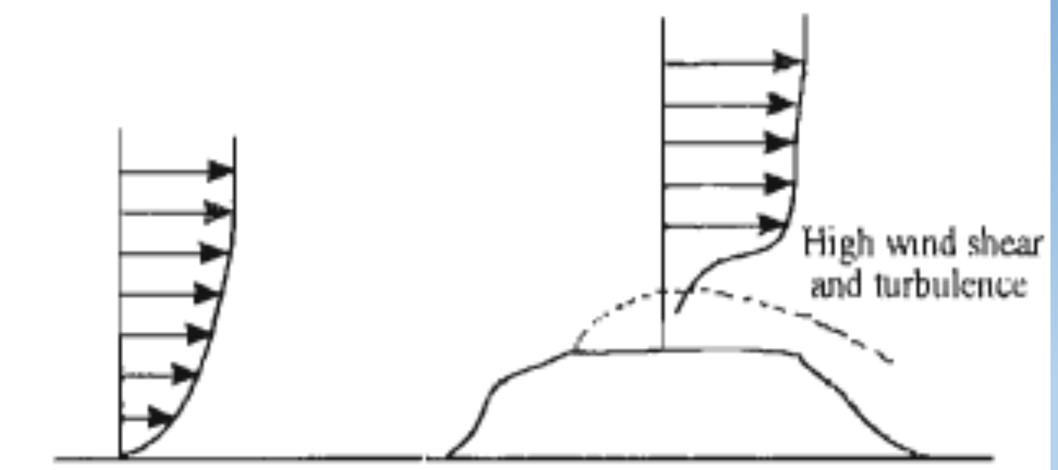


- The most basic measure of the turbulence is the turbulence intensity
- It is defined by the ratio of the standard deviation of the wind speed to the mean
- Both σ and U are calculated over a time period of usually 10 minutes
- The sample rate is at least 1 Hz

Turbulence



Turbulence behind an obstacle



Turbulence on a ridge

Turbulence = Loads = Fatigue

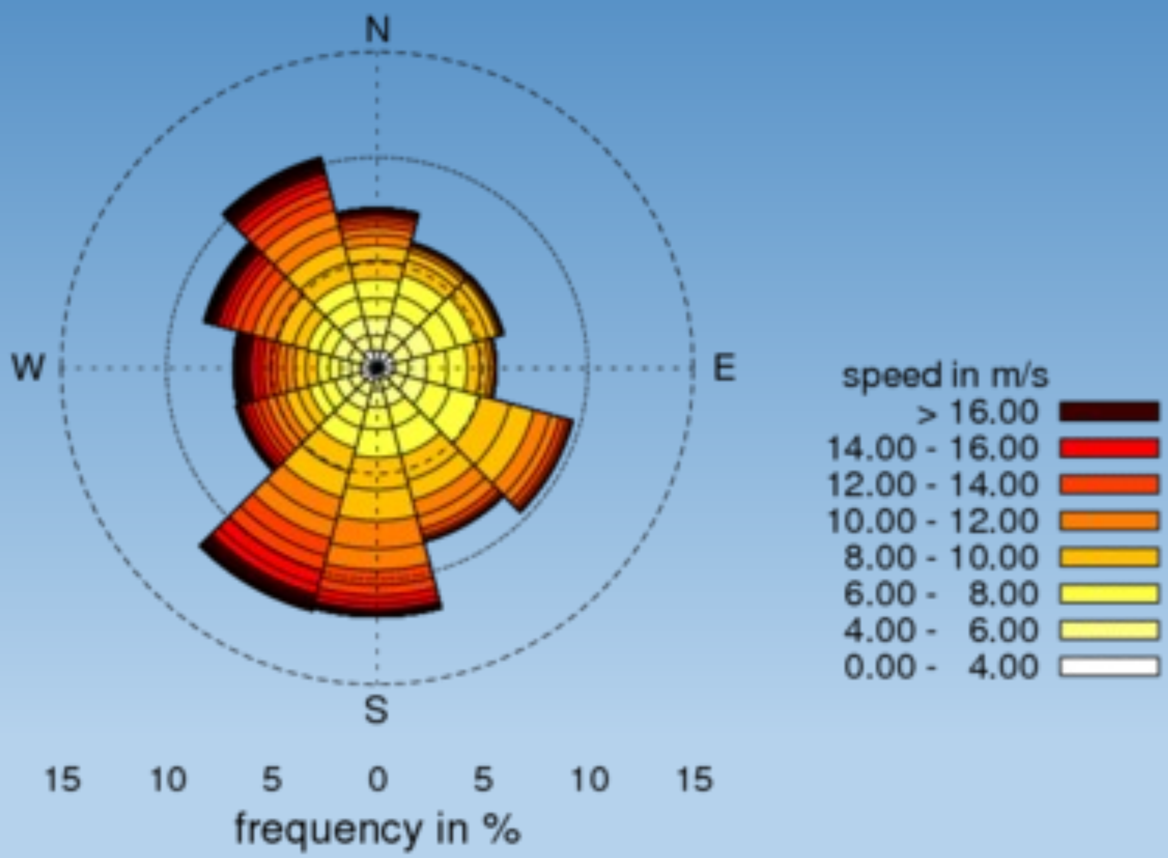
Gusts and Extremes

- Important for load evaluation
- Calculated values from wind measurements
- Used for site classification and turbine selection

Turbine manufacturers require a detailed site assessment to sell turbines that are robust enough. They want to be on a safe side.

In order not to buy a machine that is too robust (expensive) wind measurements are needed to support the decision and negotiation process

The Wind Rose

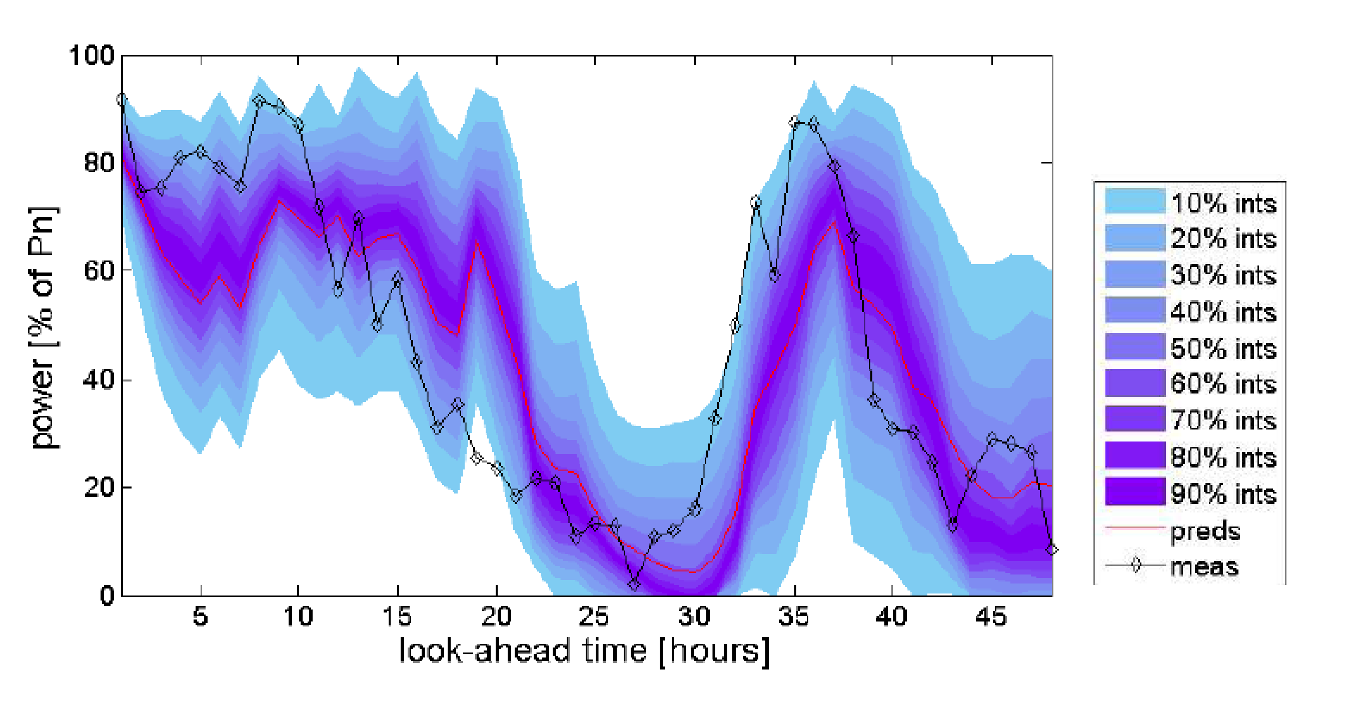


- Simple ones: share of time wind blows from each direction
- Can also combine information about the wind speeds in function of the frequency of the varying wind directions
- important for a good design of the wind farm (minimize wake losses)
- can give some early information about the site orography and obstacles

Estimating wind

Short term for next day(s) – Long term average with distributions

Short term forecasting = looking ahead



- Reliable short term prediction (~ 36 h) of future wind power generation needed to help selling electrity in markets
- Wind power plant's current reading can be used for a couple of hours ahead only (and previous, for trend)
- NWP (Numerical Weather Prediction) models derived by metereological applications to help the assessement

Long term assessment: Wind Distribution

- It is very important for the wind industry to be able to describe the variation of wind speeds over the life time.
- Turbine designers need the information to optimise the design of their turbines, so as to minimise investment costs.
- Windfarm investors need the information to estimate their income from electricity generation.

Wind Distribution: Weibull

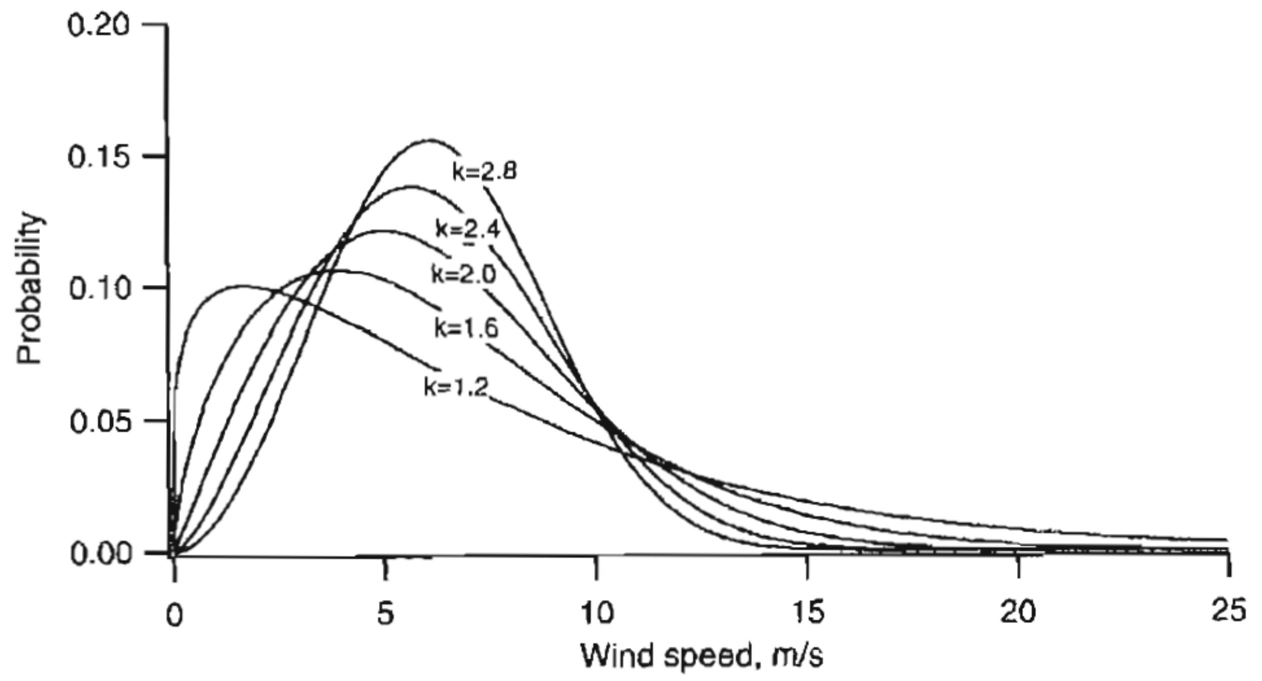
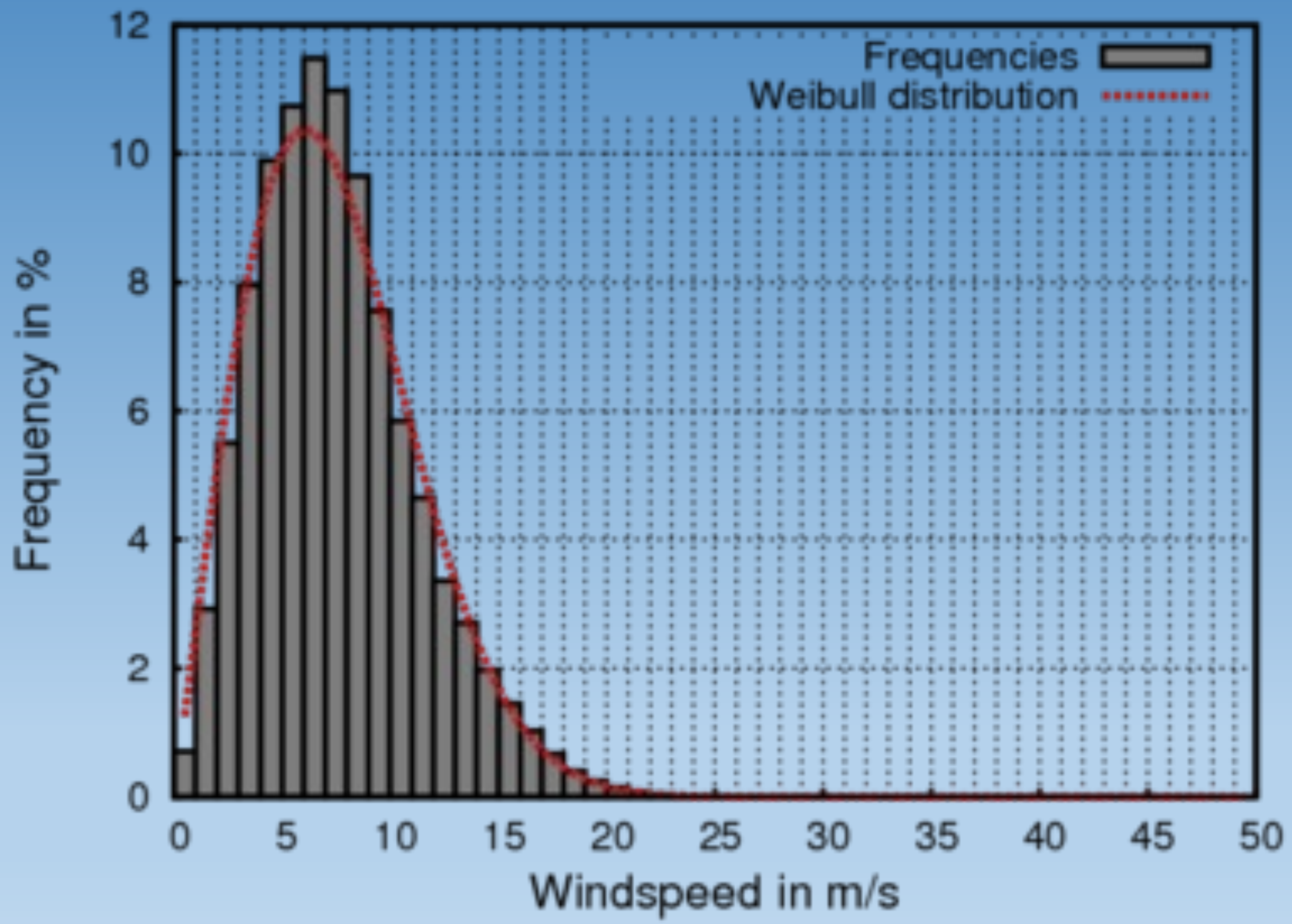


Figure 2.29 Example Weibull distributions for $\overline{U} = 8$ m/s

- The Weibull Distribution is based on two parameters:
  - K= Shape Parameter
  - A or C = Scale Parameter
- The Rayleigh distribution can be used also to represent long term wind variations. It is a Weibull distribution with k=2

Fitting a Weibull Distribution to wind data

- To calculate the Weibull Parameters for a measured wind regime various methods exist. The most common ones are:
  - Graphic Method (Least Square)
  - Maximum Likelihood Method
  - Moment Method (WAsP)



Wind Atlas

- Having a wind atlas available is important for potential site selection and preliminary planning
- Resolution and uncertainty of the results not enough when project planning goes to advanced stage
- Validation against measurements is crucial. Measurements should be:
  - accurate
  - representative
  - reliable

Wind atlas from 2009 for Finland

www.windatlas.fi
www.tuuliatlas.fi

NOTE: New European Wind Atlas NEWA more updated data

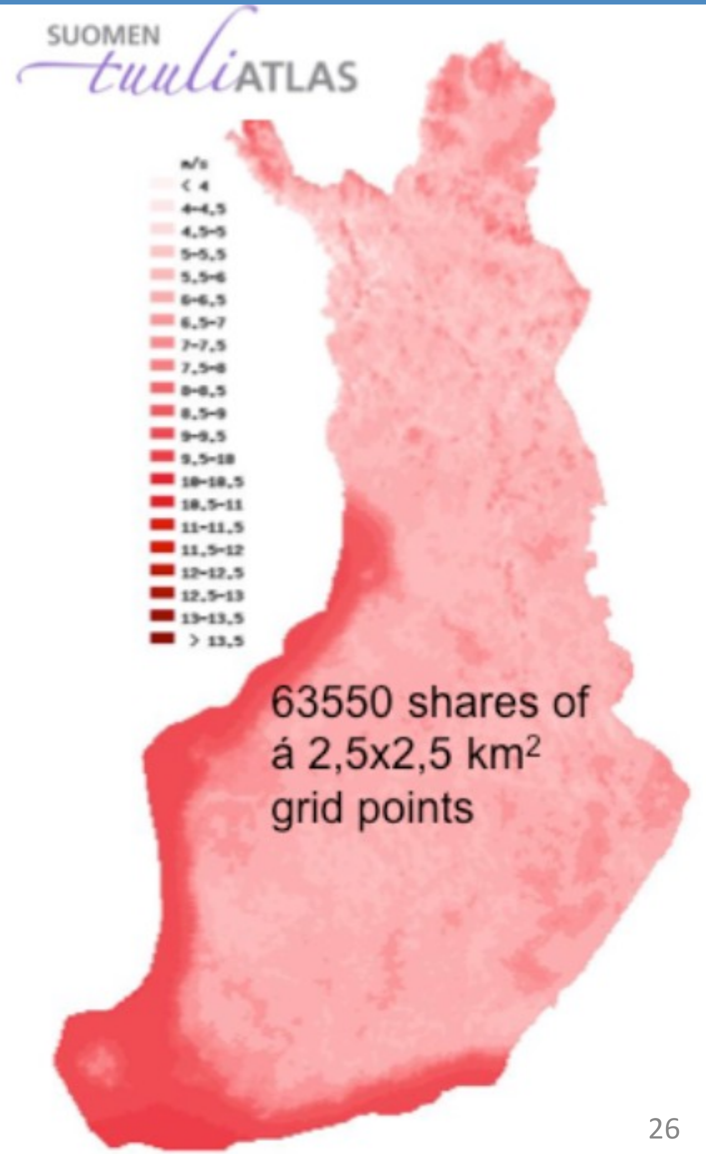
Wind atlas is a tool for estimation of potential wind energy resources (m/s and MWh). The output was planned to also the needs of land use planners.

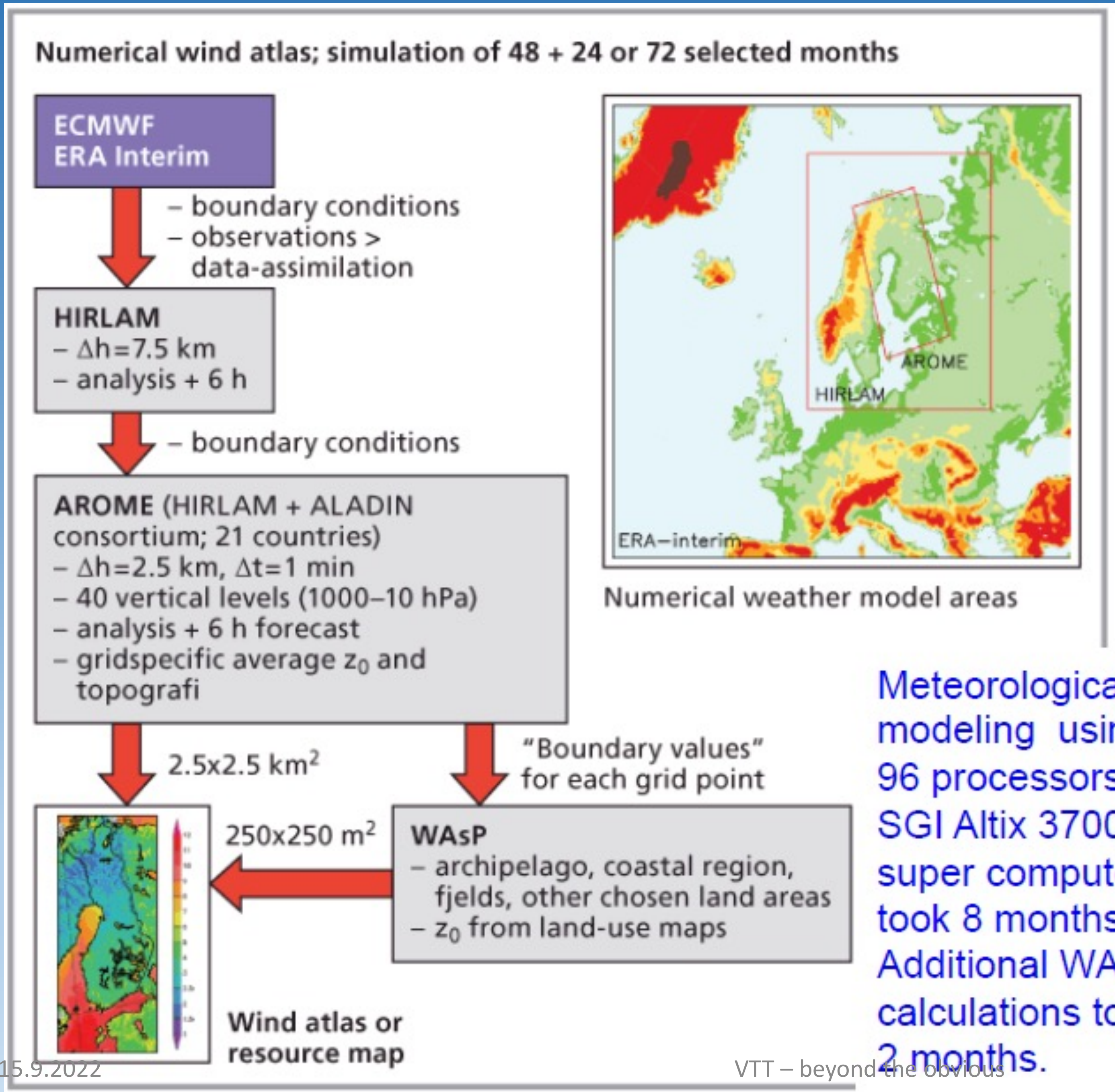
The new Finnish Wind Atlas gives in 2,5x2,5 km^2 grid resolution monthly and annual values of

- wind speed (m/s)
- Weibull A and k
- share of stable situations
- turbulence intensity
- air temperature (ºC)
- gust factor
- max wind W50
- production (MWh); 1MW, 3 MW, 5MW
- differences between average and max&min "years"

at 50, 75 , 100, 125, 150, 200, 300 ja 400m in 12 wind direction sectors.

In 250x250 m^2 grid m/s, A&k, MWh

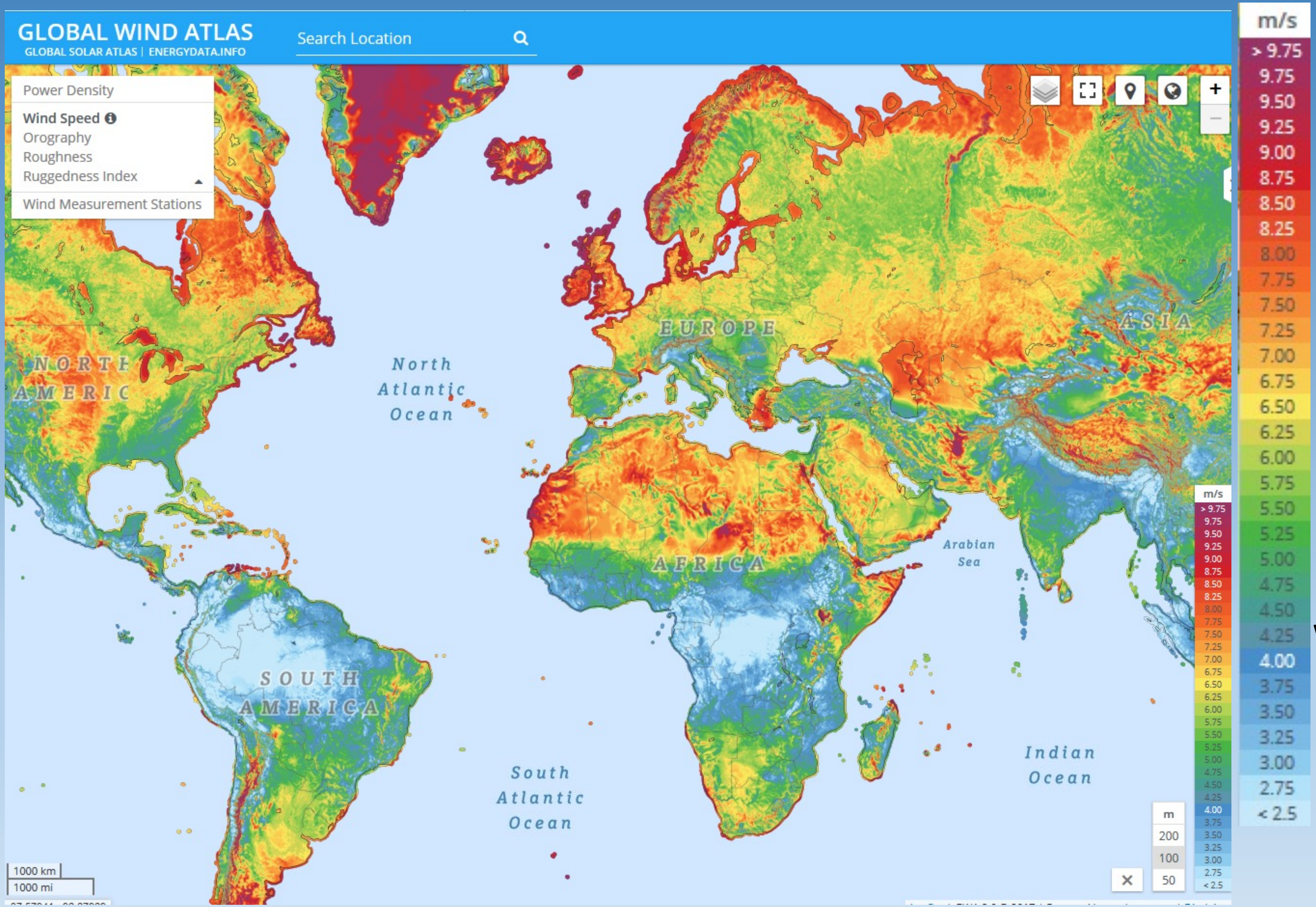




Meteorological modeling using 96 processors of SGI Altix 3700 super computer took 8 months. Additional WAsP calculations took 2 months.

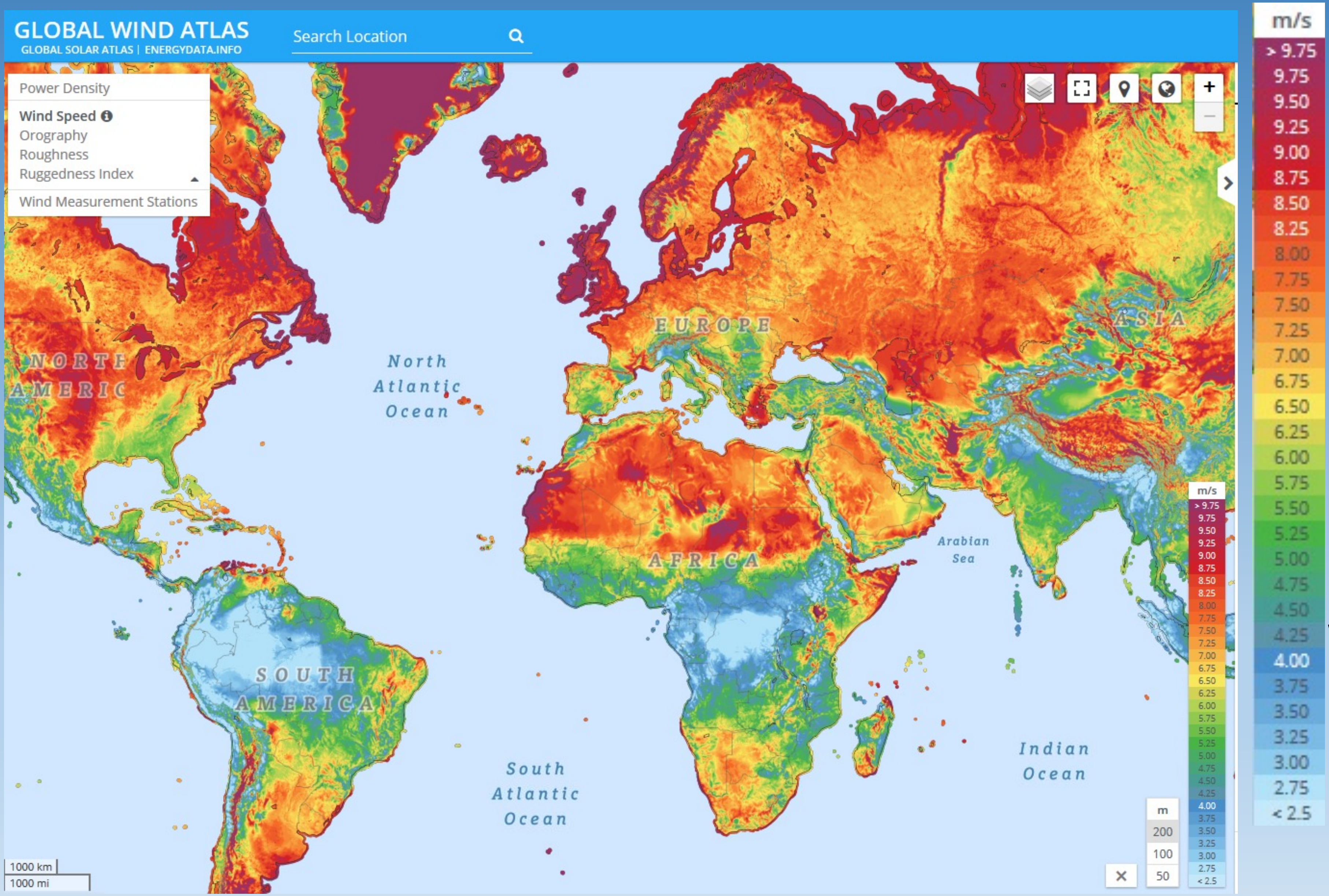
www.windatlas.fi

https://globalwindatlas.info/



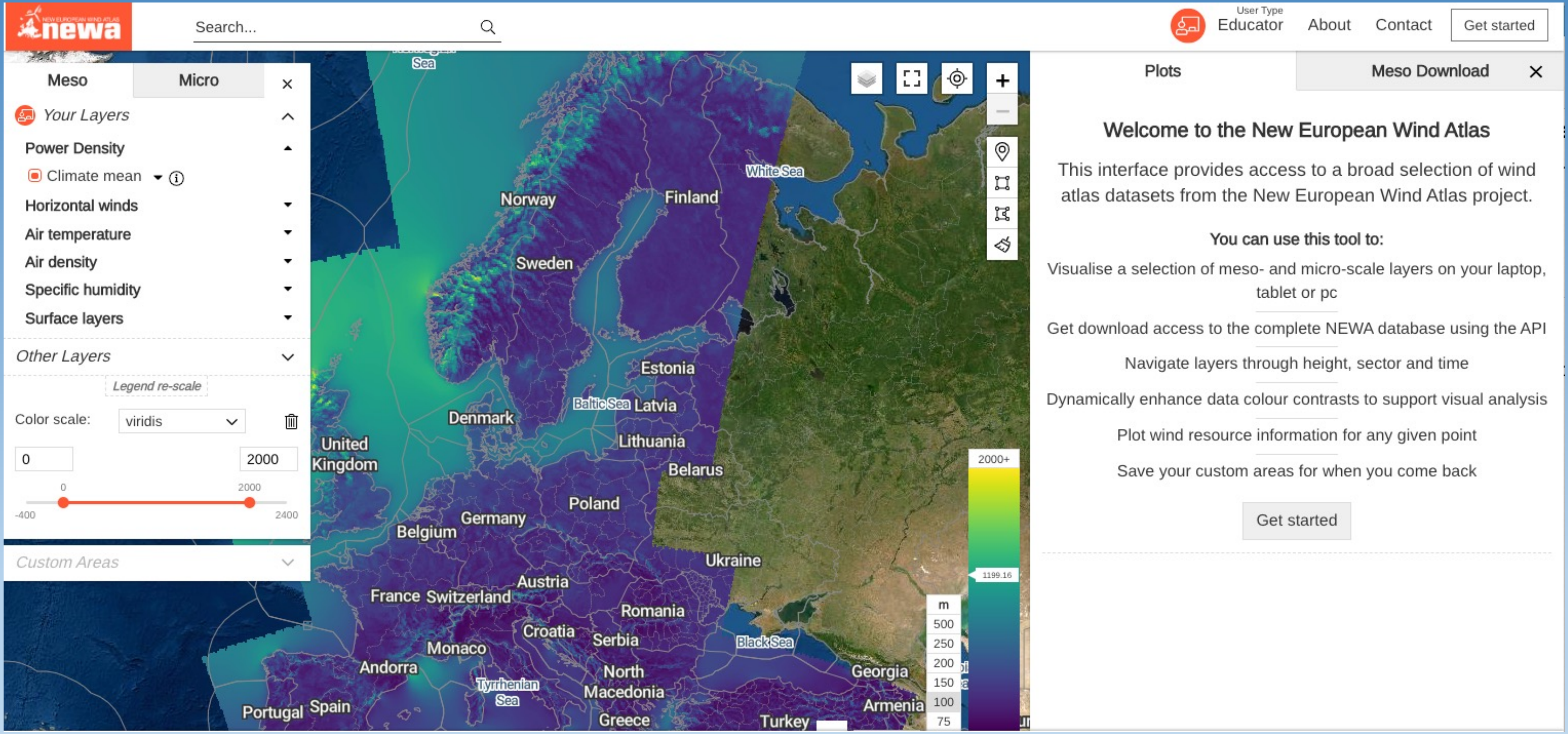
Wind speed at 100m

https://globalwindatlas.info/



Wind speed at 200m

New European wind atlas - NEWA



https://map.neweuropeanwindatlas.eu/

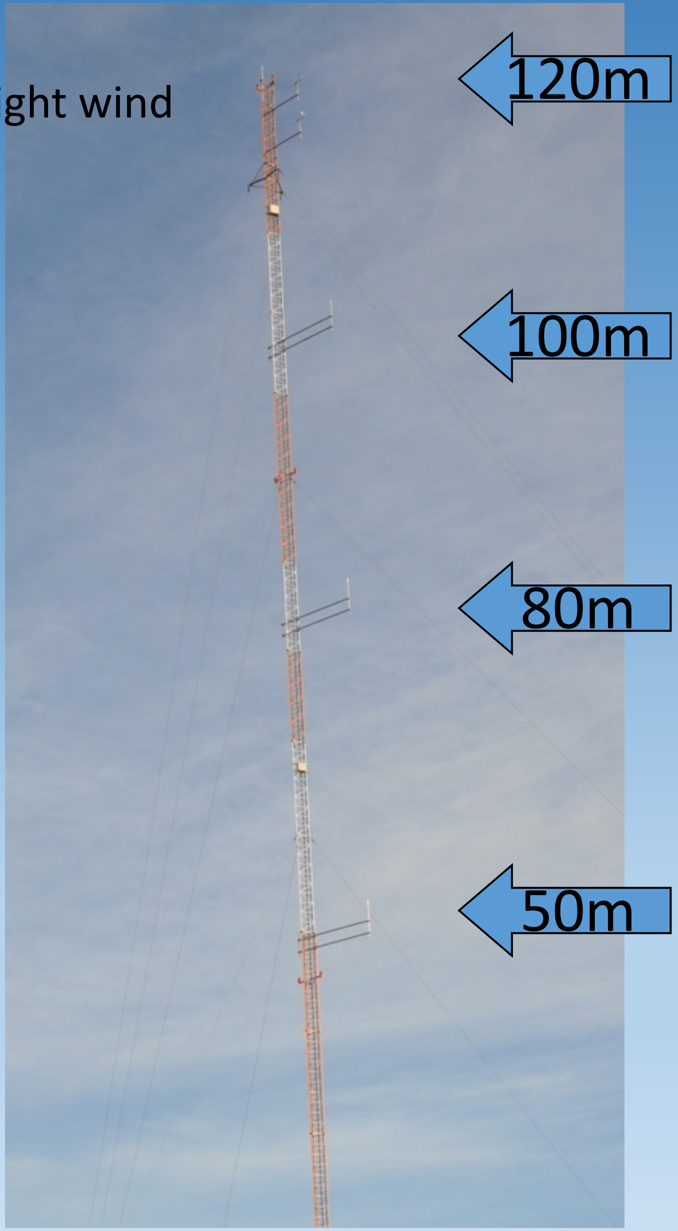
Estimating wind

Wind measurements

Wind measurements with Multiple Levels

- Vertical Profiles
  - Wind speed → shear
  - Direction → veer
  - Temperature → stability
- Backup in case of failure

Hub height wind



Cup Anemometers

- Measures the scalar wind speed
- Classification
- Calibration
- Heating: shaft or fully!

Vaisala 252

- Wind vanes for wind direction measurements

Thies first class

NRG 40

Sonic Anemometers

- Sonic anemometers measure the wind velocity by sensing the changes in the speed of sound in air.
- It can measure the wind vector (3D) or the component of the wind vector on the horizontal plane (2D)

+ Direction included

+ No moving parts

+ Extremely fast sample rate (good for turbulence studies)

+ Heating is easier to implement than in cups

- More costly than cup anemometers

2D

3D

Mast alternatives

LATTICE TOWER

+ Climbable

+ Easier maintenance

+ Sensors check up and replacement

+ Stronger structure (ice weight)

+ Allows high measurements (h>100m)

- Expensive

- Higher horizontal separation needed for sensor mounting

TUBULAR MAST

+ Lighter

+ Cheaper

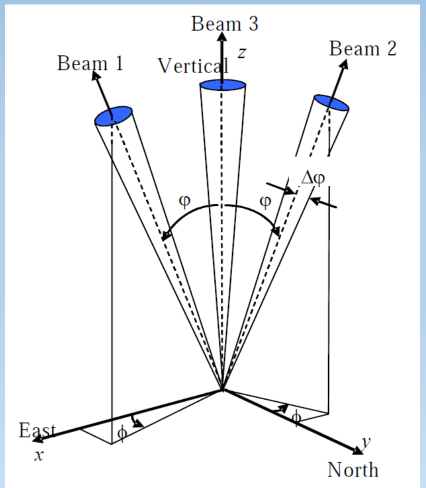
+/- Visual impact

- Maintenance allowed only by pulling it down

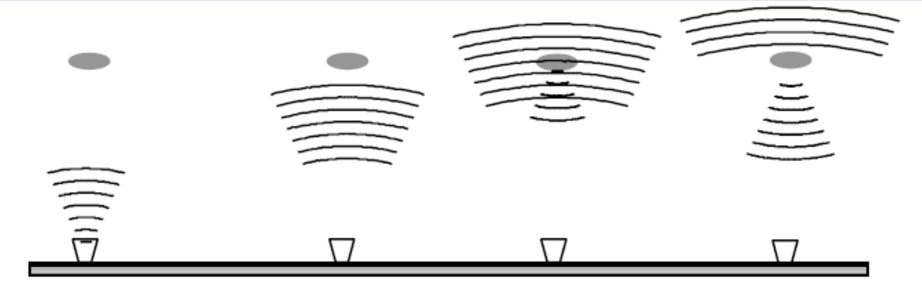
VTT

Remote Sensing - Sodars

- Wind vector measurement by sending and receiving successive pulses of sound
- Scattered sound from turbulent temperature variations
- Doppler effect in the backscattered signal
- Several measurement height from 10m up to 300m for wind energy application



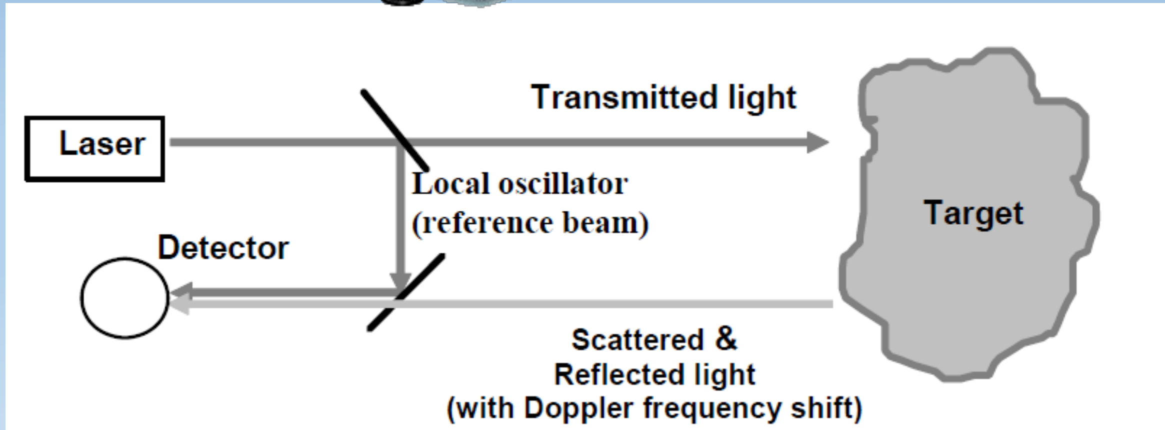
+ Cheap ≈ €40 k, (Finland need cover, ≈ €50…70k)



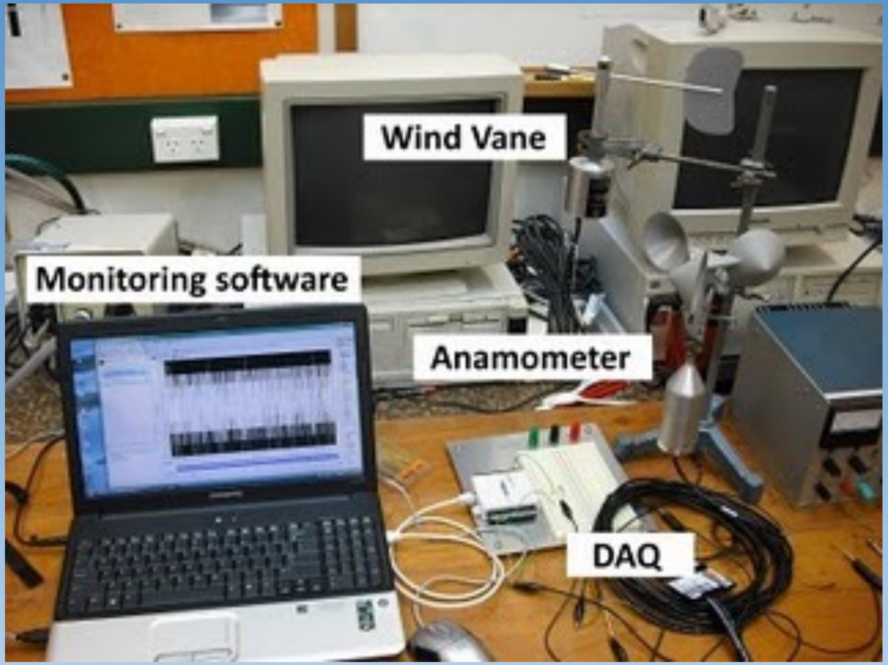
Remote Sensing - Lidar

- Wind vector measured by sending beams of light and detecting the Doppler shift in the backscattered signal from the atmosphere
- Scattered light from aerosol

+ Silent
+ No background noise problems
+ Precise and Accurate
+ Only option in offshore
- Expensive ≈ €100 k



Data Acquisition and Collection



Computer

+ Flexible

+ Full control over the measurements
  (averaging time, output format…)

+ Remote Desktop connection

- Expensive (hut and power needed)

Data Backups, ups, local support to enhance reliability!

Data logger

+ Cheaper

+ Stand alone

+ GSM connection
  (data by e-mail)

- Limited in the number/type of sensors and type of measurements

- Icing conditions??

Two Groups of Wind Modeling Tools

<u>Linear models</u>

+ Fast and simple

+ Wind industry standard

- Not good for “complex terrain”

- Usually embed other modules for comprehensive project planning (noise, visual impact,…)

• Examples: WAsP, WindPro, Windfarm

<u>CFD (Computational fluid dynamics)</u>

+/- Advanced/Complicated

+ CFD codes adapted to atmospheric flows

+ CFD is a well established technology. Application to wind energy is quite new.

+ Good for complex sites

+ Turbulence

- Requires very experienced users for good results

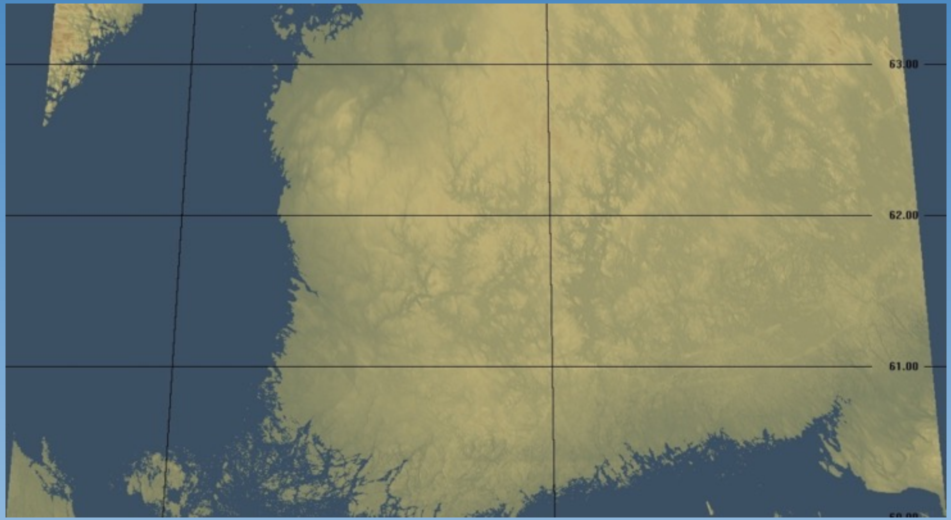
▪ Examples: Windsim, Meteodyn, In-house codes

Simple Terrain

Complex Terrain Regions

Input data other than wind

GIS = big help

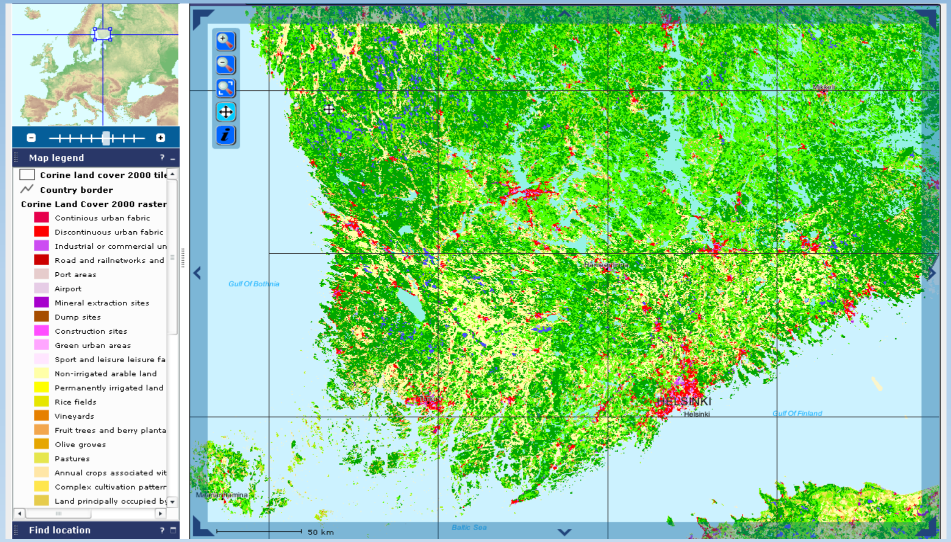


Elevation Data:

- Height Contours or Gridded
- Manual digitalization
- Digital terrain model from National land survey(s)
- SRTM data (Shuttle Radar Topography Mission) only at Lat < 61º

Roughness Data:

- From National land survey(s) satellite images
- Corine Land Cover

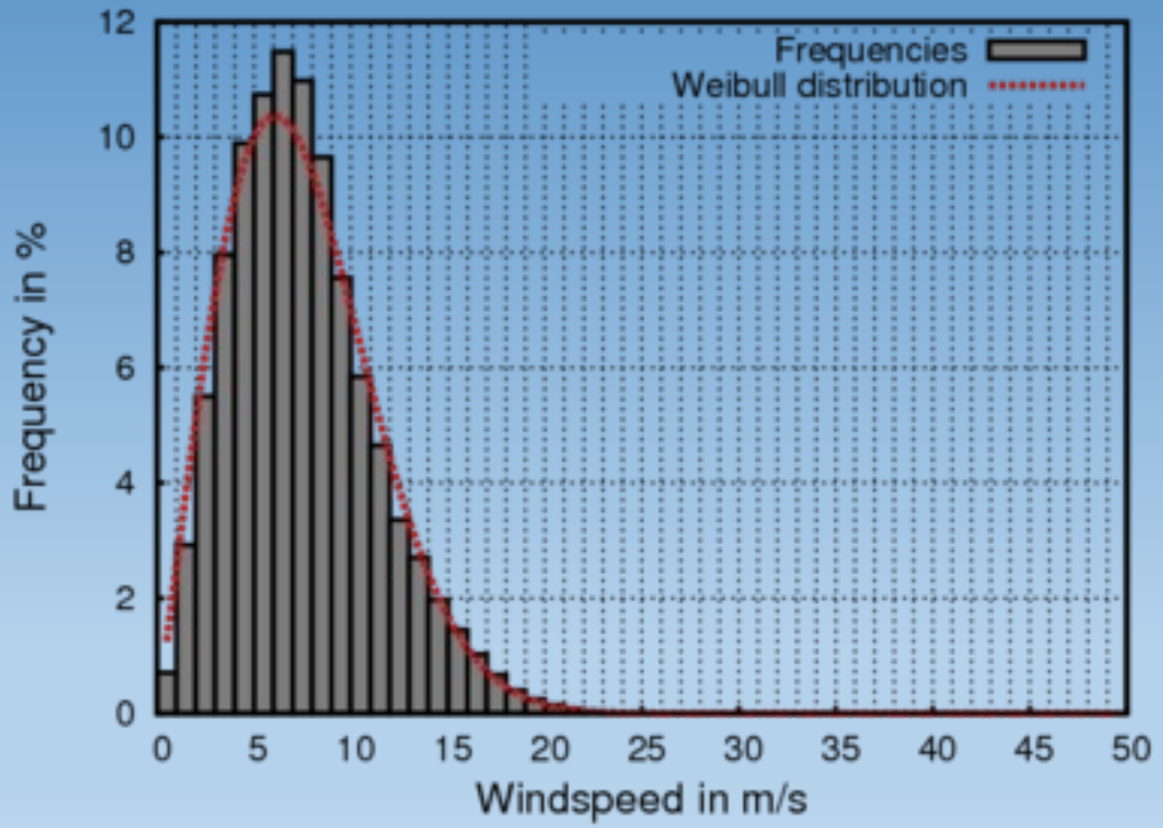


VTT

Estimating wind energy generation

From wind to power/energy

From wind speed distribution to wind energy



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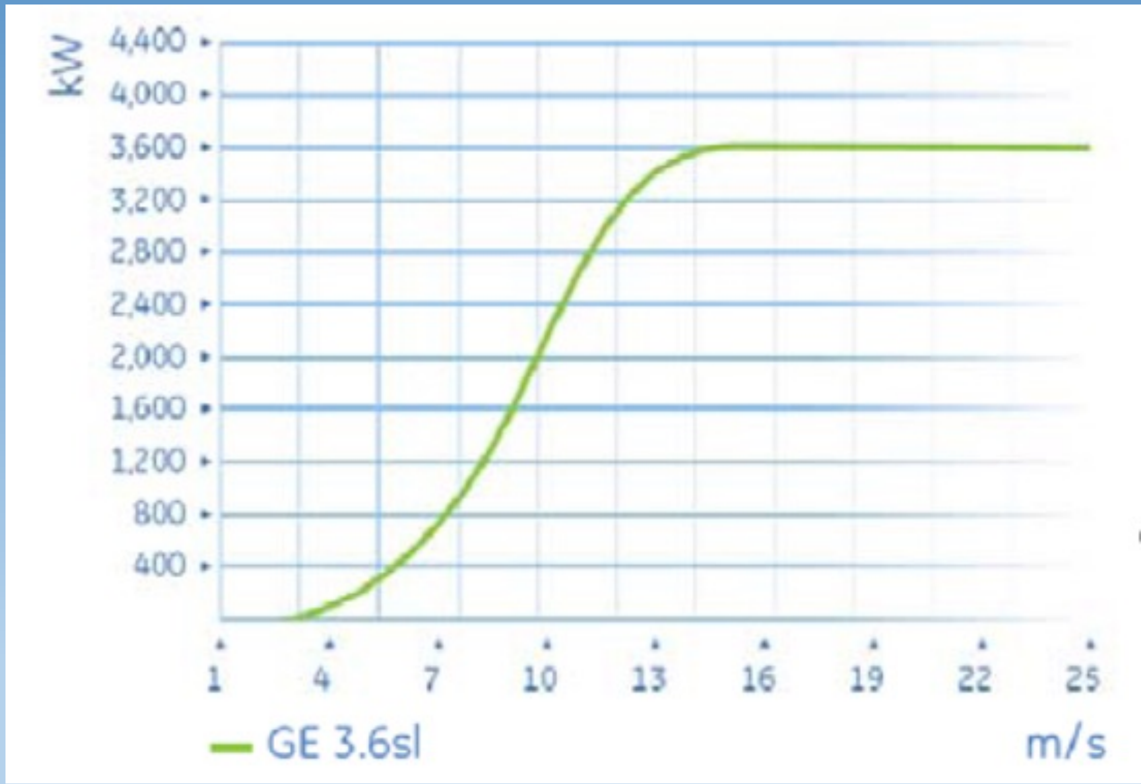
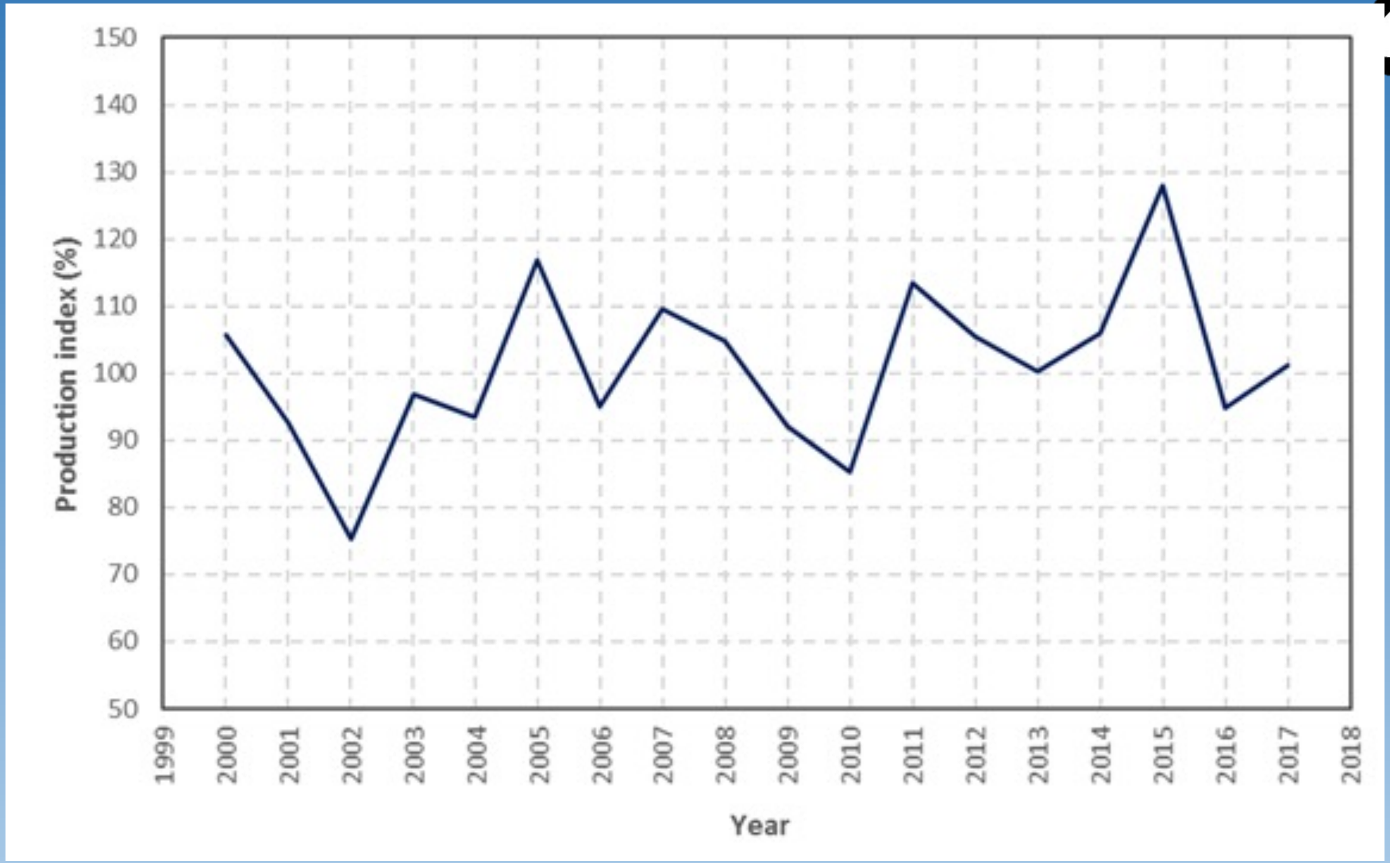


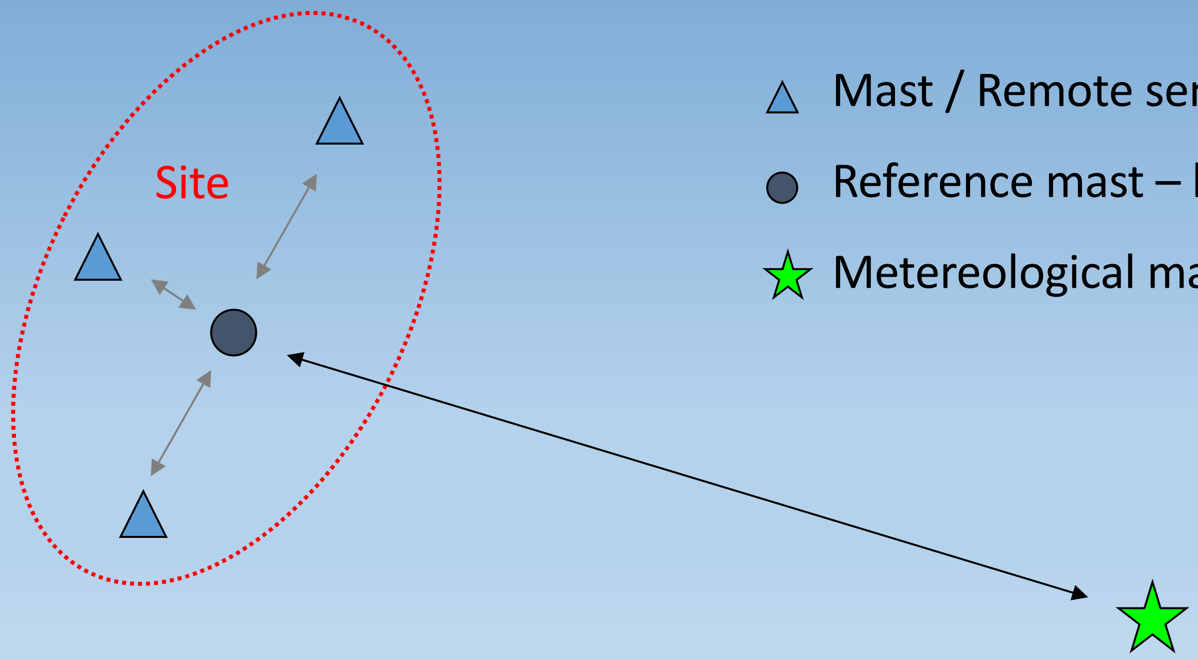
Long term assessment = looking backwards



- Average wind conditions varies year by year
- We need a wind distribution as representative as possible of the wind conditions that the wind farm will face during its operational life
- MCP technique can be used to establish a prediction of the longterm wind resource

MCP: Measure-Correlate-Predict

- MCP technique can be used between the reference mast and other measurement points



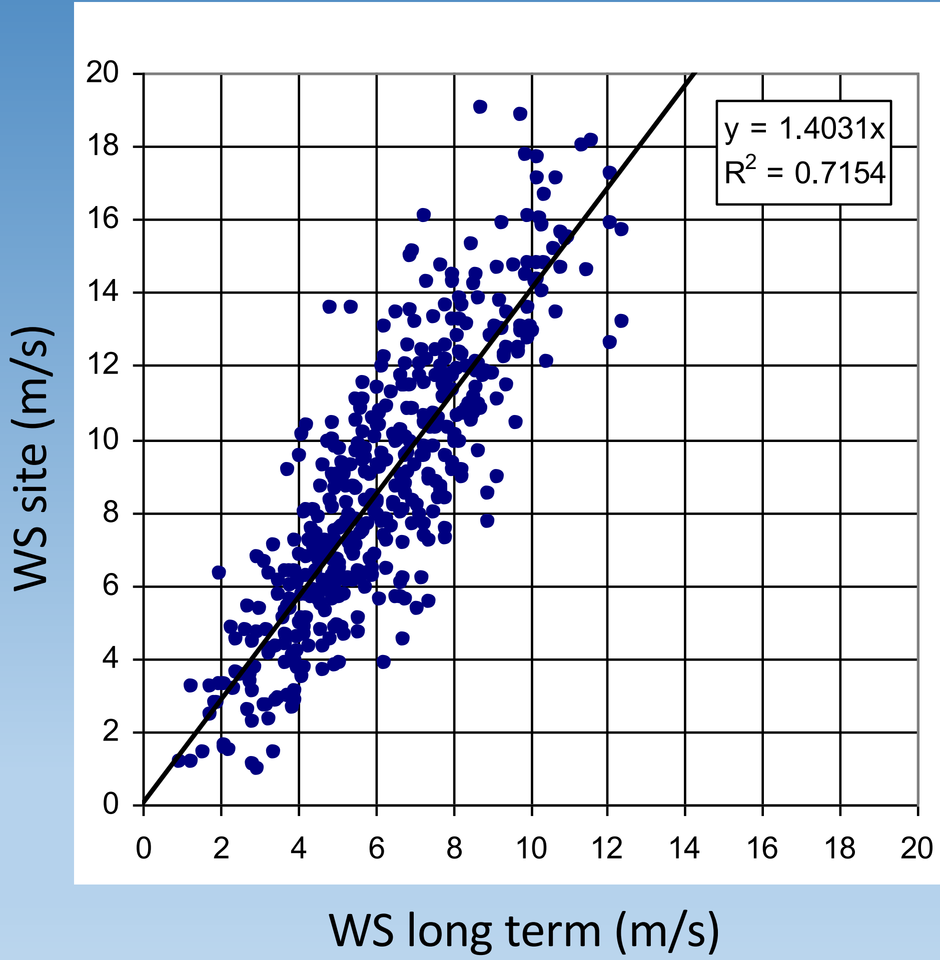
△ Mast / Remote sensing – shorter measurements

● Reference mast – longer measurements

★ Metereological mast – ~20 years of data

Shorter measurement period: MCP Measure-Correlate-Predict

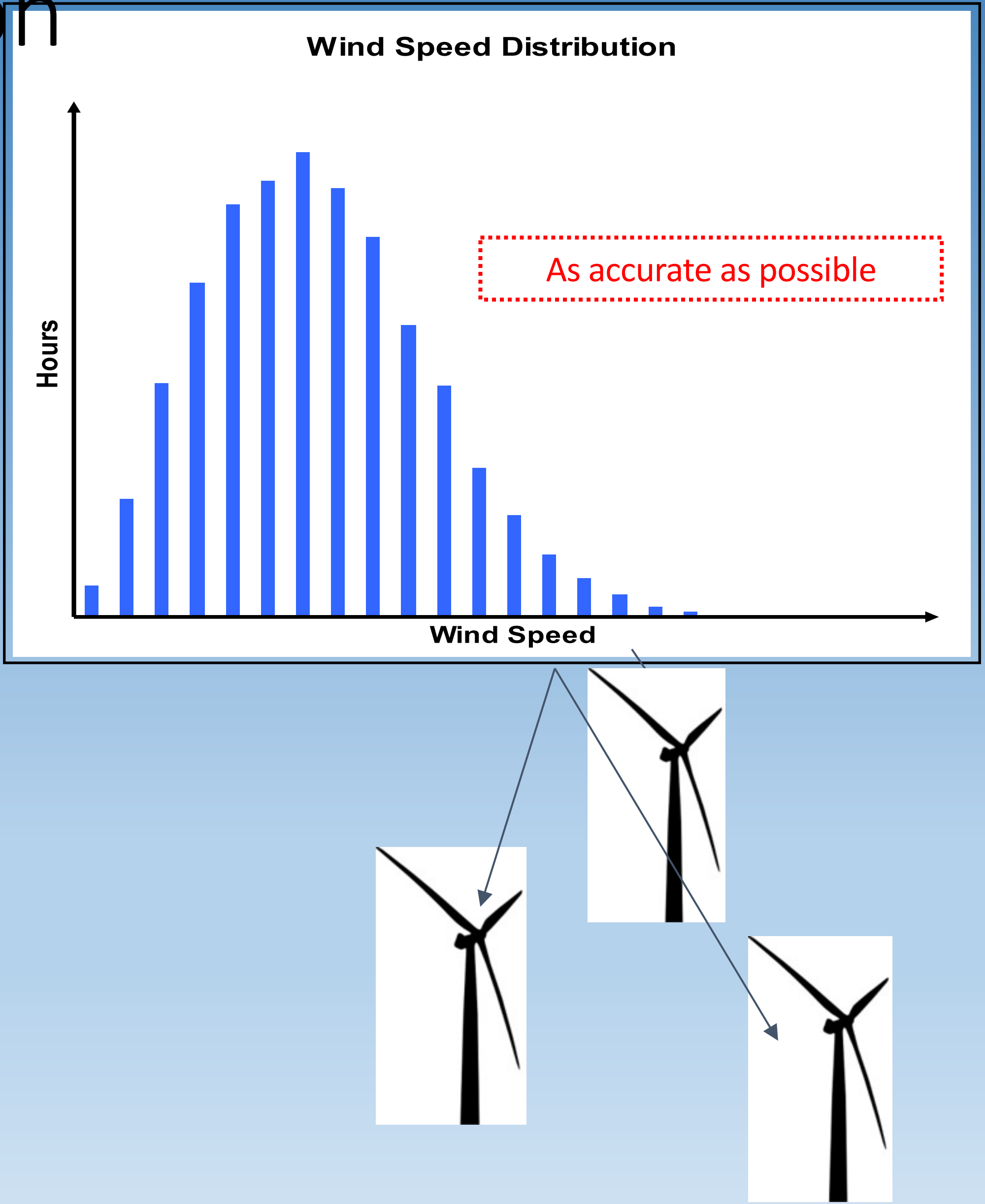
- The MCP approach is based on taking a series of measurements of wind speed at the wind farm site and correlating them with simultaneous wind speed measurements made at a meteorological station
- Linear regression used to establish a relationship between the measured site wind speed and the long-term meteorological wind speed data
- Same averaging time (10 min, 1 h, 1 day)
- Metereological station representative of the wind climate at the site
- Directional bin-wise MCP analysis (12 sectors - 30° wide)



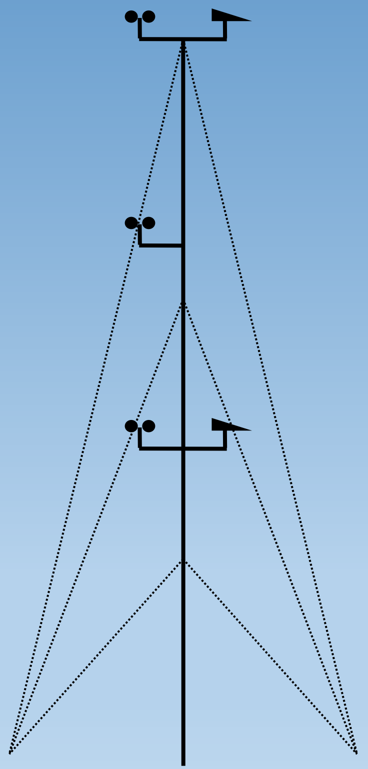
$$U_{\text{site}} = a + bU_{\text{long-term}}$$

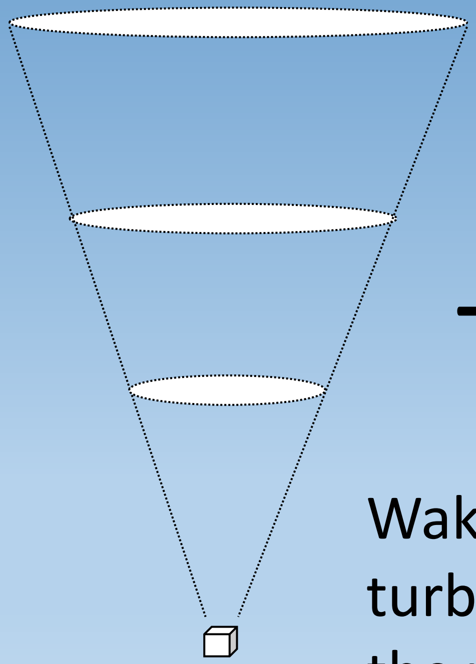
Project Feasibility: From Potential Site identification to Micrositing

- A potential site is identified by looking at:
  - Preliminary wind resource analysis
  - Enviromental impact
  - Engineering standpoint
  - Public acceptance
- Once a potential site has been identified then more detailed, extensive and expensive, investigations are required in order to confirm the feasibility of the project.
- The wind farm energy output, and hence the financial viability of the scheme, will be very sensitive to the wind speed seen by the turbines over the life of the project.



This is possible with a good combination of on-site wind measurements and wind modelling…





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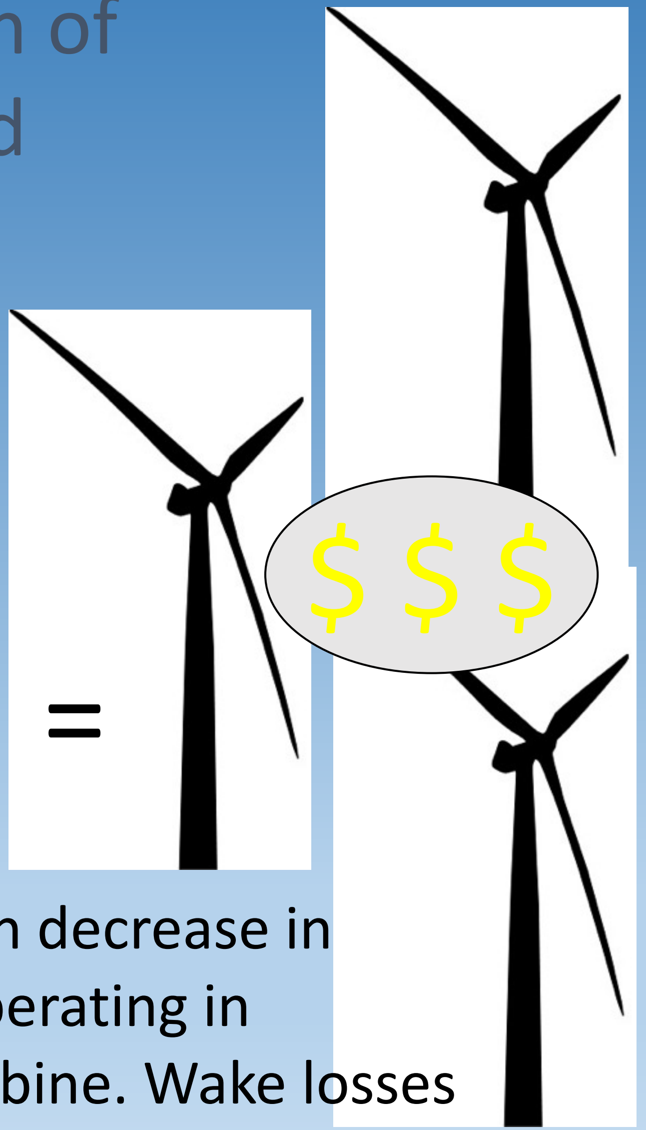


Wake effect – how much decrease in turbine output when operating in the wake of another turbine. Wake losses as well as other losses due to availability, icing,… calculated for all turbines in a wind farm

Summary

Summary: Wind Measurements

- IEC 61400-12-1 compliant
- Near hub height masts
- Classified anemometers
- Sufficiently heated anemometers for icing conditions
- High quality sensors
- Calibrated sensors
- Good mounting
- Good data acquisition
- Experienced data analysis

…and as a support:

- Remote sensing (Lidars, Sodars)
- Modeling (MCP, CFD, WAsP)

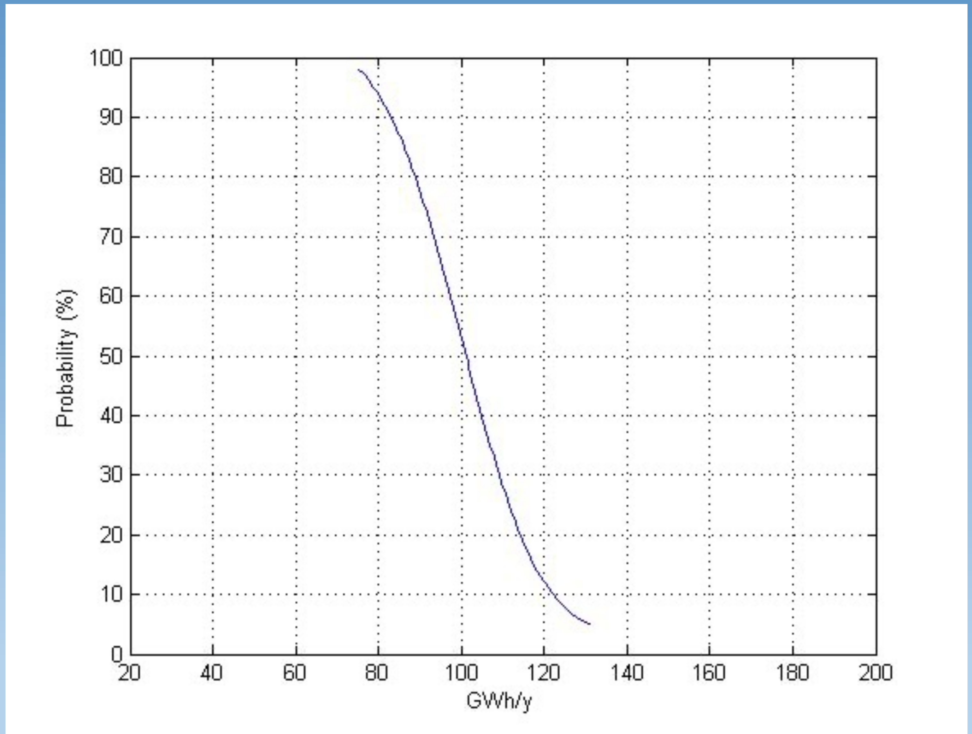
An example, moderately complex terrain, consequences of too much saving money : save 50.000 $ on measurements for a 100.000.000 $ project

Saving money=>Uncertainties

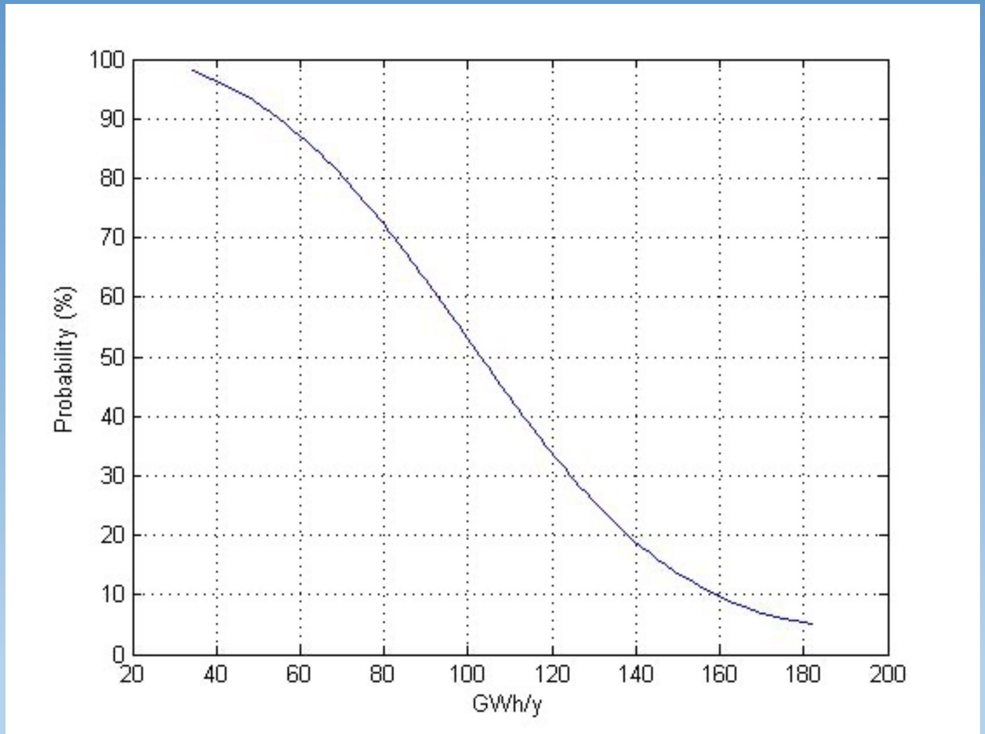
- Don’t calibrate anemometers, 10%
- Masts too low, 25%
- Poor maintenance, data less than a year, 15%
- Unprofessional analysis ”based on our experience, speed-up factor for this hill will be 8%”, we do not need models. 25%
- TOTAL uncertainty = 40%

Good Assessment Uncertainty =15%

Bad Assessment Uncertainty = 40%



Probability of exceedance	
P50	100 GWh
P75	89.9 GWh
P90	80.8 GWh



Probability of exceedance	
P50	100 GWh
P75	73.0 GWh
P90	48.7 GWh

How much did we save?

- Revenue calculated 15 M$/y
- 40% uncertainty:
  - 75% probability of reaching 11 M$/y or more
- 15% uncertainty:
  - 75% probability of reaching 13.5 M$/y or more
- We saved 0.05 M$, lost 2.5 M$/y of selling price potential

“Who would make money must begin by spending it”

Summary of today

- What you need to measure/estimate for wind power projects
- How you make wind resource estimates
- What is important to take into account to get accuracy

References

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Thank you for your attention

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