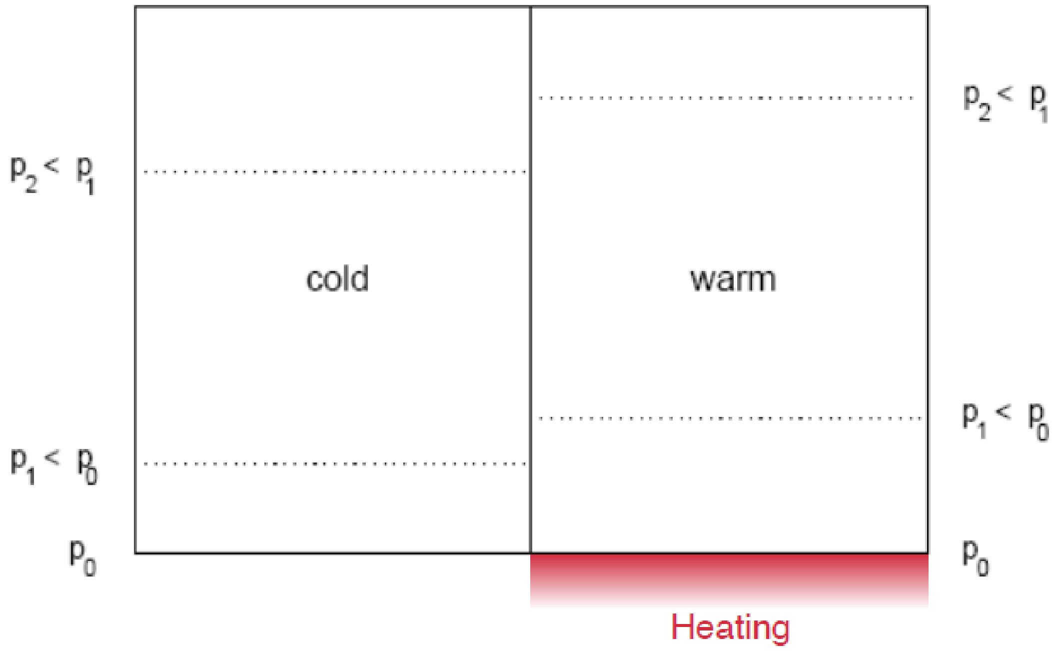
Generation of available potential energy and kinetic energy

Concept of Differential Heating



1

Two (initially identical) air masses are separated by a wall and heated differently

—> horizontal gradients of p, ρ, T establish across the wall

2

Removing the wall:

—> rearrangement of the air masses ("warm on top of cold")

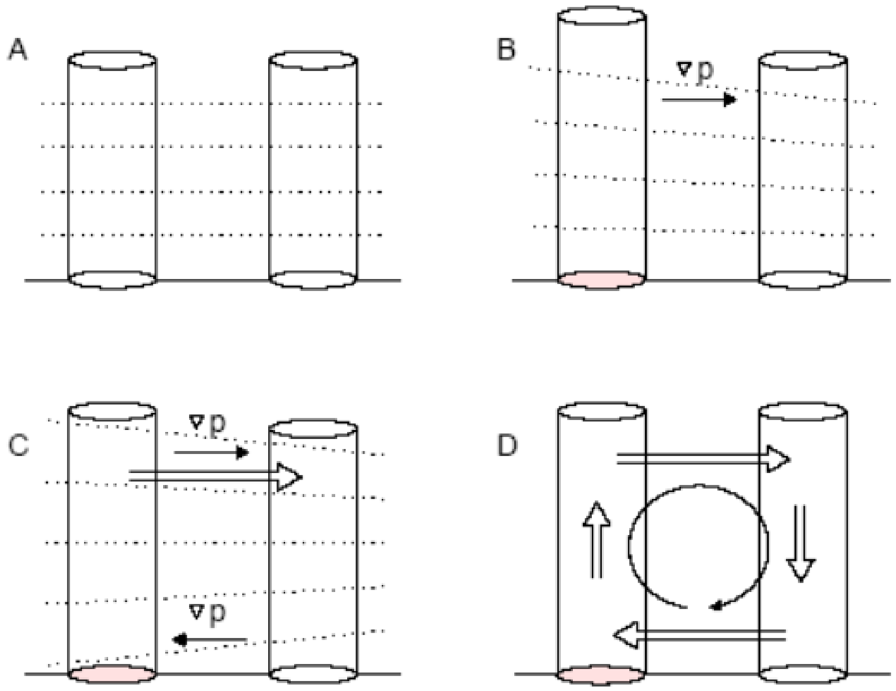
—> stable hydrostatic balance

3

Difference between total potential energy at start- and at end-point of rearrangement:

—> available potential energy which can be converted into kinetic energy

Development of a wind system



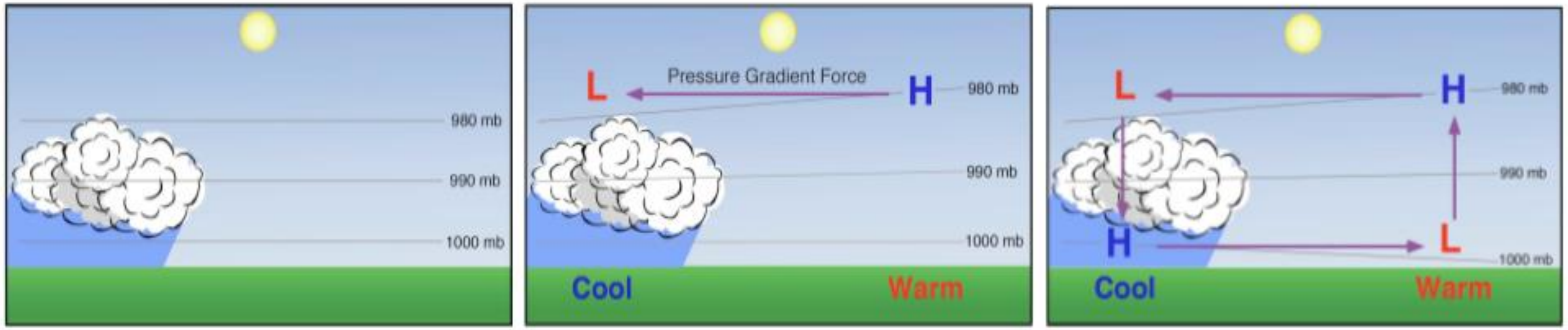
A. Two columns of air are in **hydro-static equilibrium** each. The air is in rest.

B. **Differential heating** causes the temperature of the left column to rise and a horizontal pressure gradient between the two columns in larger heights establishes.

C. This results in a **horizontal wind flow** directed towards lower pressure and thus produces a horizontal pressure gradient (and a wind flow) at the surface in the opposite direction.

D. Due to the conservation of mass **vertical motion of air** is neces-sary to close the circulation.

Formation of a thermal circulation system



(A)

Unequal heating of the Earth's surface and lower atmosphere

(B)

Isobars over the heated area spread apart because of convection and air expansion

—> horizontal pressure gradient in the upper atmosphere

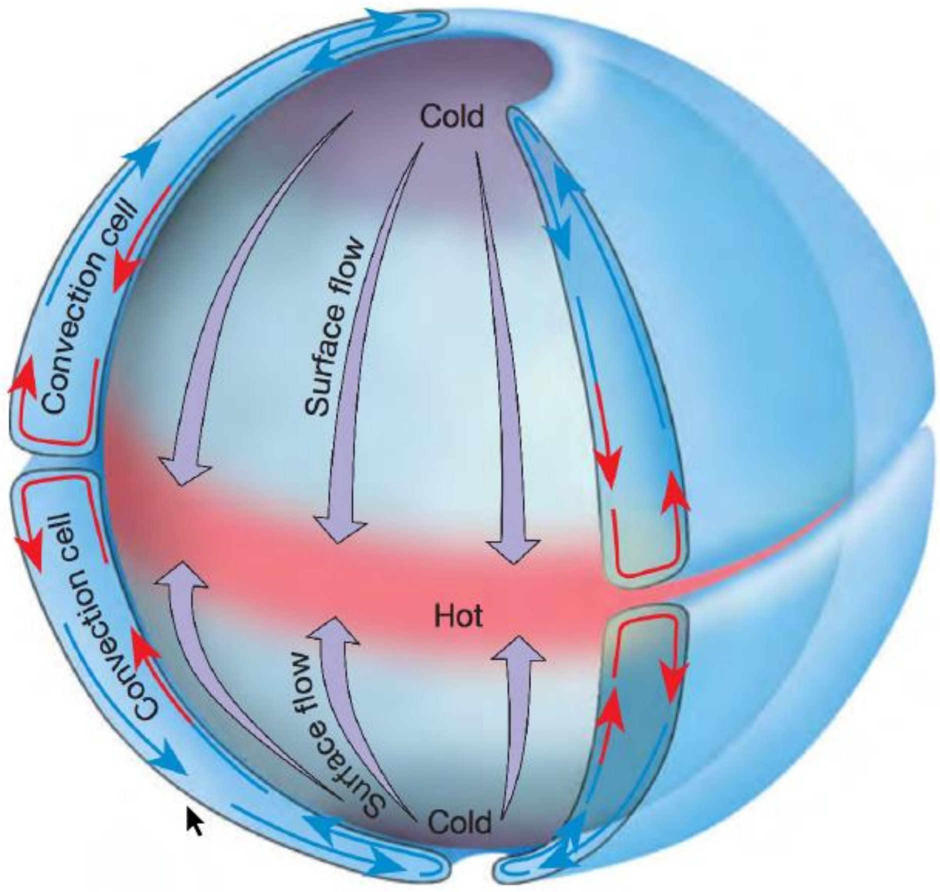
—> horizontal flow of air in the upper atmosphere

(C)

Air flow patterns in the vertical and near the ground surface completing the circulation system

Source: Pidwirny (2006), http://www.physicalgeography.net/fundamentals/7o.html

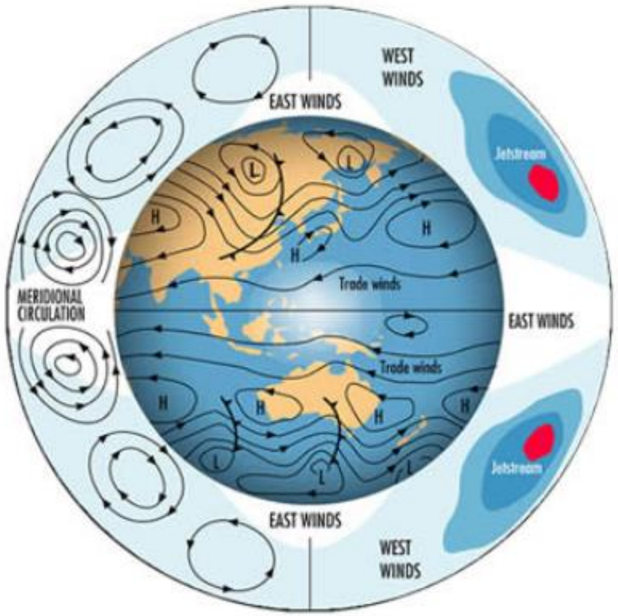
Global atmospheric circulation



Source: Lutgens & Tarbuck: The Atmosphere (2013)

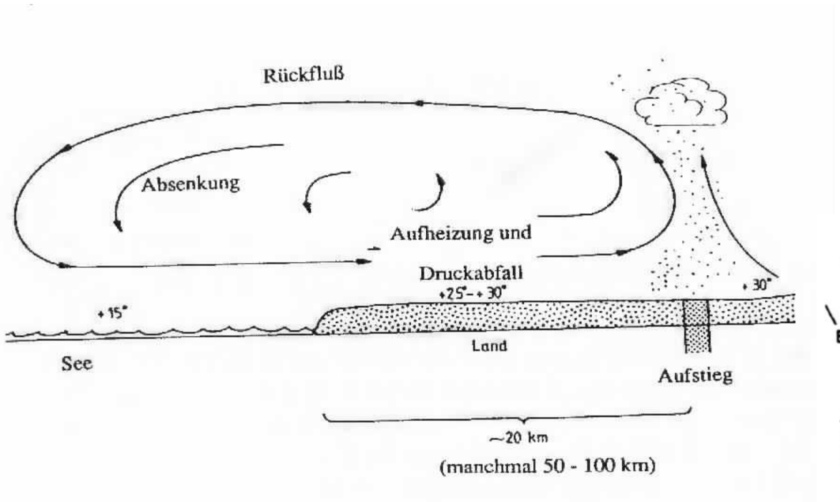
Assuming a non-rotating sphere with uniform smooth surface characteristics:

Simple convection system resulting from differential heating of the atmosphere

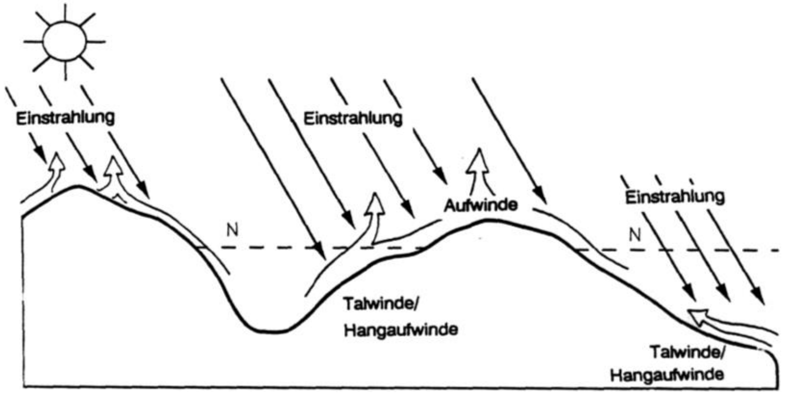


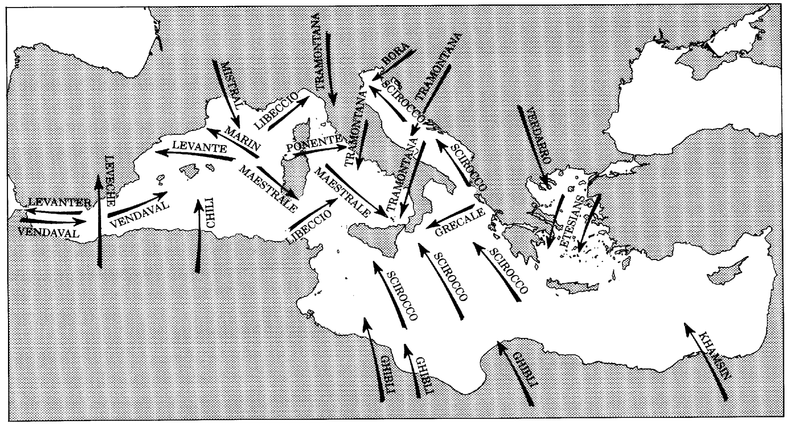
Further effects… in addition to differential heating

- Coriolis force
- Land / sea breeze
- Mountain and valley winds, impact of orography and surface roughness
- Regional wind systems



←→ Local wind systems





Exercise

Have a look at:

https://globalwindatlas.info/

https://map.neweuropeanwindatlas.eu/

– Find spots with (very) high and (very) low wind resources – why is this?

– Compare offshore and onshore regions

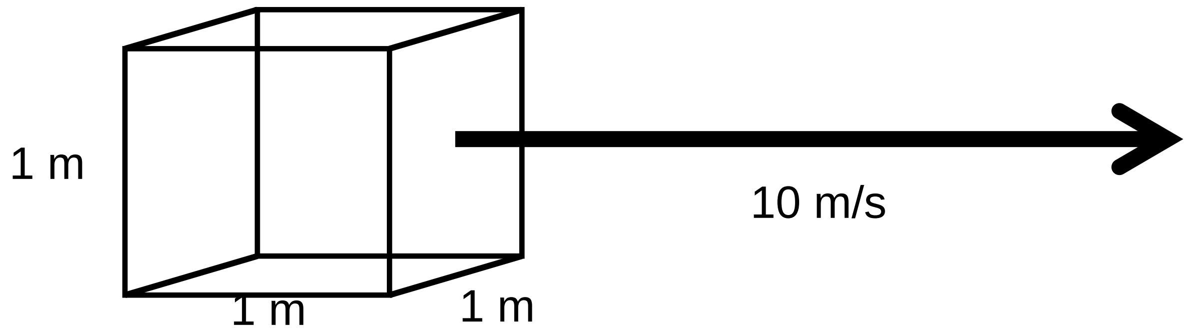
– Consider different altitudes

– …

– Collect further observations

Kinetic energy in a volume of air

- How much energy does wind contain?
- How much kinetic energy does a volume of 1x1x1 m³ air with the velocity of 10 m/s contain?



Kinetic energy in a volume of air

The mass m of air is	$m = \rho V$
Wind contains kinetic energy	$E = \frac{1}{2} m v^2$

m = mass

ρ = air density

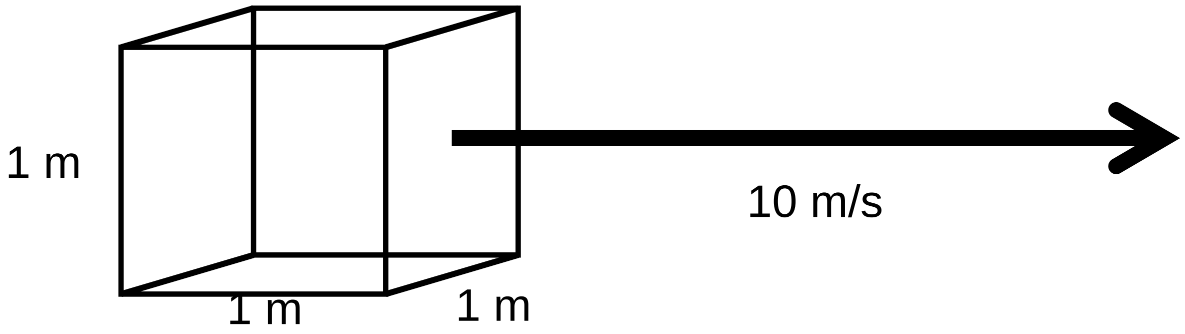
V = volume

E = kinetic energy

V = velocity

Kinetic energy in a volume of air

- How much energy does wind contain?
- How much kinetic energy does a volume of 1x1x1 m^3 air with the velocity of 10 m/s contain? (Assume air density of 1.2 kg/m^3)



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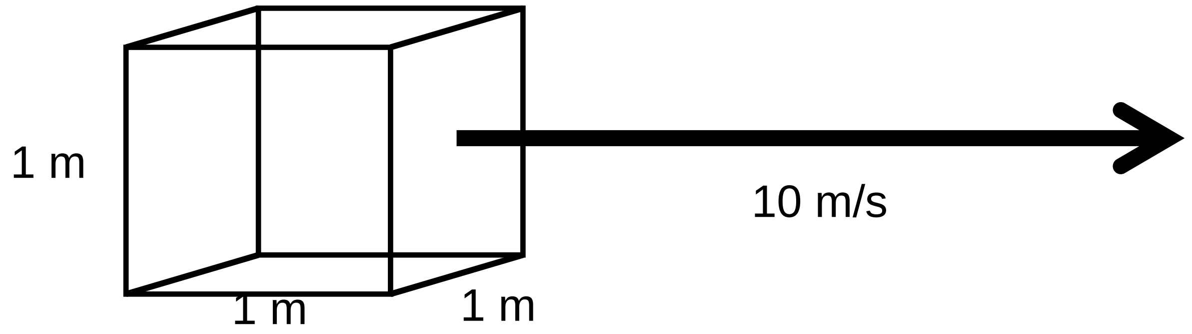
Wind contains kinetic energy $E = \frac{1}{2} m v^2$

Kinetic energy in a volume of air

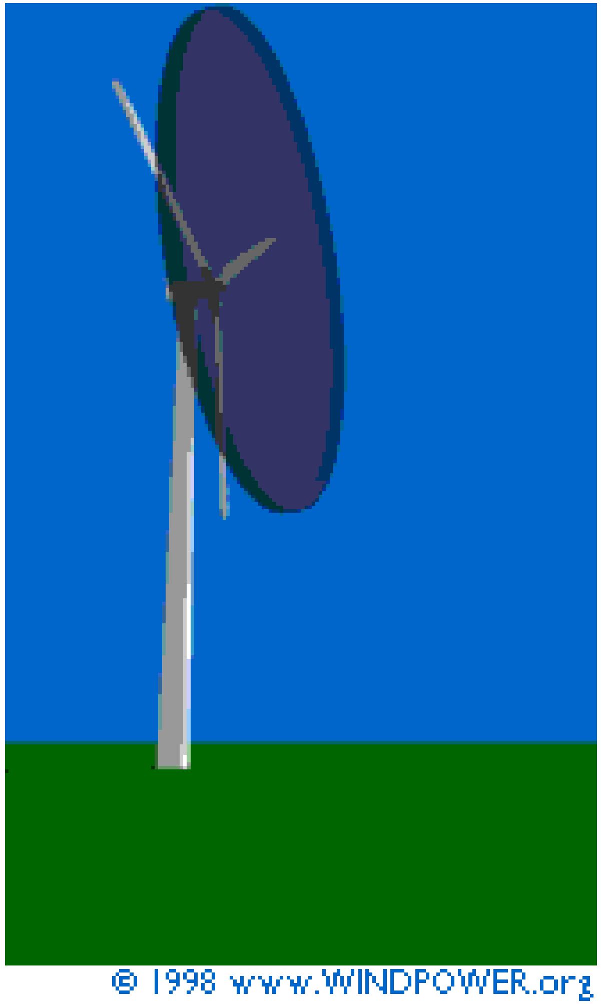
- How much energy does wind contain?
- How much kinetic energy does a volume of $1 \times 1 \times 1\ m^3$ air with the velocity of 10 m/s contain? (Assume air density of $1.2\ kg/m^3$)



The mass m of air is $m = \rho V = 1.2\ kg/m^3 \cdot 1\ m^3 = 1.2\ kg$

Wind contains kinetic energy $E = \frac{1}{2} m v^2 = \frac{1}{2} \cdot 1.2\ kg \cdot 100\ m^2/s^2 = 60\ J$

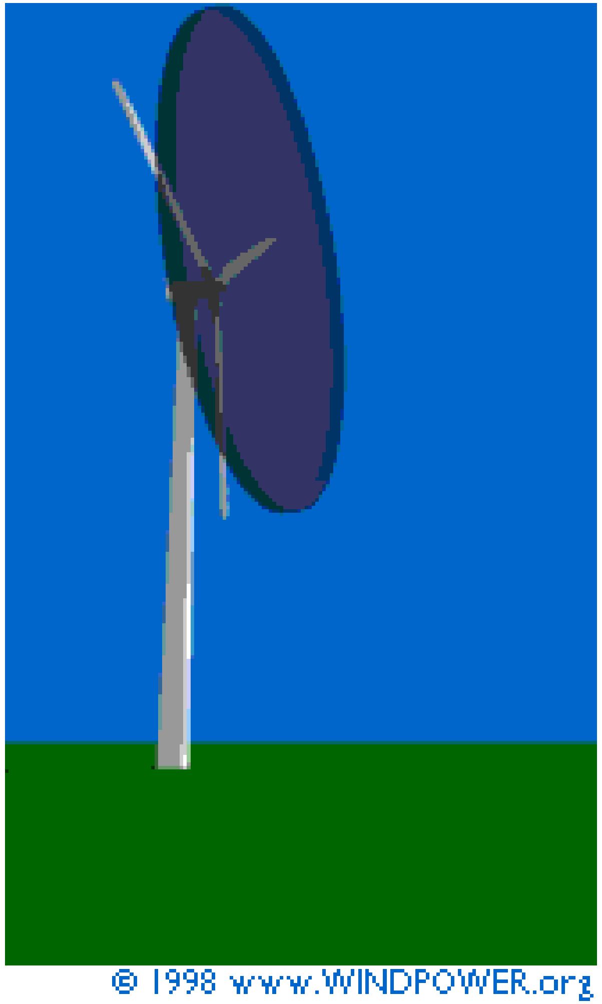
How much kinetic energy is in wind?



How much kinetic energy contains a 1-meter-thick air disc moving through a rotor plane? (Assume air density of 1.2 kg/m³ and rotor diameter of 100 m)

The mass m of air is	$m = \rho V$
Wind contains kinetic energy	$E = \frac{1}{2} m v^2$

How much kinetic energy is in wind?



How much kinetic energy contains a 1-meter-thick air disc moving through a rotor plane? (Assume air density of 1,2 kg/m^3 and rotor diameter of 100 m)

The mass m of air is $m = \rho V$

$= 1.2\ kg/m^3 \cdot \pi \cdot 2500\ m^2 \cdot 1\ m = 9425\ kg$

Wind contains kinetic energy $E = ½\ m\ v^2$

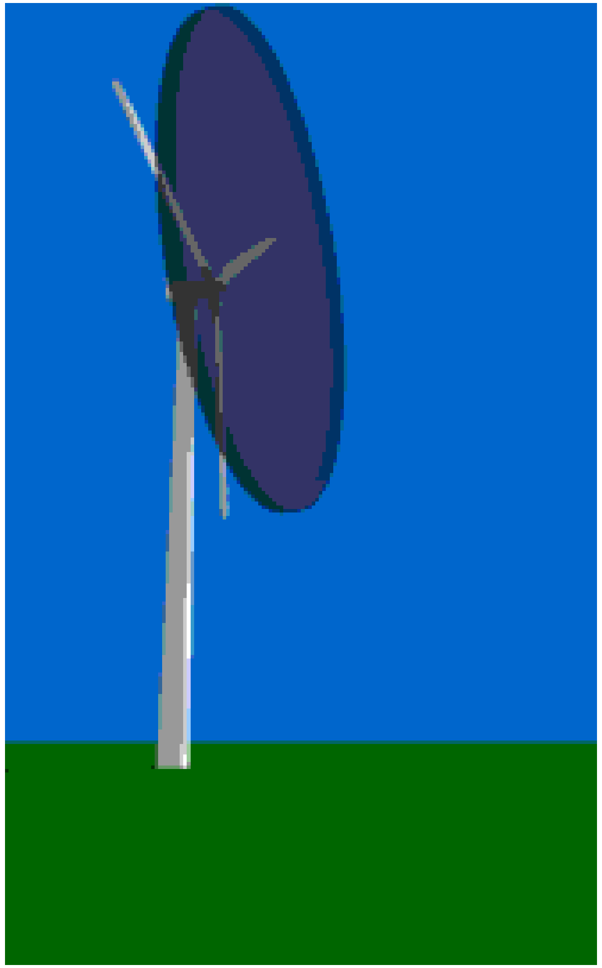
$= ½ \cdot 9425\ kg \cdot 100\ m^2/s^2 = 471$ J or W.s

Flow of kinetic energy (=power) through a rotor plane?

The mass m of air is	$m = \rho V$
Wind contains kinetic energy	$E = \frac{1}{2} m v^2$
Flow rate of air mass	$dm/dt = \rho A \, dx/dt = \rho A v$
Flow rate of energy (= power):	$P = dE/dt = \frac{1}{2} \, dm/dt \, v^2 = \frac{1}{2} \rho A v^3$

m = mass [kg]
ρ = air density [kg / m³]
V = volume [m³]
E = kinetic energy [J = kg m²/s²]
v = velocity [m/s]
A = area [m²]
x = distance [m]
P = power [W = kg m²/s³]

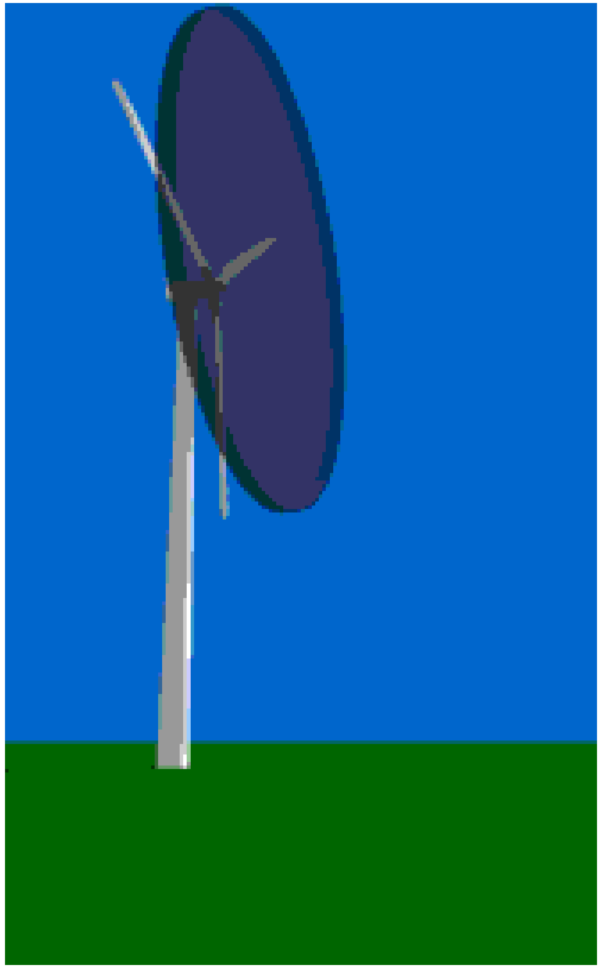
How much power through a rotor plane?



How much power is in the wind moving through a rotor plane? (Assume air density of 1.2 kg/m³ and rotor diameter of 100 m)

Flow rate of energy (= power): $P = \frac{1}{2} \rho A v^3$

How much power through a rotor plane?



© 1998 www.WINDPOWER.org

How much power is in the wind moving through a rotor plane? (Assume air density of 1.2 kg/m³ and rotor diameter of 100 m)

Flow rate of energy (= power): $P = \frac{1}{2} \rho A v^3$

$= \frac{1}{2} \cdot 1.2\ \mathrm{kg/m^3} \cdot 7854\ \mathrm{m^2} \cdot 1000\ \mathrm{m^3/s^3} = 4.7\ \mathrm{MW}$

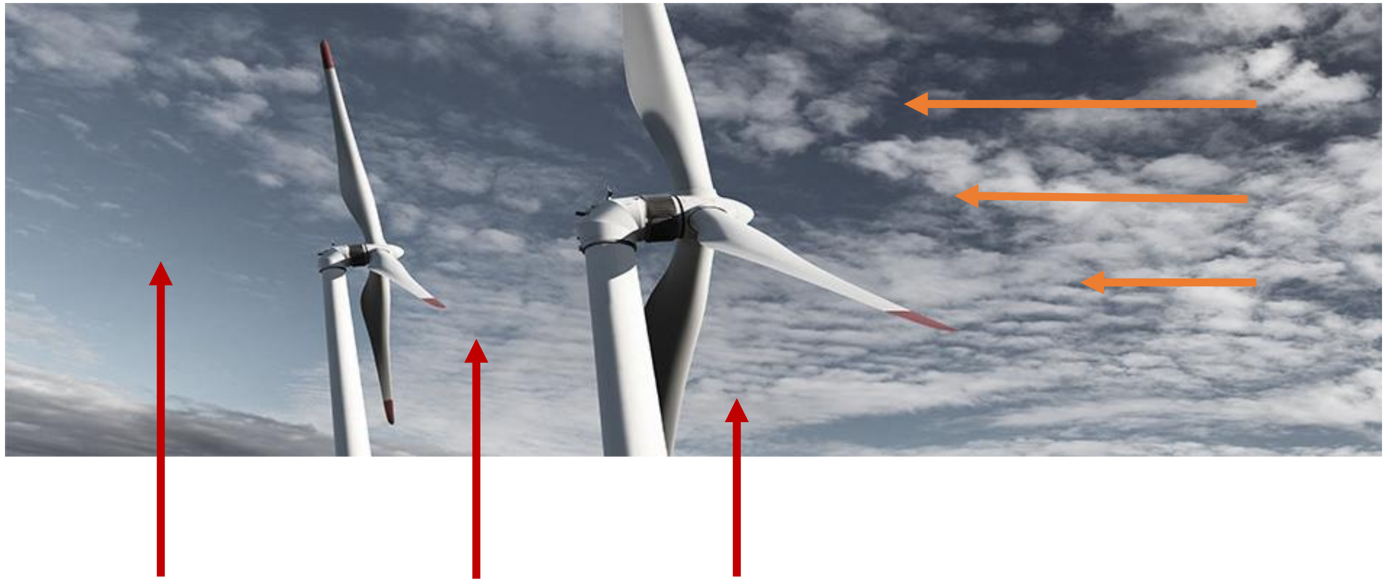
So, what does the energy (power) in the wind depend on?

Wind as a "resource"… for wind energy conversion *

Wind turbine generates (electrical) energy from wind –
no wind $\Rightarrow$ no energy

* wind resource = „Windpotenzial"

Wind as a “resource“… for wind energy conversion *



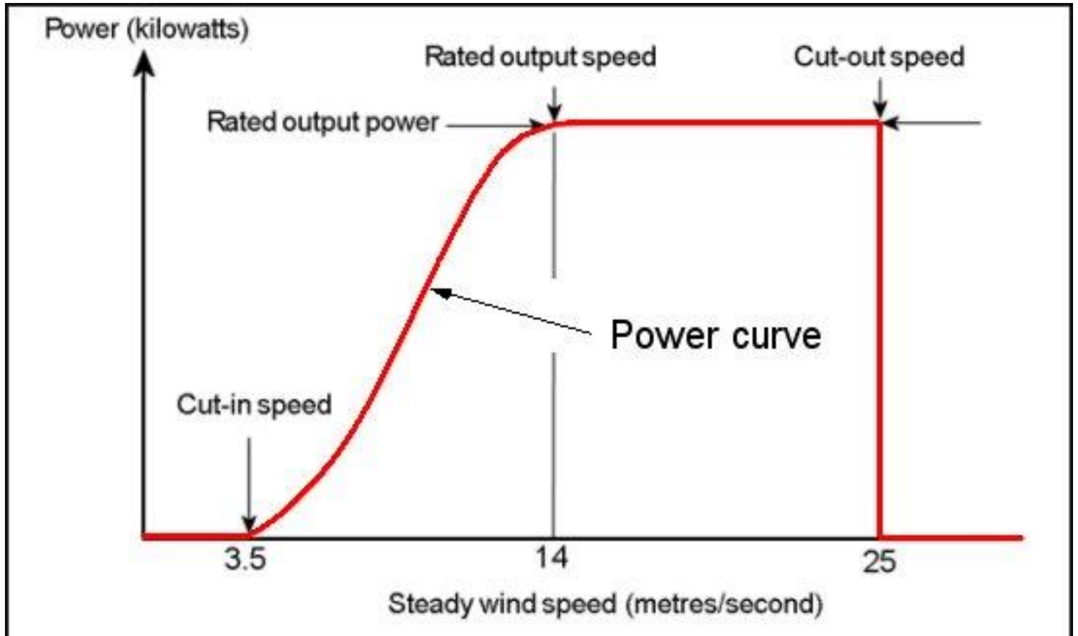
Wind turbine generates (electrical) energy from wind –
no wind $\Rightarrow$ no energy

Wind input is “resource” but also “loading” [not topic of this lecture]

Wind turbine also affects wind field
$\rightarrow$ wake deficit and increased turbulence behind / induction effects in front of turbine
[also not topic of this lecture]

How is the wind resource defined?

Power curve describes relation between wind and power output



Typical wind turbine power output with steady wind speed.

Power (kinetic energy flux) in the wind:

$$P_{\text{wind}} = \int \frac{1}{2} \rho V^3 dA$$

Power output:

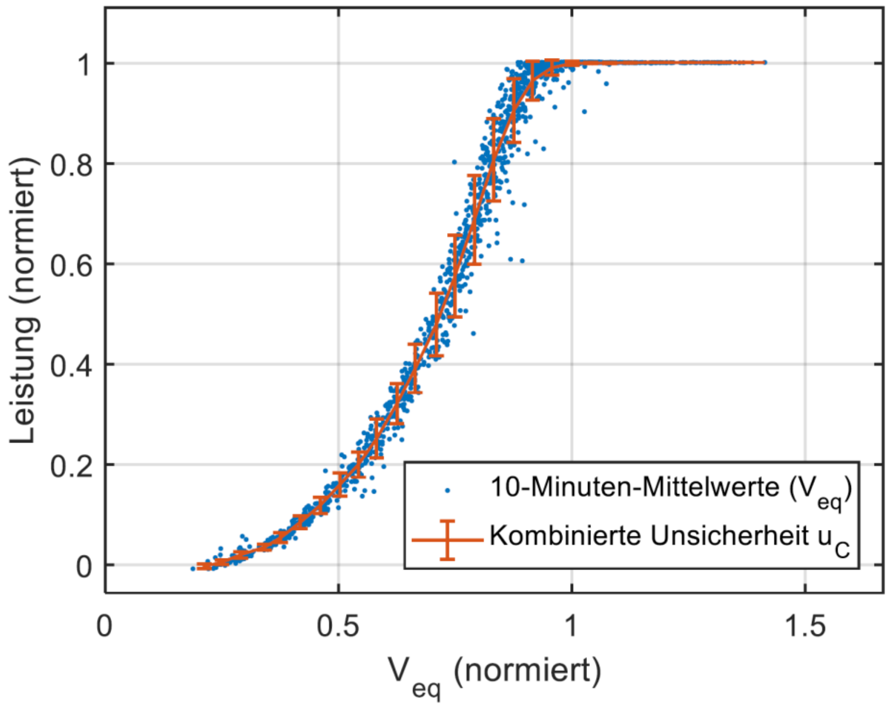
$$P = \frac{1}{2} c_P \rho V^3 A_{\text{rotor}}$$

By multiplying **power curve** with (some representative) **wind distribution**

$\rightarrow$ we derive **AEP** (Annual Enery Production / in [MWh])

(Standard) power curves are measured and derived according to IEC 61400-12-1

Power curves are to be measured as part of wind turbine prototype testing
~ following IEC 61400-12-1 standard:

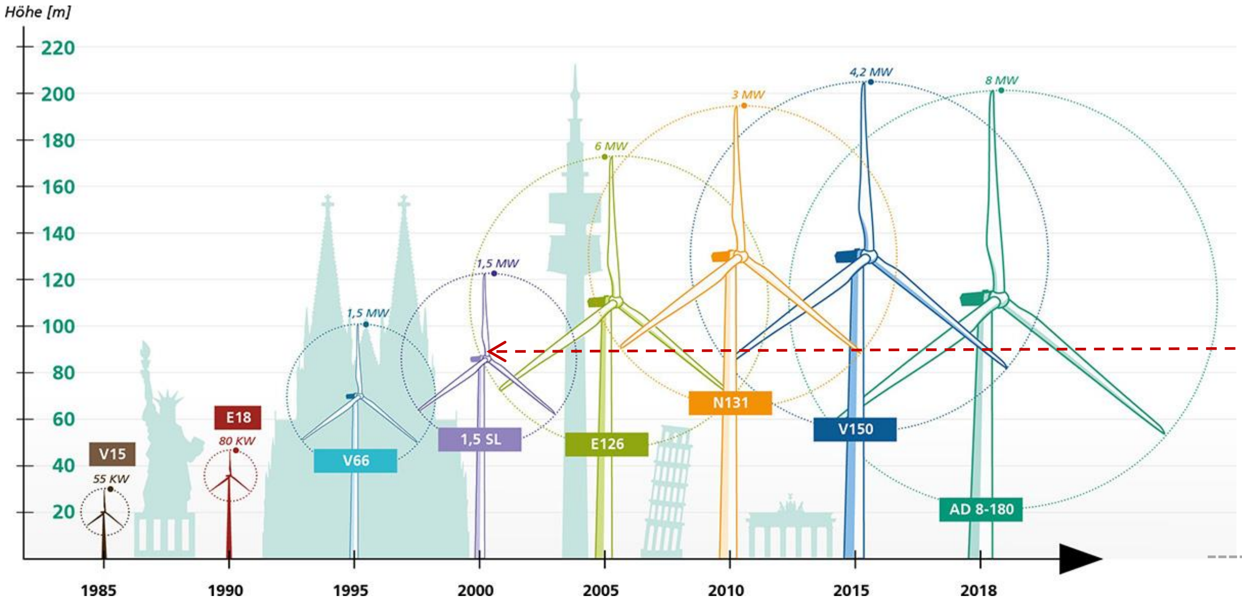


– 10-min averages of power output and representative wind data

– application of “method of bins”

→ which „**wind speed**“ is **representative**?

Representative wind speed: hub-height vs. rotor-equivalent



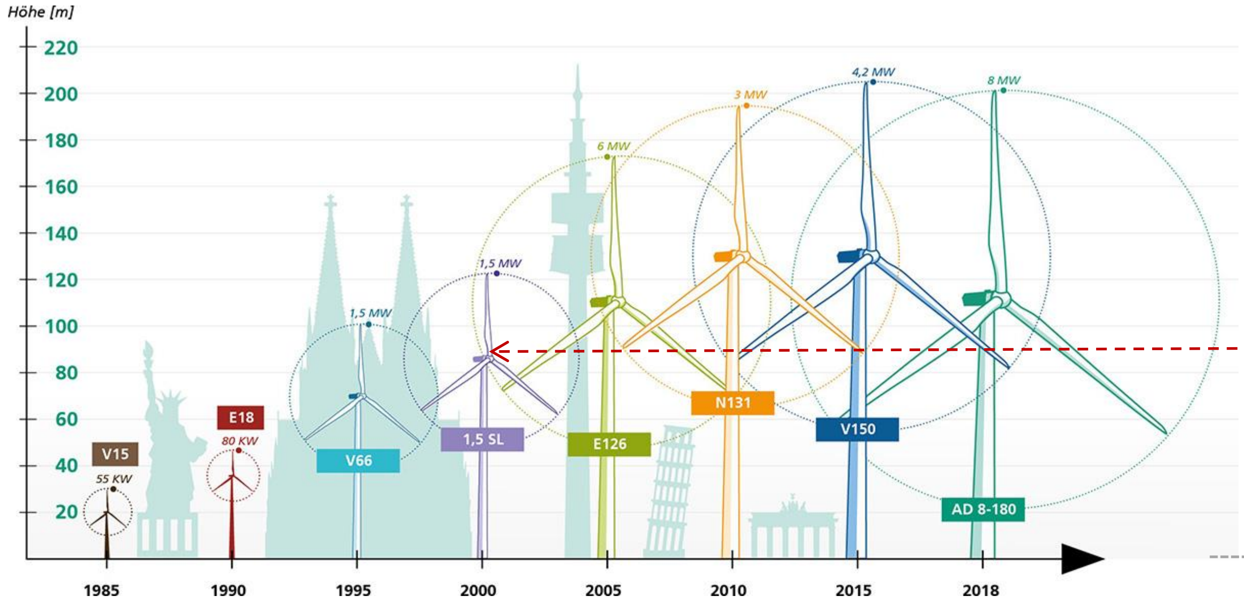
IEC 61400-12-1:2005

[medium-size turbines, not too complex sites]

Met mast with cup anemometer at hub height

2-4 D (rotor diameter)
in front of turbine

Representative wind speed: hub-height vs. rotor-equivalent



IEC 61400-12-1:2005

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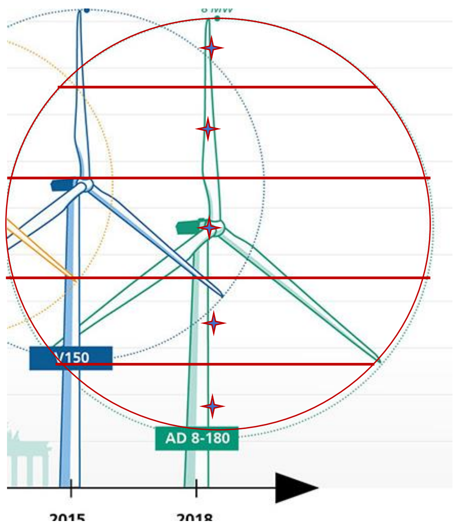


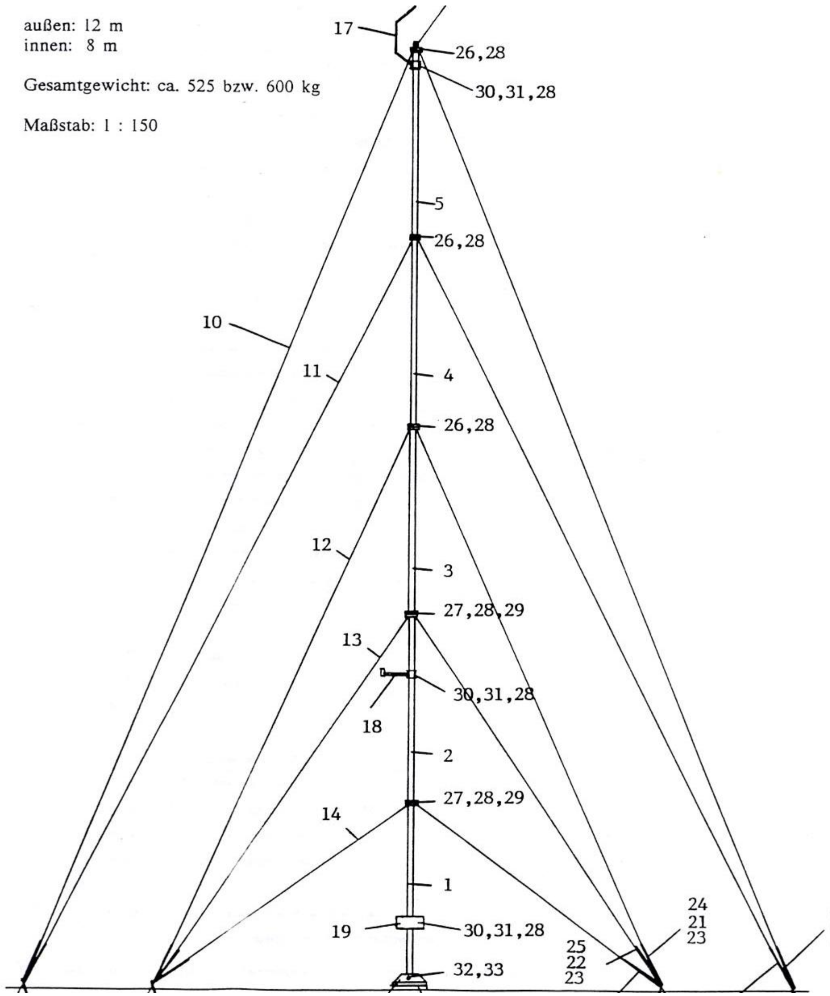
IEC 61400-12-1:2017

[much larger rotors]

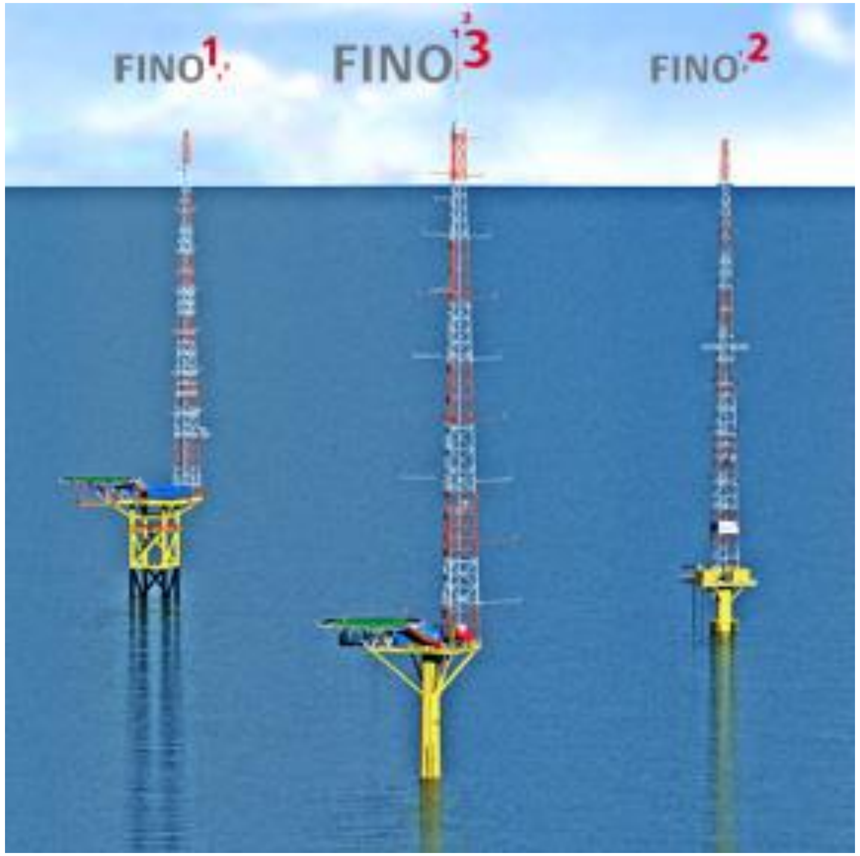
<u>Rotor-averaged / equivalent wind speed</u> from tall mast,
or hub-height (short) mast and **lidar**
still 2-4 D

$$v_{\text{eq}} = \left(\sum_{i=1}^{N} v_i^3 \frac{A_i}{A}\right)^{1/3}$$

Onshore meteorological masts

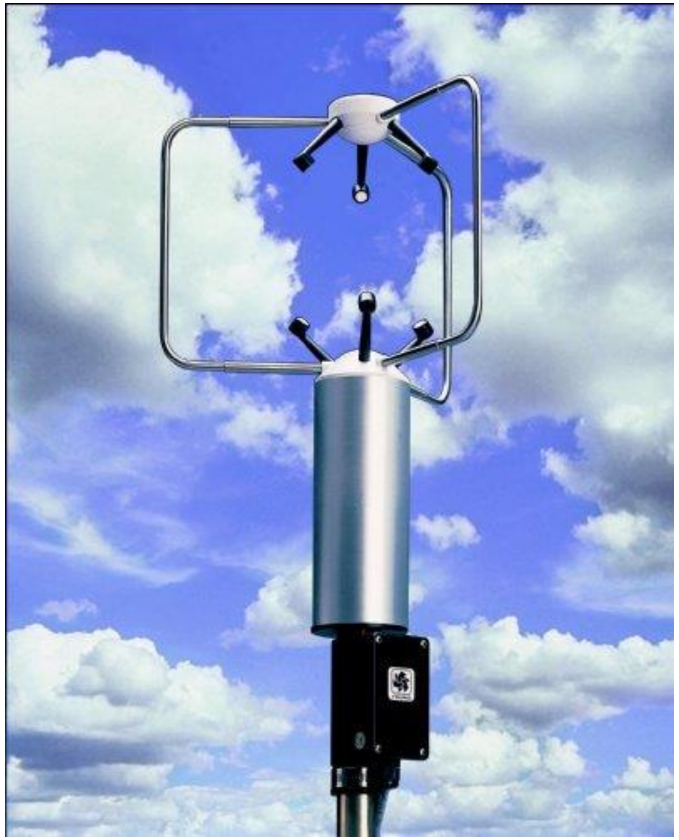


Offshore meteorological masts



https://www.fino-offshore.de/de/index.html

In-situ sensors / anemometers



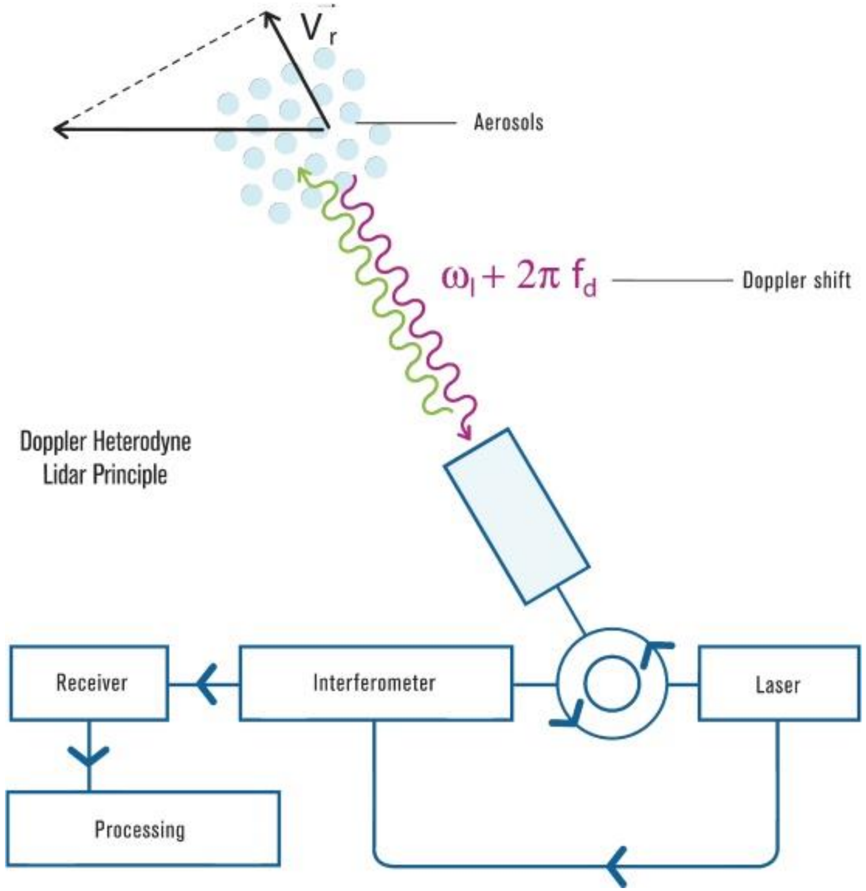
Source: www.ammonit.de

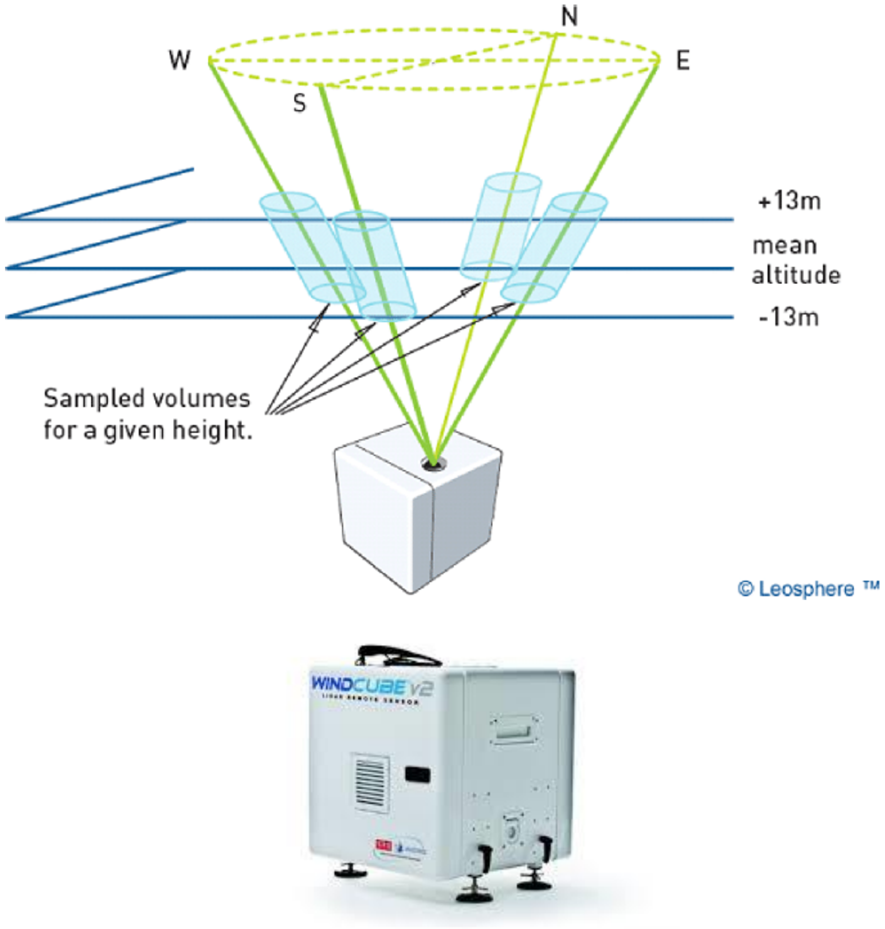
What is (a) lidar / LiDAR?

- Measurement device that provides wind profile measure-ments → vertically profiling Doppler wind lidar, accepted / covered by IEC 61400-12-1:2017 standard

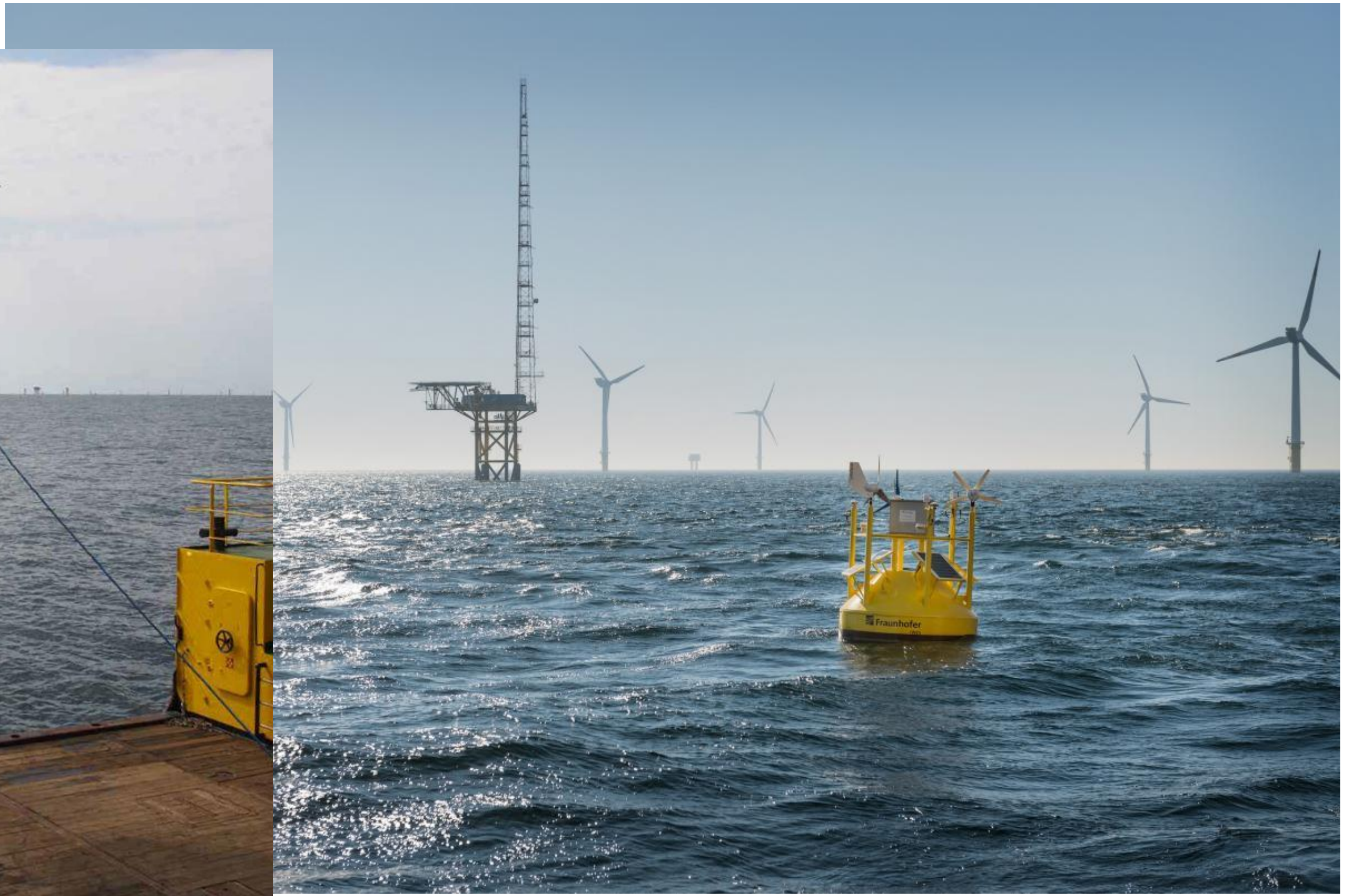
- Based on “Light Detection And Ranging“ measurement principle

LiDAR (Light Detection And Ranging)

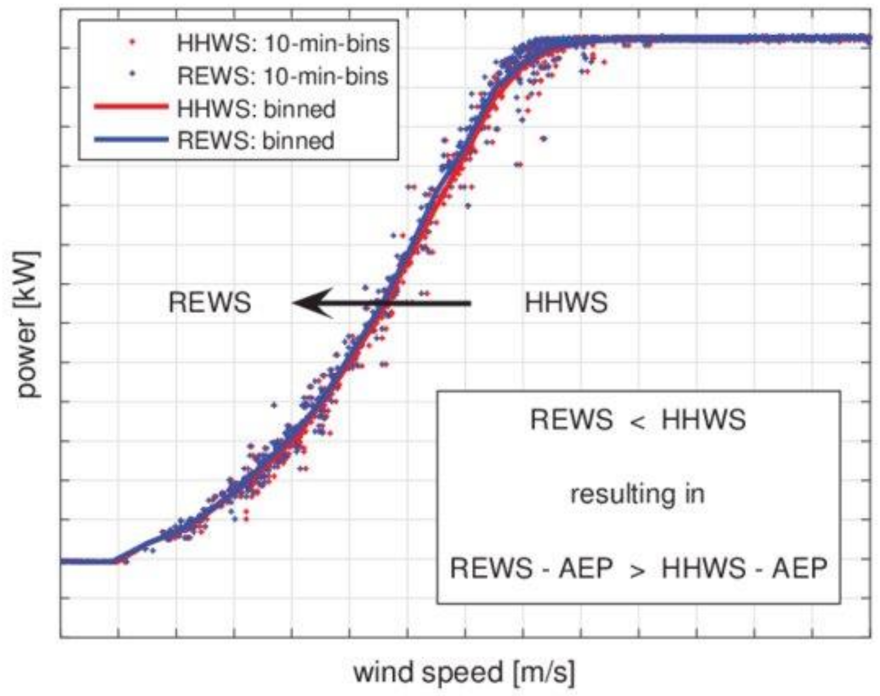




Offshore wind measurements with lidar
(→ floating lidar)



Relevance of power curve uncertainties



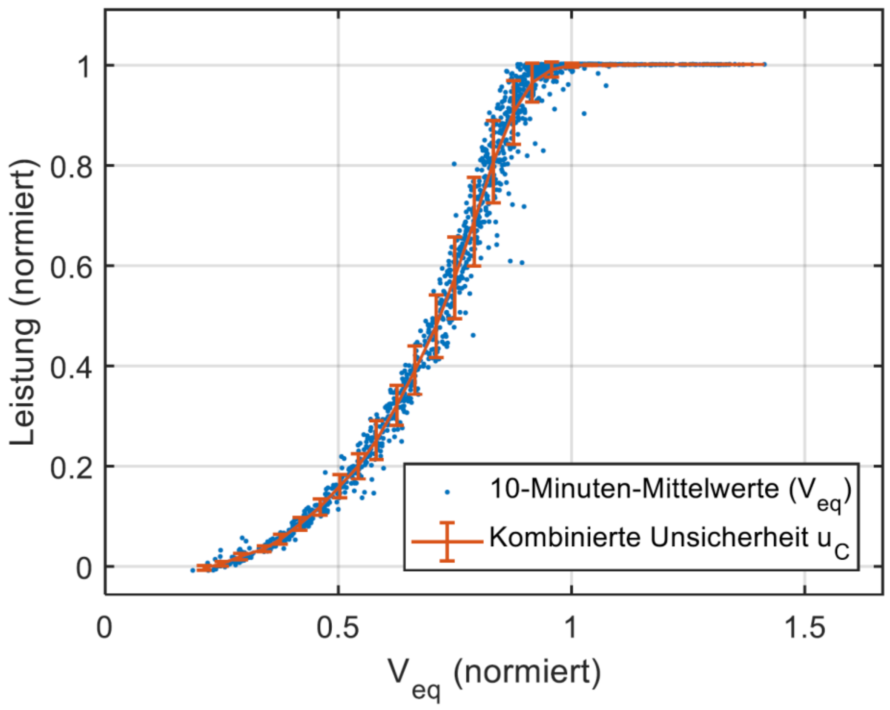
IEC 61400-12-1:2017

… allows for both hub height wind speed (HH) and rotor-equivalent wind speed (REWS) power curve → resulting power curves are not the same

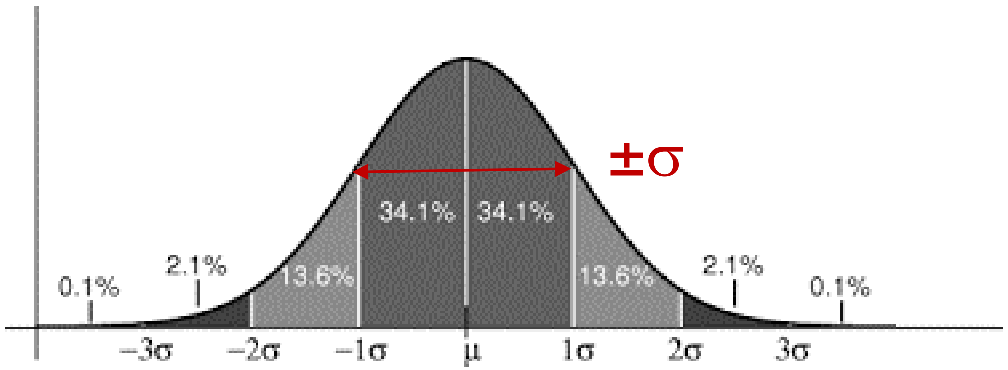
… further introduces additional “method” uncertainties for not taking wind shear into account

→ Power curve (⇒ AEP) with lower (combined) uncertainty is better (?)

What a (wind speed / power curve / AEP) uncertainty means



- combines statistical und sytematic (category A/B) uncertainty components
- 68% of possible results within uncertainty bounds



- Uncertainty covers what we don‘t know / take into account

(thought experiment: perfectly representative wind speed → field)

Wind as a “resource“… for wind energy conversion

How is the wind resource defined?

How do we estimate the wind resource for a site?

Calculation of AEP (Annual Energy Production)

In IEC 61400-12-1: “multiply” $\boxed{\text{Rayleigh distribution for given } V_{ave}}$ with power curve

$$AEP = N_h \sum_{i=1}^{N} \left[F(V_i) - F(V_{i-1})\right] \left(\frac{P_{i-1} + P_i}{2}\right)$$

where

AEP	is the annual energy production;
N_h	is the number of hours in one year ≈ 8 760;
N	is the number of bins;
V_i	is the normalized and averaged wind speed in bin i;
P_i	is the normalized and averaged power output in bin i.

$$F(V) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{V}{V_{ave}}\right)^2\right)$$

where

$F(V)$	is the Rayleigh cumulative probability distribution function for wind speed;
V_{ave}	is the annual average wind speed;
V	is the wind speed.

Calculation of AEP (Annual Energy Production)

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where

$F(V)$	is the Rayleigh cumulative probability distribution function for wind speed;
V_{ave}	is the annual average wind speed;
V	is the wind speed.

Use instead site-specific wind distribution (wind speed and direction) for reference period that is representative for turbine life time

→ **Energy yield estimation / wind resource assessment** (as part of wind project planning)

How to obtain a site-specific representative wind distribution

Example: AD 8-180 test site BHV

- Measurement data from site, [typically] some distance away from turbine site (here: at 30 m height, 2011-14) + terrain data for whole area

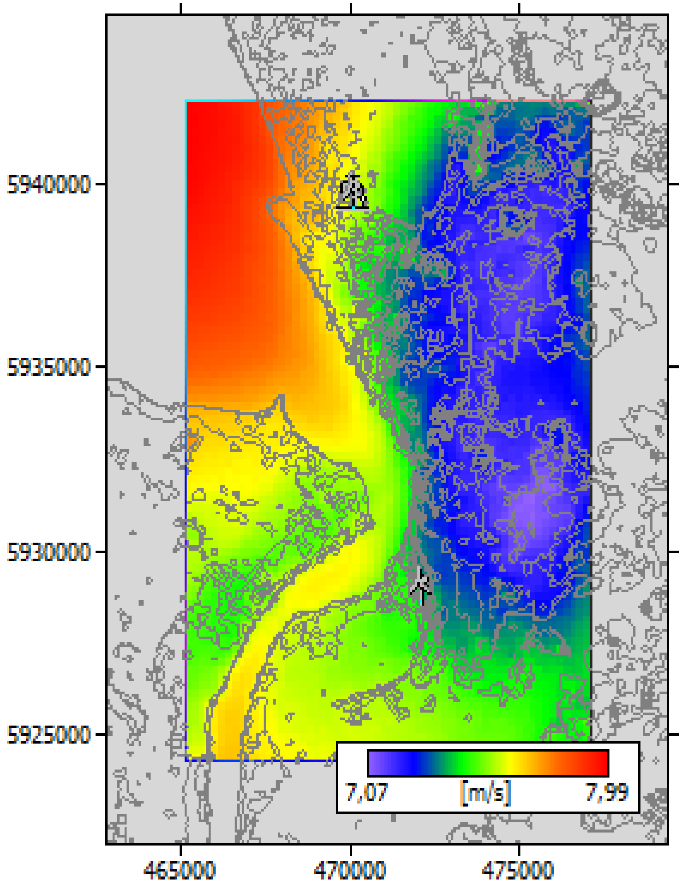
→ Only consider complete years of measured data with sufficient availability (no systematic bias due to seasonal effects or similar)

→ correct for wake effects from obstacles (turbines, buildings, …)

→ apply long-term correction [correlation with reference data]

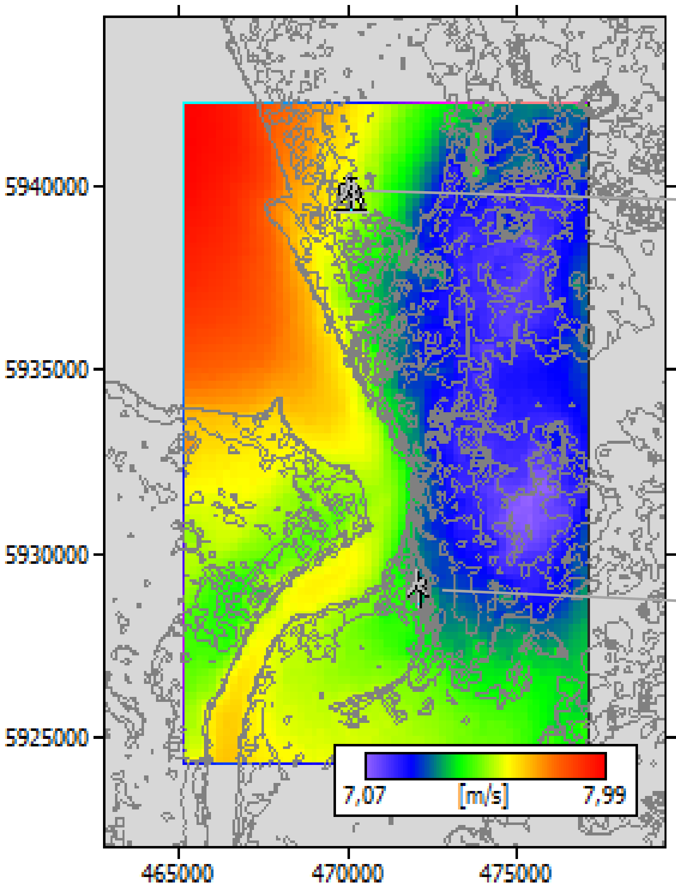
→ vertical extrapolation to hub height [use wind profile model]

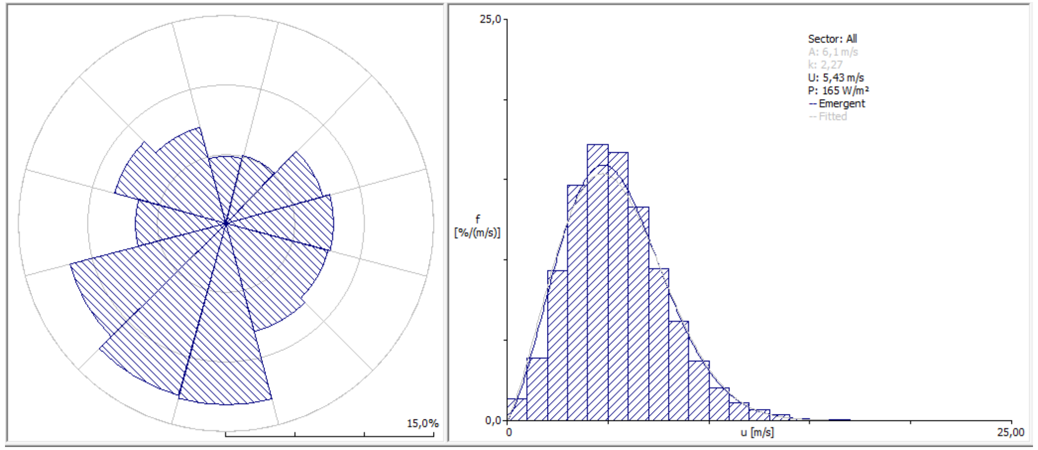
→ horizontal extrapolation [use flow modelling]



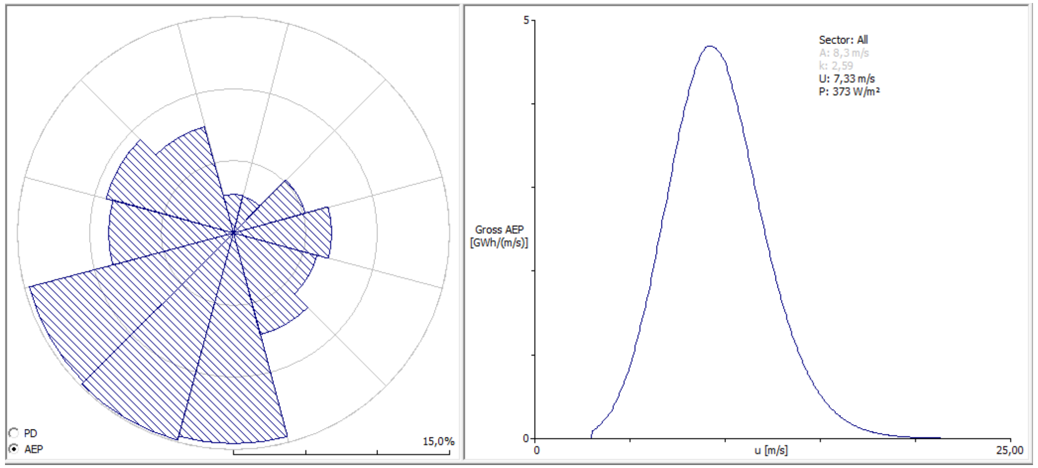
How to obtain a site-specific representative wind distribution

Example: AD 8-180 test site BHV





Frequency distribution of “observed” wind data with Weibull fit (k, A), sectorwise and combined



After “modelling” wind conditions at turbine site, and taking power curve into account → gross AEP is area under curve (without losses)

Procedure for energy yield assessment according to TG 6 (FGW)

Winddatenbasis	Modellierung Windpotenzial	Berechnung Energieertrag
1. Kurzzeitwind-daten Windmessungen WEA-Ertragsdaten	**3. Windfeldmodellierung** Strömungsmodell Eingangsdaten Horizontale und vertikale Übertragung	**5. Ertragsberechnung** WEA Leistungskennlinie **6. Parkabschattung** Wake Modell WEA-Schubbeiwerte
2. Langzeitkorrek-tur Langzeitdatenquelle Konsistenztest Abbildungsalgo-rithmus	**4. Anpassung Windpoten-tialberechnung** Abgleich mit WEA Er-tragsdaten und/oder Wind-messungen Diskussion des Abgleichs	**7. Mindererertragsberech-nung** Betriebsmodi bzw. WEA-Abschaltungen und andere technische Verluste
Unsicherheitsbetrachtung		

Abb. 2–1: Generalisierte Struktur von Energieertragsermittlungen

From: FGW, Technical Guideline / Richtlinie 6, Version 10

Procedure for energy yield assessment according to TG 6 (FGW)

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Unsicherheitsbetrachtung		

Abb. 2–1: Generalisierte Struktur von Energieertragsermittlungen

From: FGW, Technical Guideline / Richtlinie 6, Version 10

Today quite often with vertically profiling lidar (due to high flexibility and eventually lower costs)
– at least in simple terrain;

in more complex (onshore) terrain → „Geländefehlerkorrektur“ based on flow modelling

Procedure for energy yield assessment according to TG 6 (FGW)

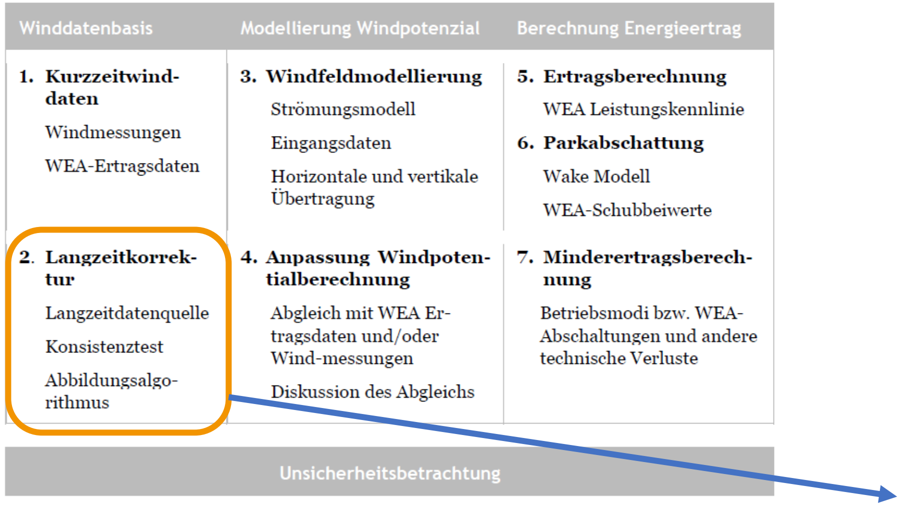
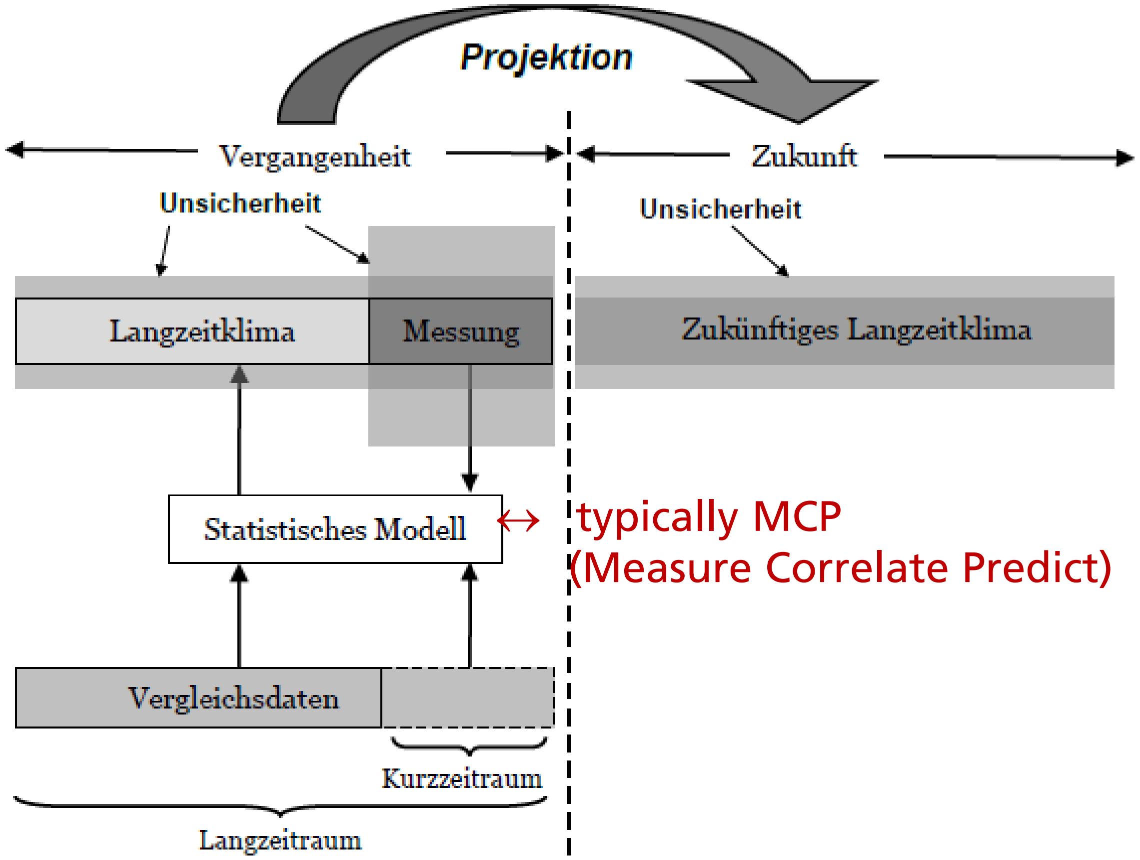


Abb. 2–1: Generalisierte Struktur von Energieertragsermittlungen

Long-term data form reanalysis datasets (ERA-R, MERRA, …) or possibly <u>mesoscale wind atlas</u>



↔ typically MCP (Measure Correlate Predict)

Abb. 2–2: Schematische Vorgehensweise zur Langzeitanpassung

From: FGW, Technical Guideline / Richtlinie 6, Version 10

Procedure for energy yield assessment according to TG 6 (FGW)

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Unsicherheitsbetrachtung		

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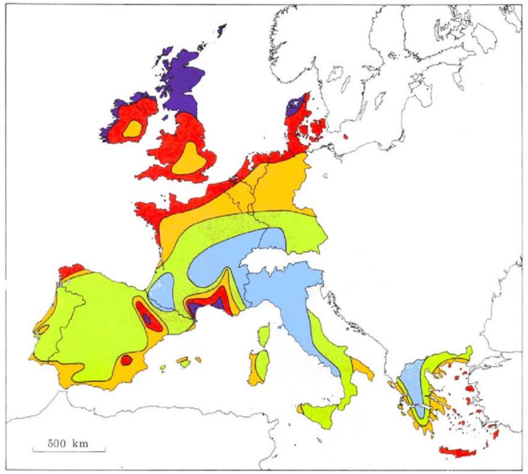
WAsP methodology […]

Abb. 2–1: Generalisierte Struktur von Energieertragsermittlungen

From: FGW, Technical Guideline / Richtlinie 6, Version 10

WAsP / Wind Atlas Methodology

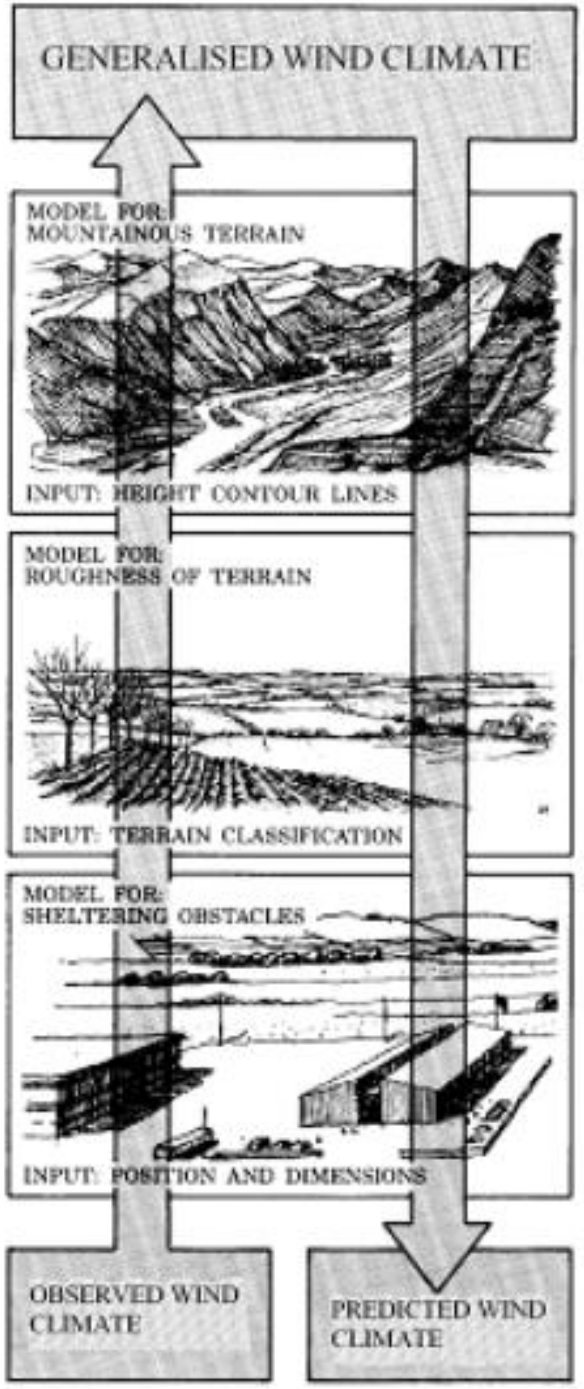
WAsP – Wind Atlas Analysis and Application Programme
(developed by DTU Wind Energy / Risø since the 1980s)



Resursi vetra[1] na visini od 50m iznad tla za pet različitih topografskih stanja										
	Zaklonjen teren[2]		Otvoren teren[3]		Obala mora[4]		Otvoreno more[5]		Brda i grebeni[6]	
	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

(see www.wasp.dk)

- central point in the wind transformation model of WAsP (so-called Wind Atlas Methodology) is the concept of a Regional or *Generalized Wind Climate*, or Wind Atlas → hypothetical wind climate for an ideal, featureless and completely flat terrain with a uniform surface roughness, assuming the same overall atmospheric conditions as those of the measuring position;
- basic "machine" of WAsP is a flow model, representing the effect of different terrain features incl.
  - terrain height variations
  - terrain roughness
  - sheltering obstacles



From the European Wind Atlas to NEWA

- European Wind Atlas for EU12 was published in 1989

- Objective of **New European Wind Atlas** (NEWA) **project** (2015-19) has been to consider / make use of technical developments of 2-3 decades in between… in terms of

  → flow modelling

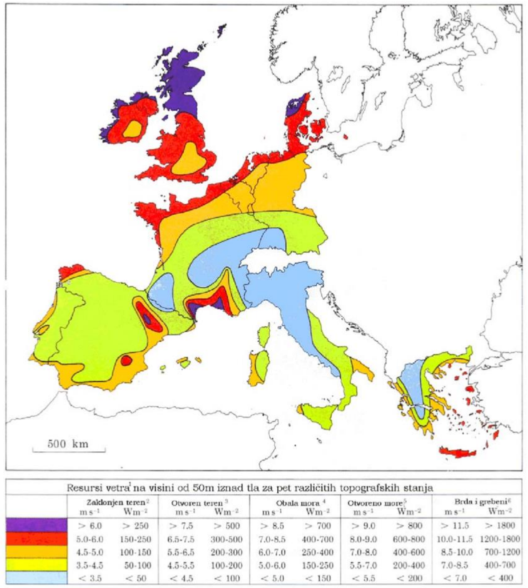
  → HPC capacities

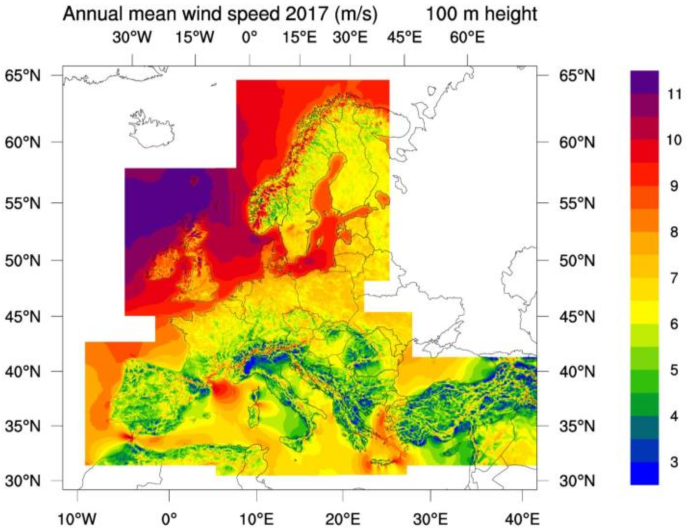
  → extended region

  → taller wind turbines (~ heights of interest)

  → more demanding (and educated?) users

  → available measurement data for validation





https://map.neweuropeanwindatlas.eu/

From the European Wind Atlas to NEWA

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  → flow modelling

  → HPC capacities

  → extended region

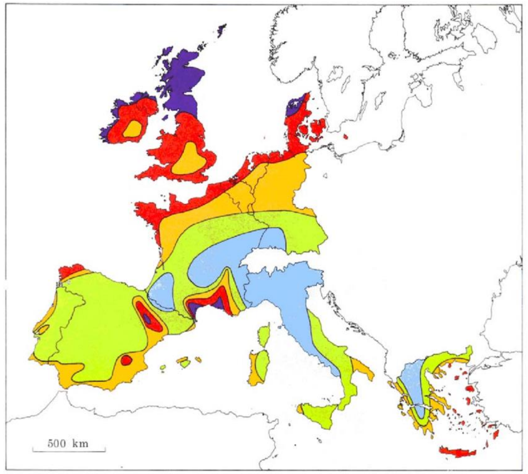
  → taller wind turbines (~ heights of interest)

  → more demanding (and educated?) users

  → available measurement data for validation

… or the Global Wind Atlas (GWA)

https://globalwindatlas.info/



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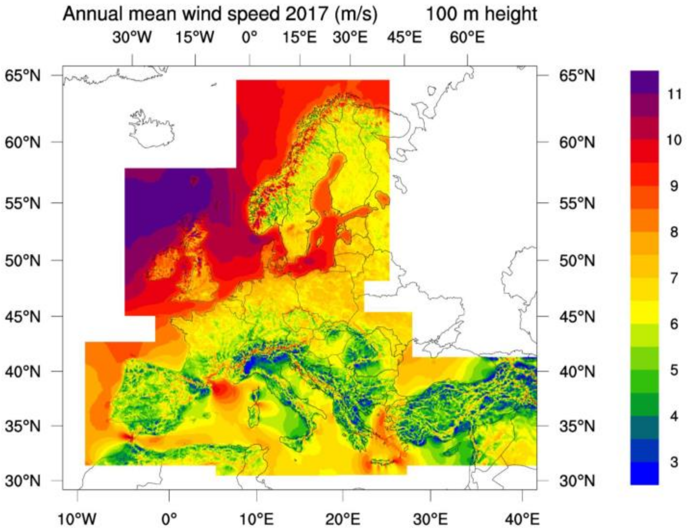


Energy yield assessment uncertainties

Winddatenbasis	Modellierung Windpotenzial	Berechnung Energieertrag
1. Kurzzeitwinddaten Windmessungen WEA-Ertragsdaten	**3. Windfeldmodellierung** Strömungsmodell Eingangsdaten Horizontale und vertikale Übertragung	**5. Ertragsberechnung** WEA Leistungskennlinie **6. Parkabschattung** Wake Modell WEA-Schubbeiwerte
2. Langzeitkorrektur Langzeitdatenquelle Konsistenztest Abbildungsalgorithmus	**4. Anpassung Windpotentialberechnung** Abgleich mit WEA Ertragsdaten und/oder Wind-messungen Diskussion des Abgleichs	**7. Minderertragsberechnung** Betriebsmodi bzw. WEA-Abschaltungen und andere technische Verluste
Unsicherheitsbetrachtung		

Abb. 2–1: Generalisierte Struktur von Energieertragsermittlungen

From: FGW, Technical Guideline / Richtlinie 6, Version 10

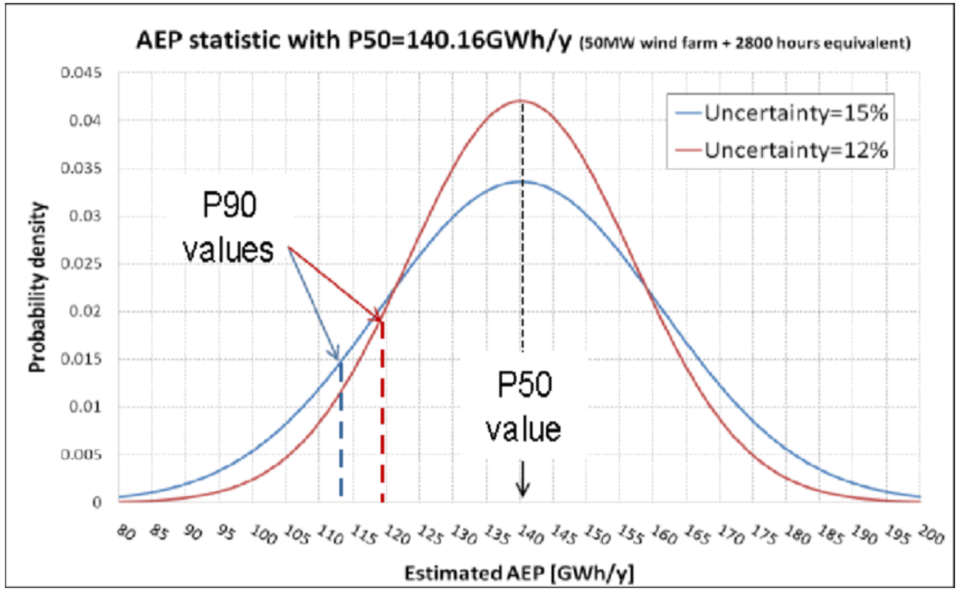
2.7.7 ÜBERSICHT ÜBER DIE MINDESTENS ZU BESTIMMENDEN UND ZU DOKUMENTIERENDEN UNSICHERHEITEN

Winddatenbasis	Standortbezogene Windmessung	Mastmessung	Kalibrierung
			Anemometerklassifizierung
			Montageeffekte
			Datenerfassung und -verarbeitung
			gegebenenfalls Datenkorrekturen
			Datenintegrität
		Fernmess-verfahren	Verifikationstest
			Klassifizierung
			Monitoring / Zweiter Verifikationstest
			Aufstellungseffekte
			Datenerfassung und -verarbeitung
			gegebenenfalls Datenkorrekturen
			Datenintegrität
	Vergleichs-WEA	Daten und deren Erhebung, Detaillierungsgrad, Informationsgüte.	
		Verfahren zur Ausreißereliminierung und Verfügbarkeitskorrektur	
		Parkabschattung	
		Unsicherheiten „Eingangsdaten“ WEA	
	Langzeitkorrektur	Konsistenz der Langzeitdatenquellen	
		Abbildungsalgorithmus Langzeit => Kurzzeit	
		Länge des Abgleichzeitraums	
		Repräsentanz des Bezugszeitraums in der Vergangenheit	
		Projektion des Bezugszeitraums auf den zukünftigen WEA-Betriebszeitraum	
		Repräsentativität der Langzeitdaten für den Standort	
Modellierung	Eingangsdaten (z. B. Topographie)		
	Unsicherheit Übertragungsverfahren, oft sinnvollerweise aufgeteilt in:		Horizontaltransfer
			Vertikaltransfer
Parkabschattung			
Eingangsdaten WEA	Leistungskurve		
	Serienstreuung		
	Gültigkeit der Kennlinie am Standort		
	Variation von WEA-Steuerungsparametern		
Energieverlustfaktoren			

Tbl. 2–2: Übersicht zu Unsicherheiten

Why uncertainties are relevant

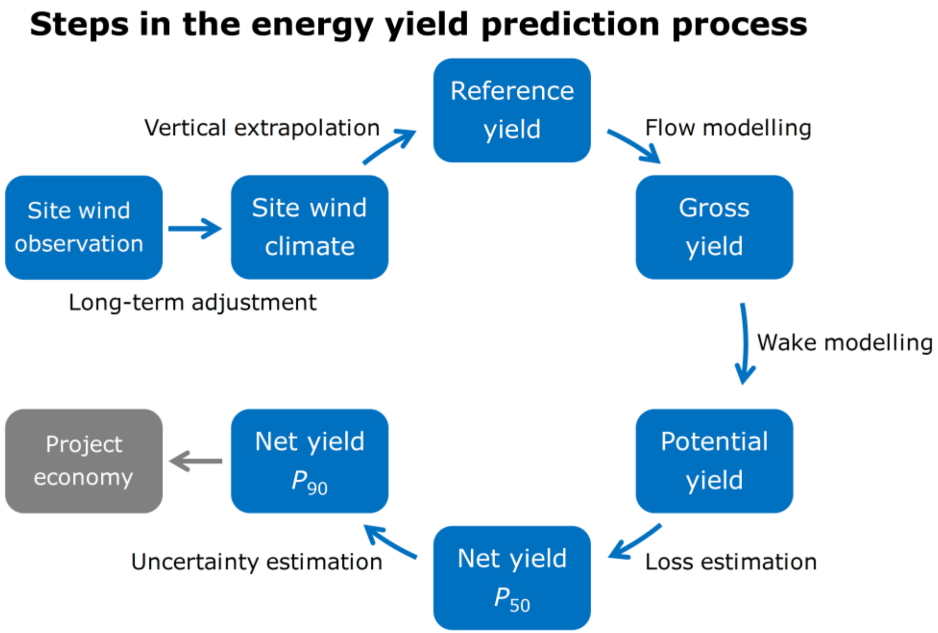
- Wind resource data and energy yield assessment need to be “bankable” (incl. well defined uncertainties according to accepted methodology)
  → typically 3 surveys from independent (accredited) consultants, should more or less agree in numbers
- Most important result (in addition to expected AEP) is P90, P95, … exceedance probability

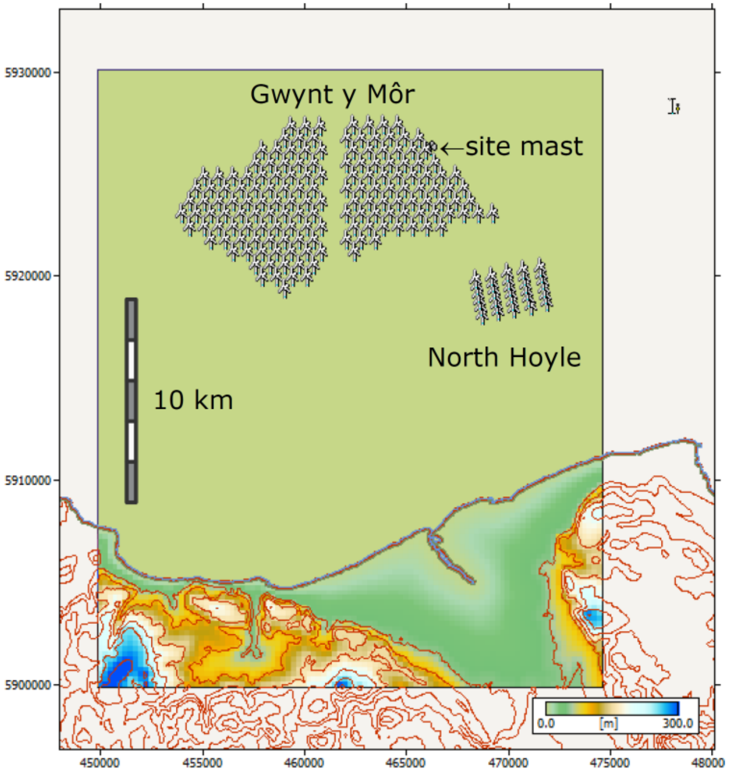


Where do (the highest) uncertainties come from?

Energy yield prediction process offshore
(Example: Offshore CREYAP*)

*Comparative Resource and Energy Yield Assessment Procedures – results presented at EWEA Offshore 2013

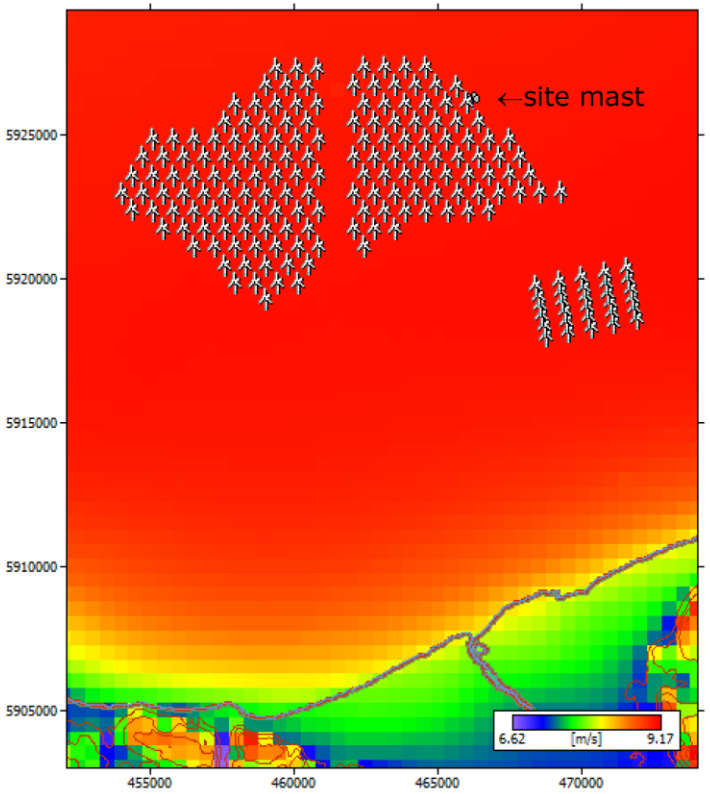




Energy yield prediction process offshore
(Example: Offshore CREYAP)

Gwynt y Môr wind farm

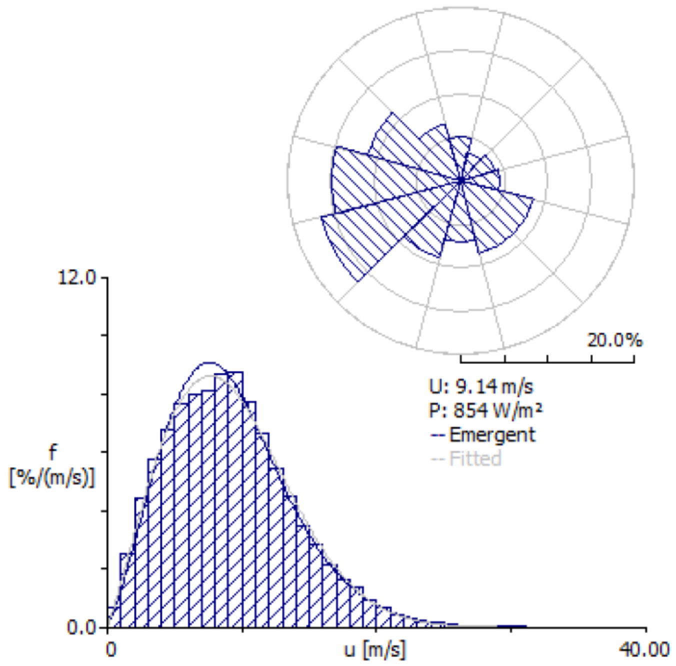
- 160 wind turbines (576 MW)
  - Rated power: 3.6 MW
  - Hub height: 79.4 m
  - Rotor diameter: 107 m
  - Spacing: regular, 6-7 *D*
  - Air density: 1.23 kg m^{-3}
- Site meteorological mast
  - Wind speed @ 85 m
  - Std. deviation @ 85 m
  - Wind direction @ 82 m
  - Air temperature @ 20 m
  - Barometric pressure @ 20 m
- Site topographical data
  - Participants choice



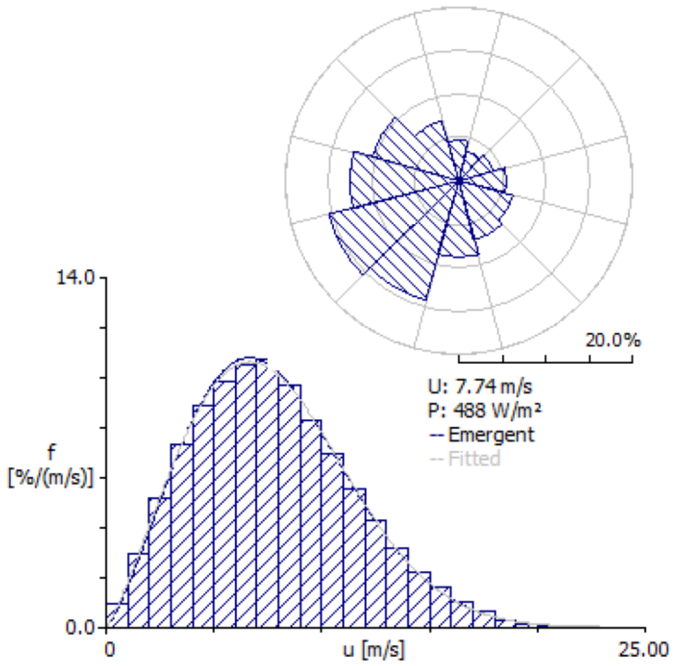
Energy yield prediction process offshore
(Example: Offshore CREYAP)

Wind-climatological inputs

Site meteorological mast
- 2.6 years of 10-min mean data



MERRA reanalysis data
- 11.4 years of hourly mean data



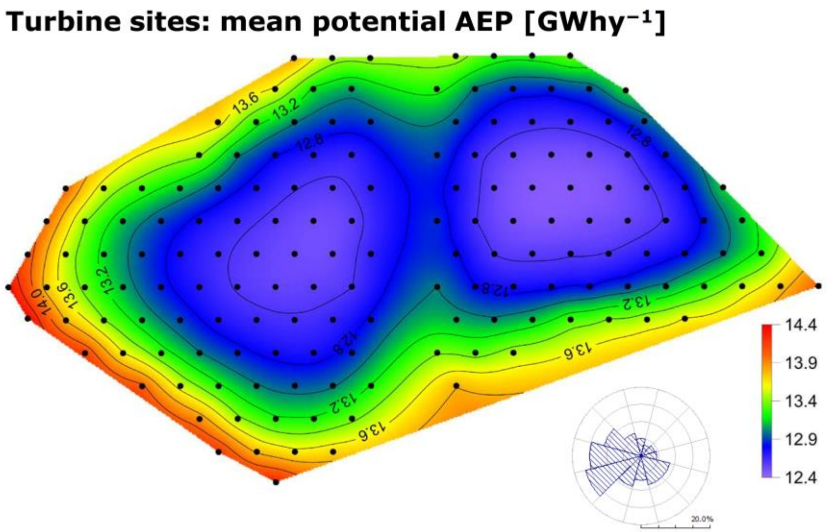
Energy yield prediction process offshore
(Example: Offshore CREYAP)

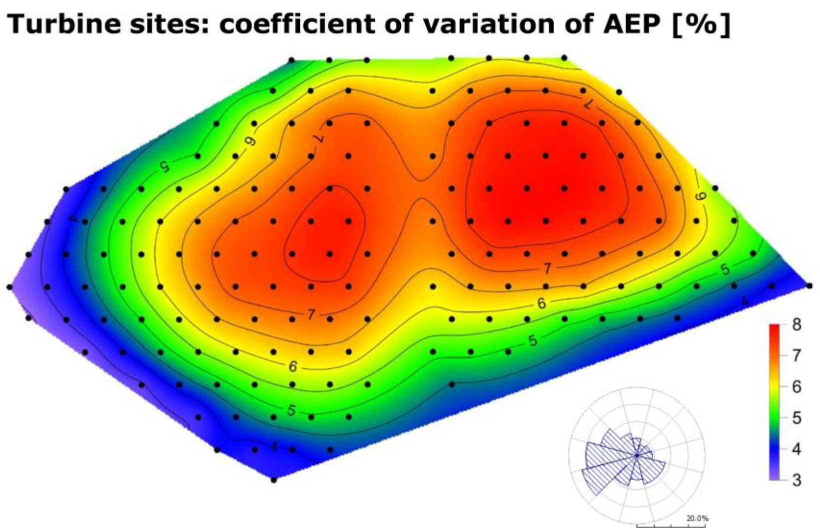
Comparisons of results and methods {definitions}

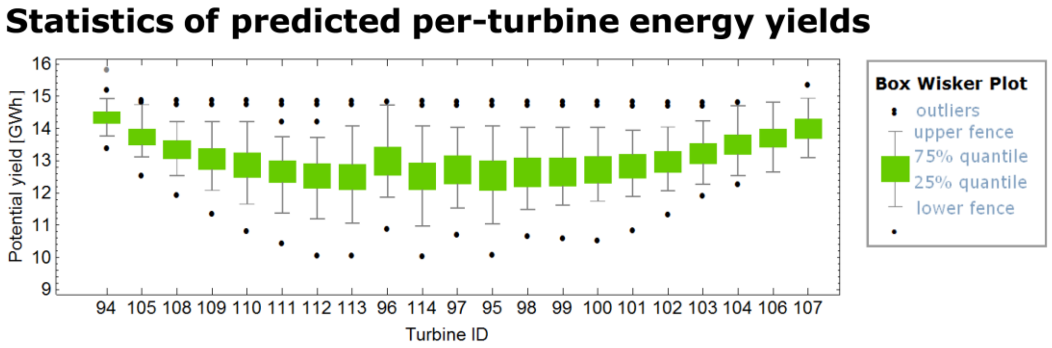
1. LT wind @ 85 m (mast) = Measured wind ± [long-term adjustment]
   - comparison of long-term adjustment methods
2. LT wind @ 79 m (hub height)= LT wind @ 85 m + [wind profile effects]
   - comparison of vertical extrapolation methods
3. Gross AEP = Reference AEP ± [terrain effects]
   - comparison of flow models
4. Potential AEP = Gross AEP – [wake losses]
   - comparison of wake models
5. Net AEP (P_{50}) = Potential AEP – [technical losses]
   - comparison of technical losses estimates
6. Net AEP (P_{90}) = Net AEP (P_{50}) – 1.282 × [uncertainty estimate]
   - comparison of uncertainty estimates
7. Comparison to teams average AEP – spread and bias

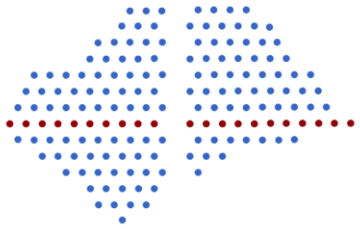
Energy yield prediction process offshore

(Example: Offshore CREYAP)







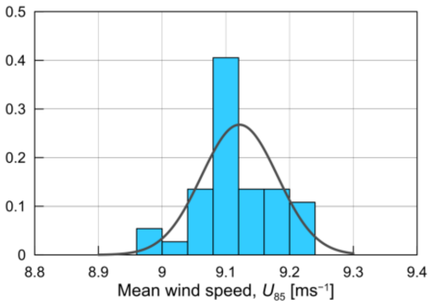


Energy yield prediction process offshore
(Example: Offshore CREYAP)

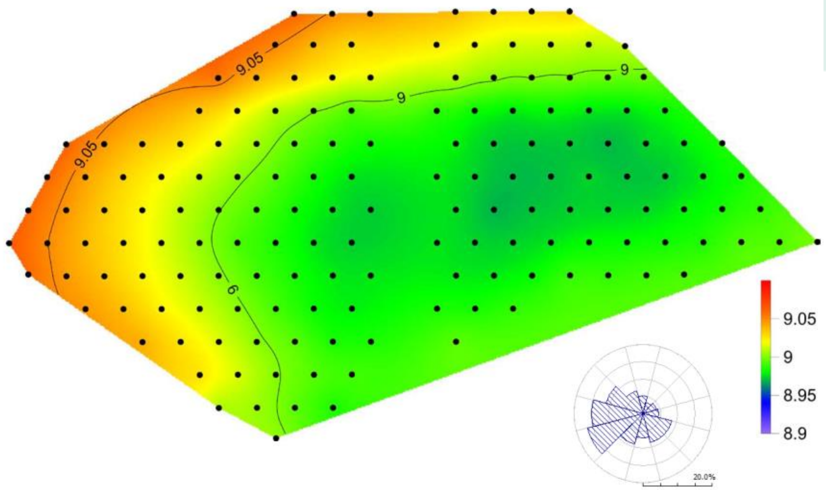
Long-term wind speed @ 85 m

Data points used = 37 (of 38)

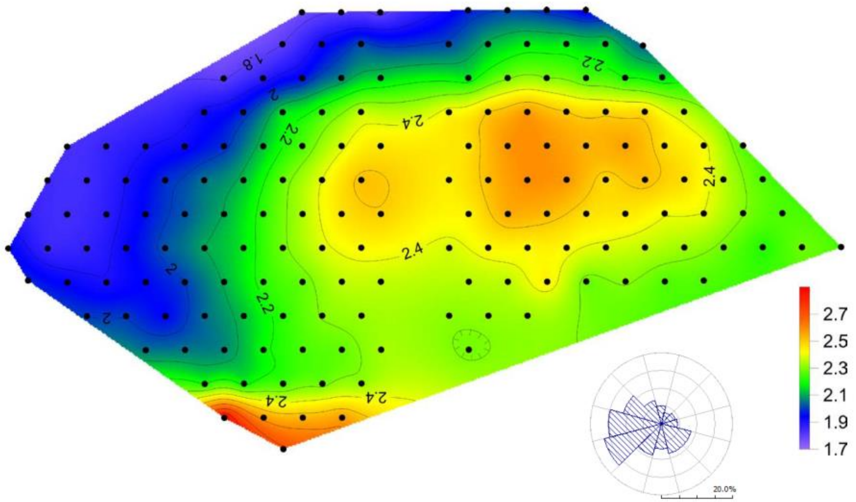
Mean wind speed = 9.12 ms^{-1}
Standard deviation = 0.06 ms^{-1}
Coefficient of variation = 0.7%
Range = 8.98 to 9.24 ms^{-1}



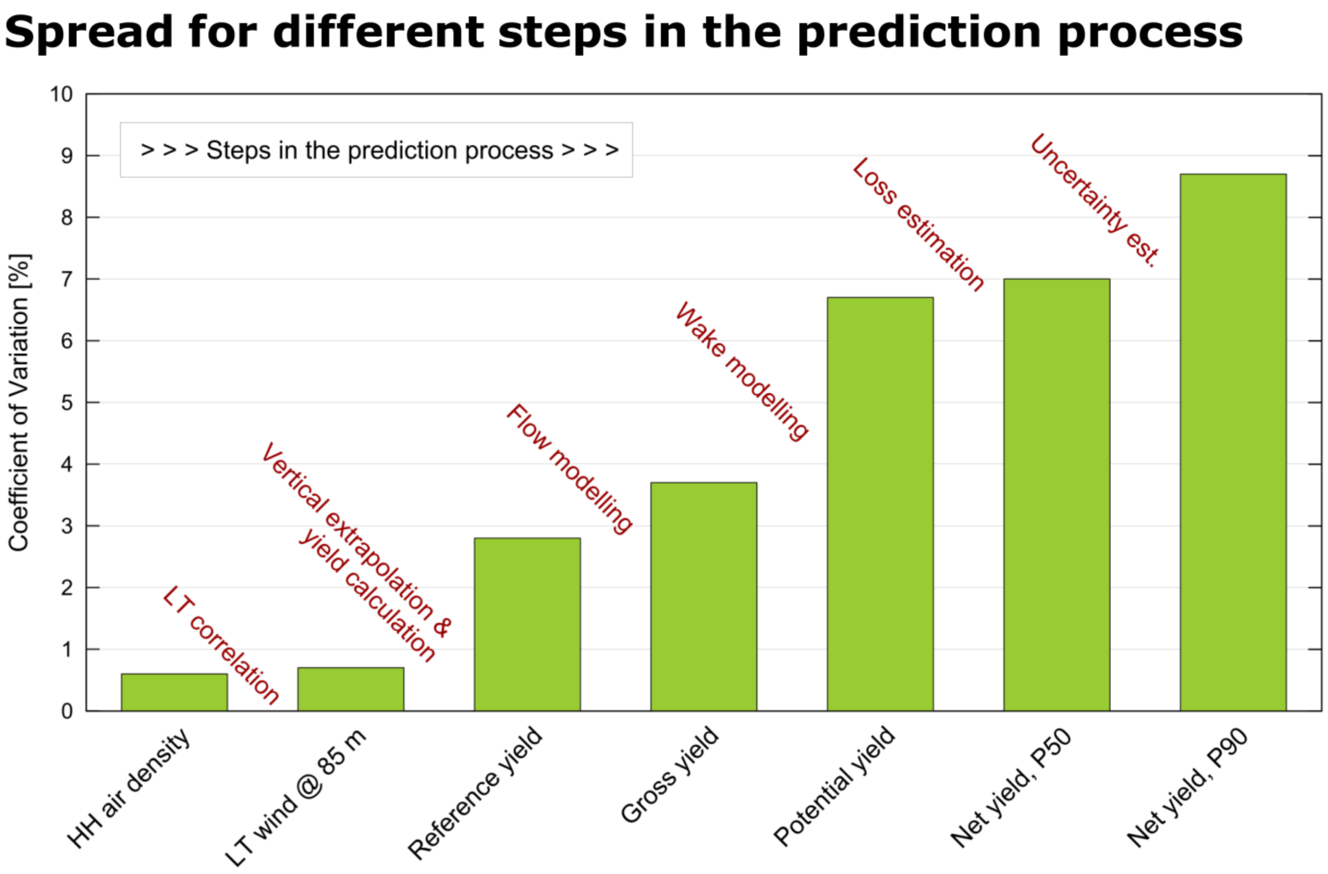
Turbine site mean wind speed [ms^{-1}]



Turbine site wind speed CV [%]



Energy yield prediction process offshore
(Example: Offshore CREYAP)



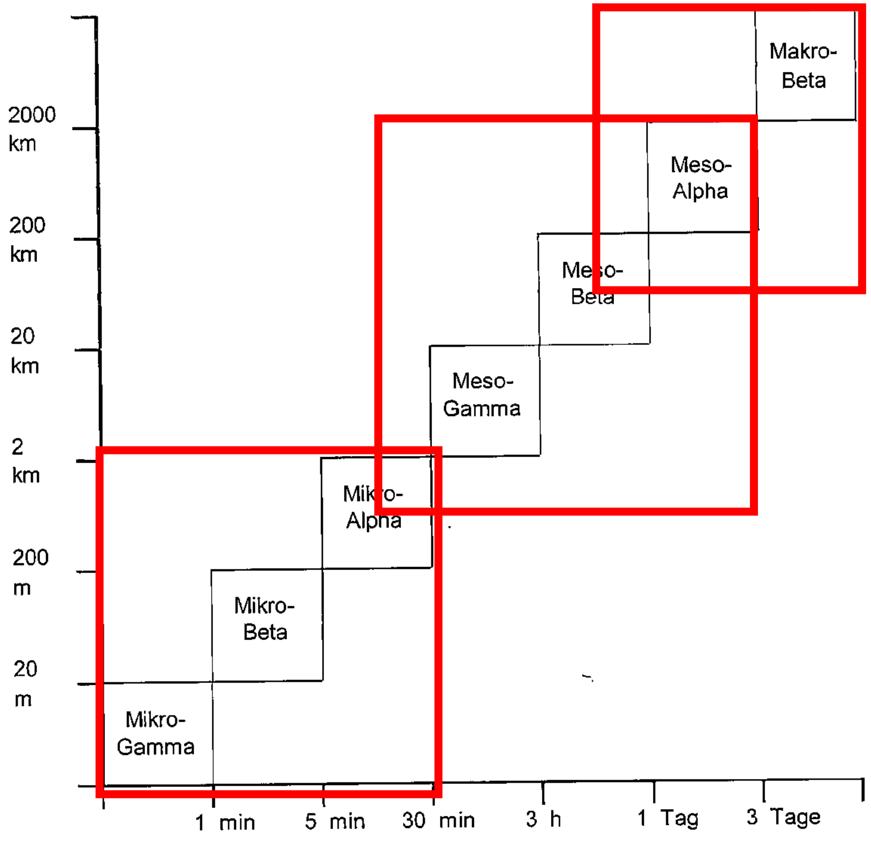
Energy yield prediction process offshore

WIND			
Wind Resource Measurment		Simple/Complex	
Accuracy Anemometers	0.1 m/s	1-2%	U
Overspeeding Bias		0,30%	U
Angular Response Characteristics		0.4% / 1.5%	U
Vertical flow Characteristics	2D IEC appr	1%	U
	3D non IEC_flat	1,70%	U
	3D non IEC_complex	2,30%	U
Tower Shadowing	2 Side mounted Anem	0,50%	U
	1 Sid emounted Anem	1%	U,k
	Tubular tower	1%	U
Boom & Mounting effects		0,42%	
Data Reduction error	X - amt of data absent in av. Data	0.03*X%	U,k
Long Term Resource Estimation			
MCP Correlation Uncertainty		5-10%	U,k
Weibull Parameter Estimation		5%	k
Changes in long term Avg Climate change		1%	U,k
Wind Resource Variability Uncertainty			
Interannual variability	N- No. Of year, ref MCP data av.	6/sqrt(N)%	U,k
Uncertainty over Turbine life		1,34%	U,k
Site Assessment Uncertainty			
Topograhical effects	WAsP, Sitewind, met masts, wt	(2 to 10)/sqrt(3)%	
Wind Shear model Uc.	Flat	5%	U
	Hilly	5%	U
	Forested	5%	U
TURBULENCE			
Roughness Length variations		5%	TI
Atmospheric Stratification		15%	TI

Numerical Flow Modelling

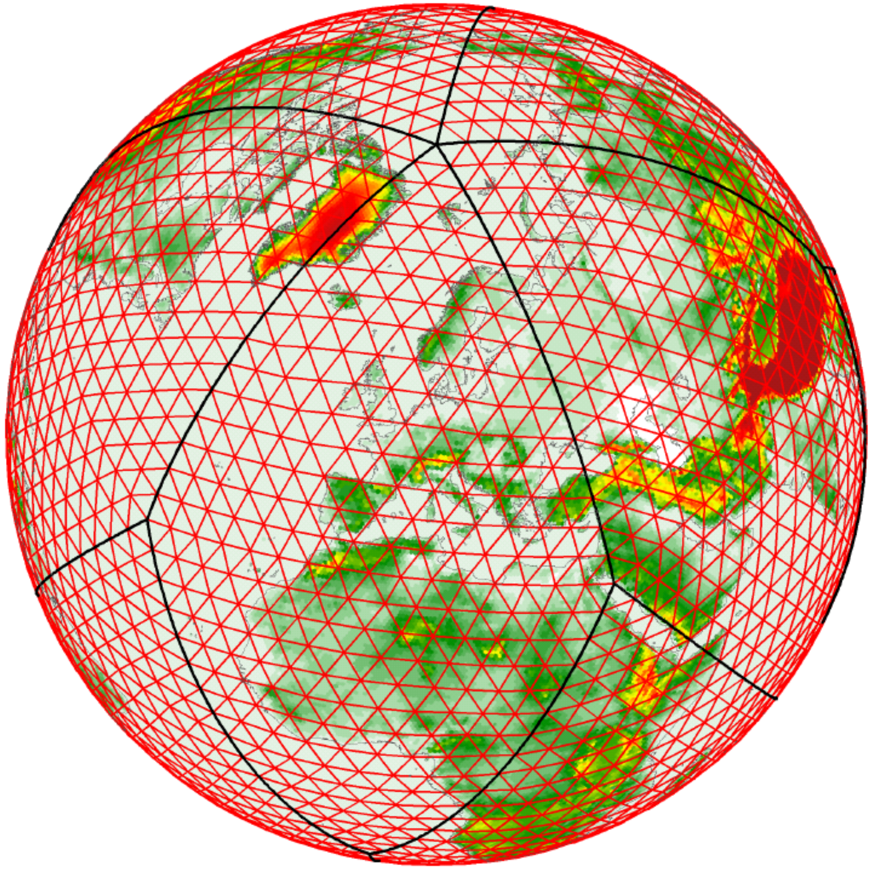
Numerical Flow Modelling

Macro	Global atmospheric models	Whole atmosphere
Meso	LAM (local area model) Mesoscale models	Boundary layer (and atmosphere)
Micro	Micrometeorological models CFD (computational fluid dynamics) models	Surface layer



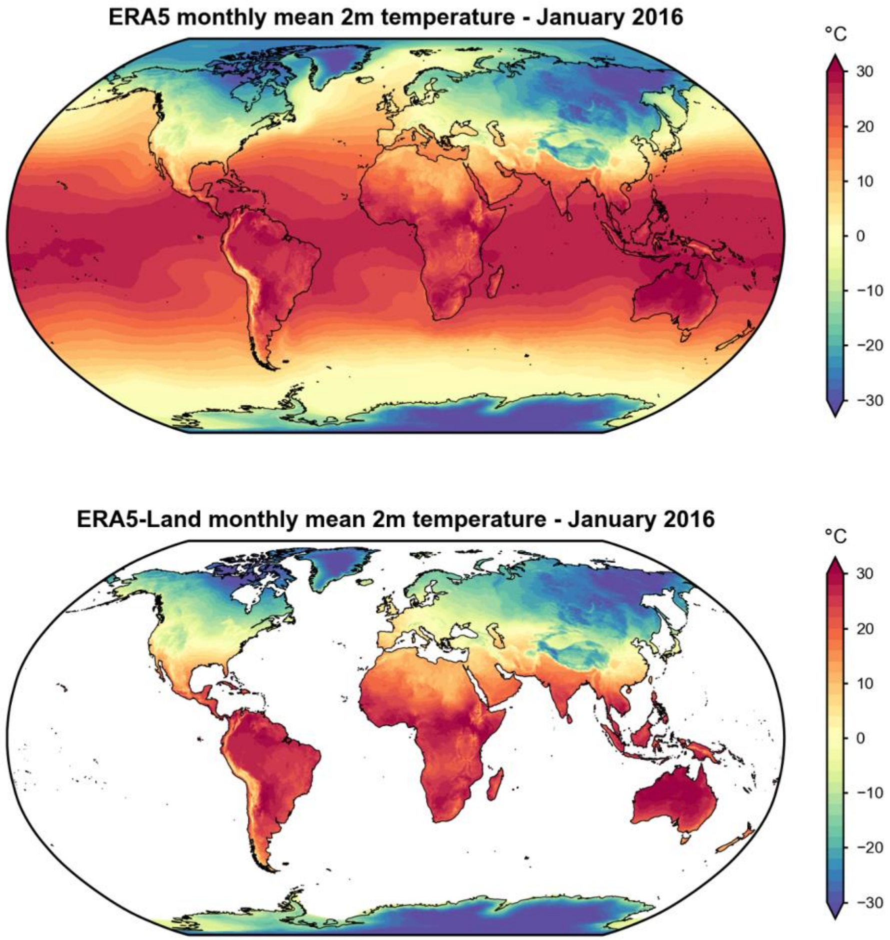
Global models of the atmosphere

- Ca. 15 worldwide
- Coarse spatial and temporal resolution
- No boundary conditions from other models necessary



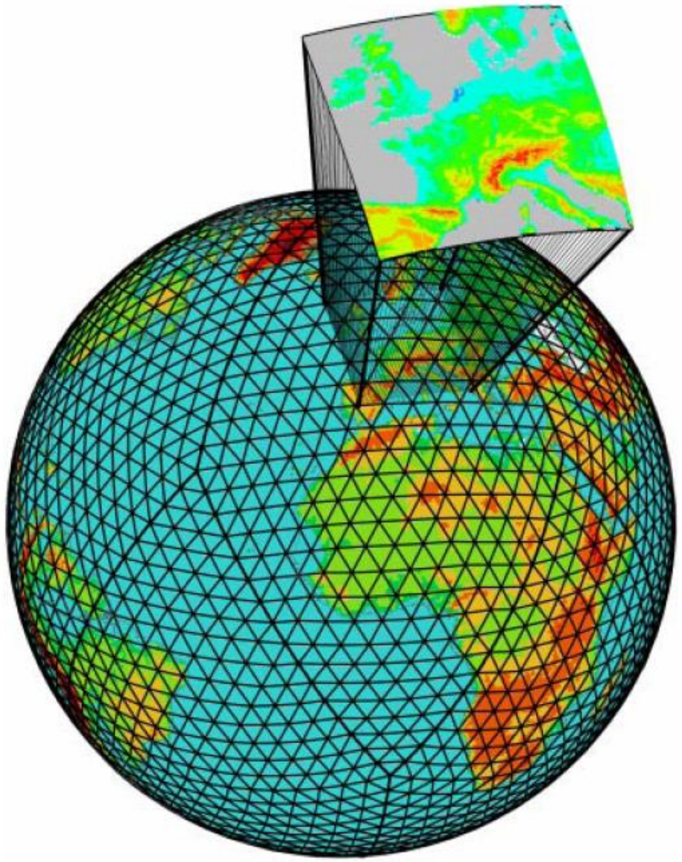
Climate reanalysis (e.g., ERA5)

- Climate reanalyses combine past observations with models to generate consistent time series of multiple climate variables.
- Reanalyses are among the most-used datasets in the geophysical sciences. They provide a comprehensive description of the observed climate as it has evolved during recent decades, on 3D grids at sub-daily intervals.



Local / Mesoscale Models

- Used for weather prediction
- Higher resolution
- Input from a global model needed

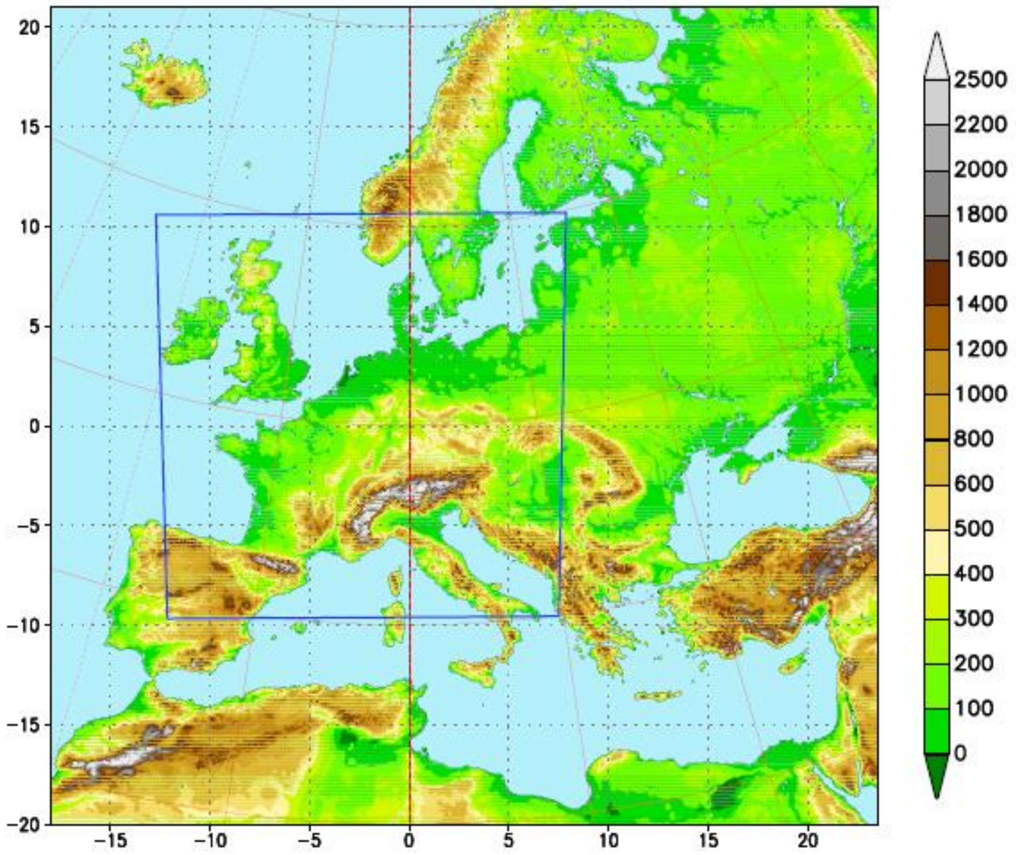


e.g. https://www.mmm.ucar.edu/weather-research-and-forecasting-model

WRF THE WEATHER RESEARCH & FORECASTING MODEL

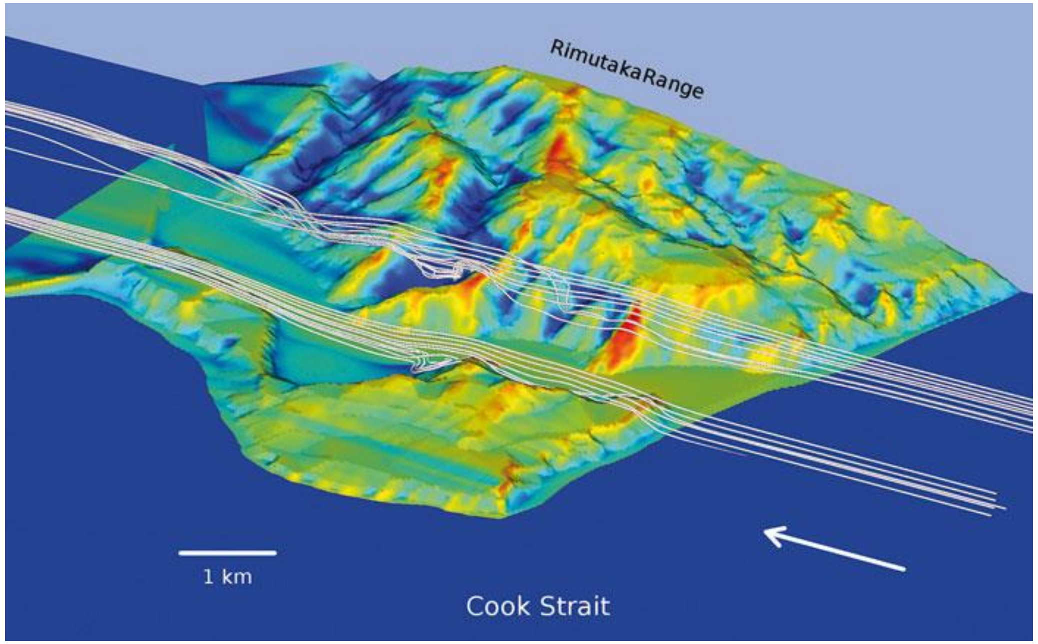
Example: Cosmo-EU model of the German weather service (DWD)

- Size: 325 x 325 grid points
- Horizontal resolution: 0,0625° (7 km)
- Forecast horizon: 48 hours
- Model runs: 00 UTC, 12 UTC



Microscale Models

- Solution of the Navier-Stokes equation
- Very detailed modelling of the flow
- High spatial resolution



Quelle: www.niwascience.co.nz

Summary