Karlsruhe Institute of Technology

Personal look-back on 31 years of wind energy research

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general time line, 47 years in atmospheric science

1975-1985	**diploma and PhD studies in meteorology, Bonn U.)**	
1985	**PhD in meteorology (synoptics), Bonn U.**	**sub-grid-scale vertical energy fluxes in mid-latitude lows**
1985-1994	**meso-scale numerical modelling, TH Karlsruhe/ FZ Karlsruhe, now KIT**	**effective roughness length, orographic drag**
1991	**stay at Risø Research Centre (Denmark, now DTU)**	**eddy covariance analyses, turbulence in flows over escarpments**
1995-2022	**surface-based remote sensing of the atmospheric boundary layer (Fraunhofer IFU, FZK, now KIT)**	**vertical wind profiles, boundary-layer turbulence, urban heat island, wind energy**

wind energy time line, 31 years in wind energy science

1991	**Risø Research Centre**	**N.O. Jensen, S. Frandsen, first simple wind farm models**
1996	**Fraunhofer IFU Garmisch**	**first sodar measurements wind profiles over hills**
2005	**FZ Karlsruhe Garmisch**	**first project on offshore wind energy, FINO 1 climatology**
2010	**KIT, IMK-IFU, Garmisch**	**first version of EFFWAKE, member of WindForS**
2012	**KIT, IMK-IFU, Garmisch**	**first project on wind energy in complex terrain**
2016	**Cologne Univ. / KIT**	**Energy Meteorology (one week block course)**
2018	**KIT, IMK-IFU, Garmisch**	**2^{nd} edition of book on wind energy meteorology**

insight 1

wind energy is more than an engineering task

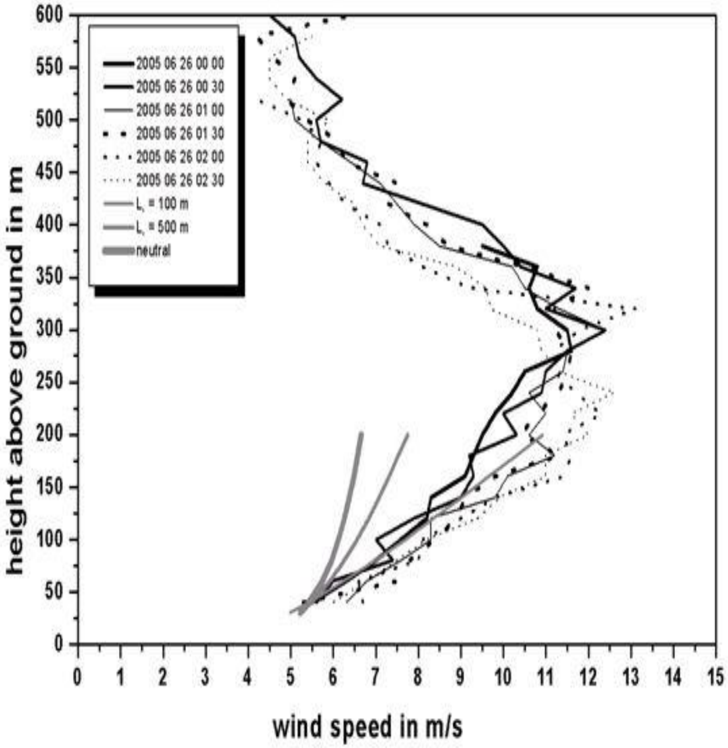
boundary-layer meteorology is mandatory in resource assessment

vertical wind profiles

turbulence

atmospheric stability

SODAR profiling in the late 1990s was first attempt to obtain wind profiles from higher layers unreachable by masts



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insight 2

boundary-layer meteorology is mandatory in resource assessment

WAsP (from 1987 onwards) is a good numerical tool for flat (non-complex) terrain (now WAsP 12.7 from December 2021)

originally based on:

- basic similarity laws of the atmospheric boundary layer, especially on "Rossby number similarity" which provides the

"geostrophic drag law" (links geostrophic wind speed with friction velocity)

- potential flow (now much elaborated)

insight 3

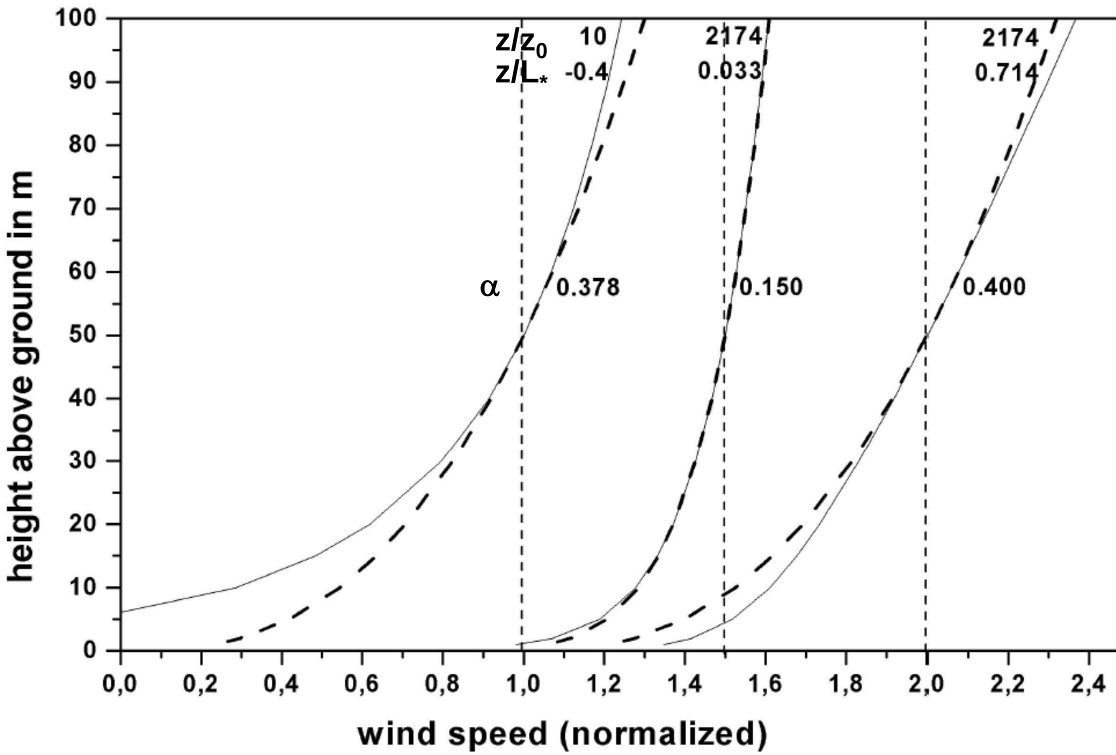
boundary-layer meteorology is mandatory in resource assessment

vertical wind profiles

"power law" versus
"logarithmic wind profile"

i.e. empirical relation versus
theoretical relation

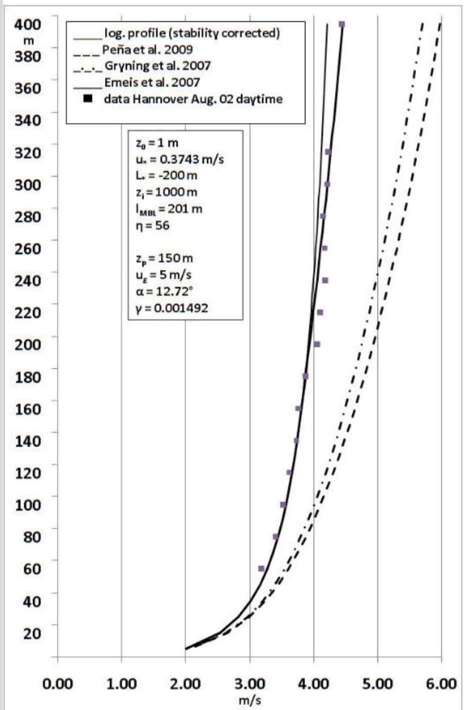
DEWI Magazine 2005

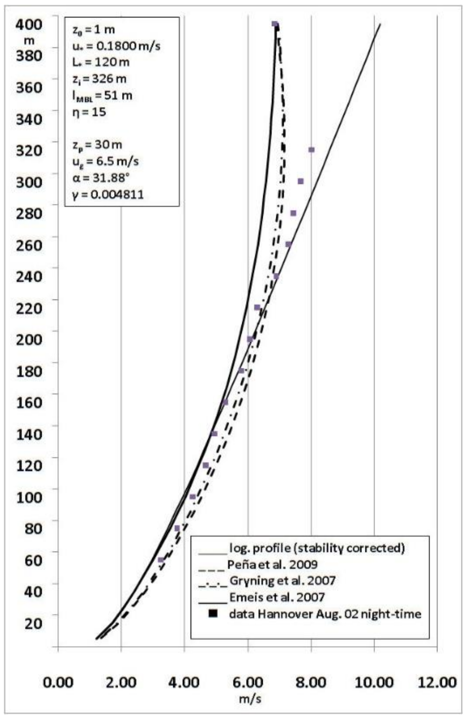


i.e. one parameter (Hellmann exponent) versus at least three parameters (roughness length, friction velocity, atmospheric stability)

insight 3

vertical wind profiles





different approaches:

- logarithmic profile (formally limited to about 80 m above ground)

- power law (empirically, exponent is roughness and stability dependent)

- potential flow (empirically, no formal limitations)

- combined profiles which consider the Ekman layer as well

measurements necessary, wind lidars, complex terrain is challenging

insight 4

boundary-layer meteorology is mandatory in resource assessment

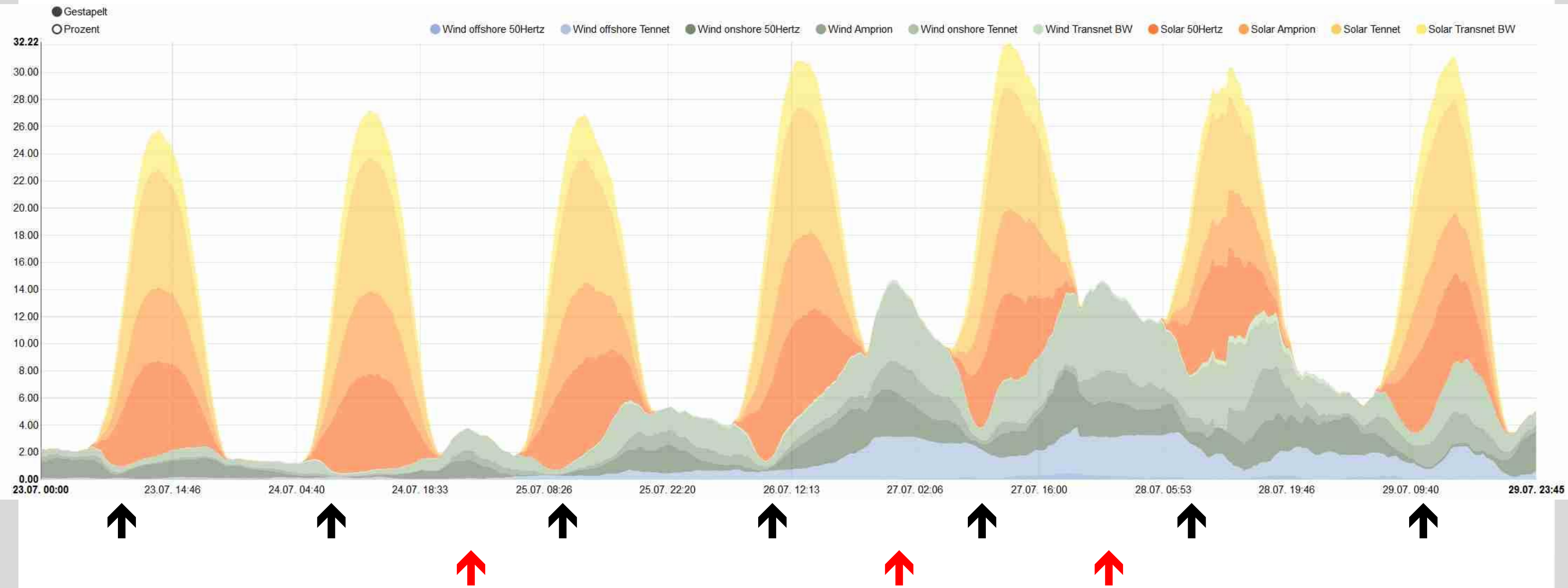
atmospheric thermal stability

“growing” wind turbines “leave” the surface layer (Prandtl layer)

- **stability effects become larger,**
- **turning of wind directions becomes an issue,**
- **low-level jets shift maximum yield towards night-time**

insight 4

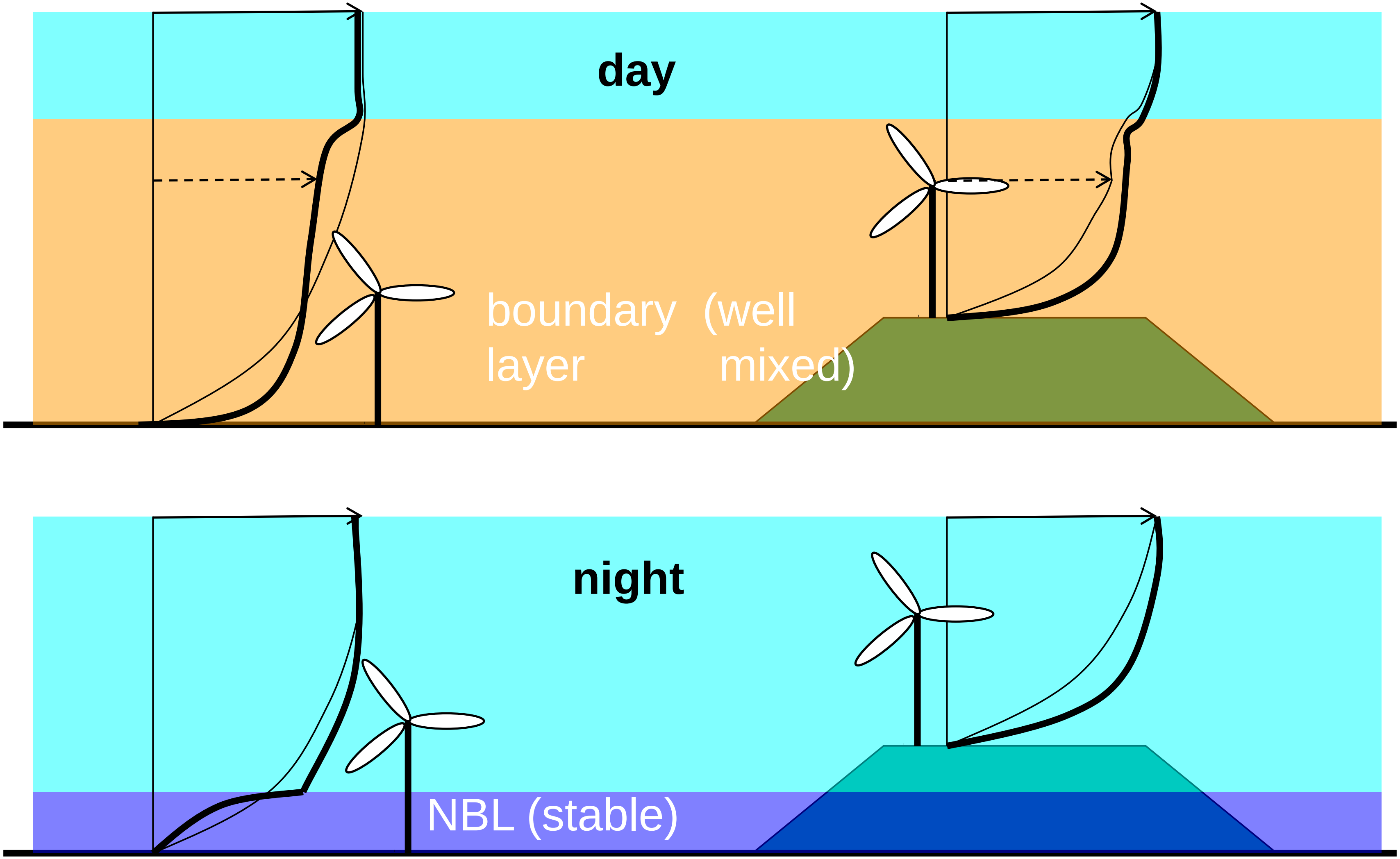
Low-level jets, morning “dip”



Wind energy (green and light blue) and solar (orange) yield in Germany
23 July 2018 to 29 July 2018 (https://www.energy-charts.de/power_de.htm)

insight 4

vertikal wind profiles **(graph from a talk in 2004)**



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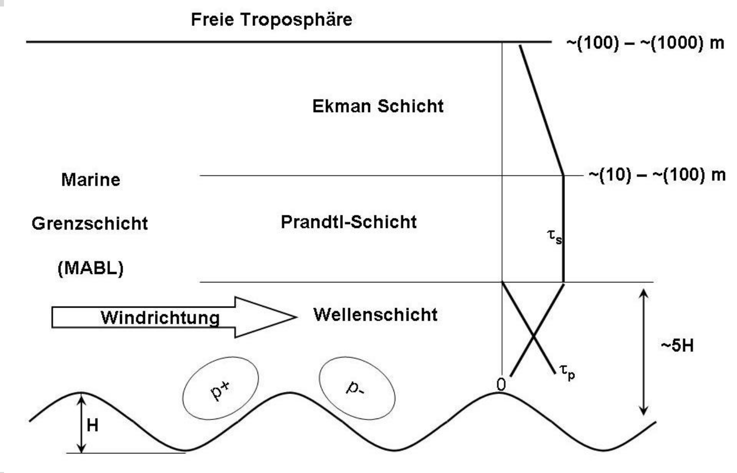
insight 5

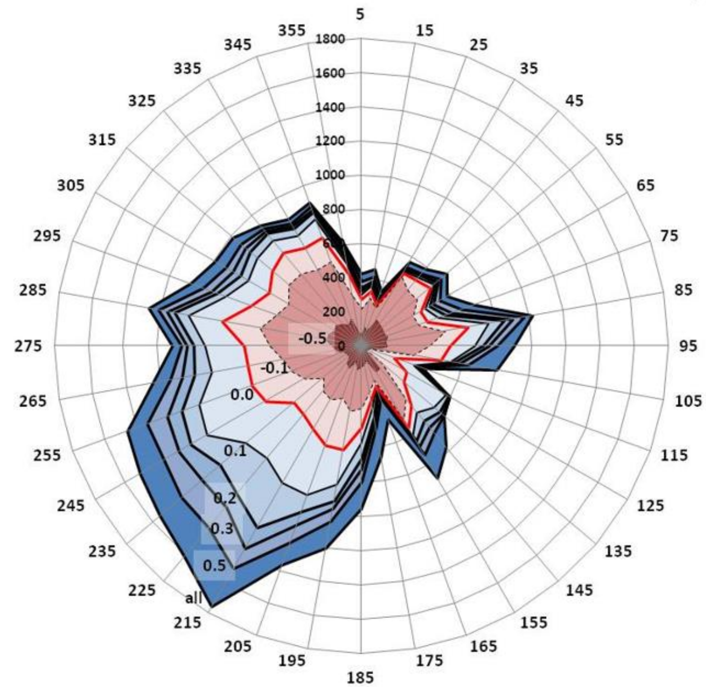
offshore boundary-layer meteorology is different

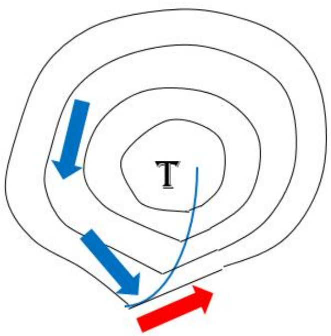
no diurnal variation

shallower Prandtl layer

correlation between wind direction and stability







FINO 1 data from 2005 (60 m asl)

insight 6

boundary-layer meteorology is mandatory in resource assessment

complex terrain requires deviations from simple boundary-layer laws

- speed-up over hills

- deformed vertical profiles

- problems in sodar and lidar measurements in complex terrain

- WAsP doesn’t work any longer ➔ NEWA

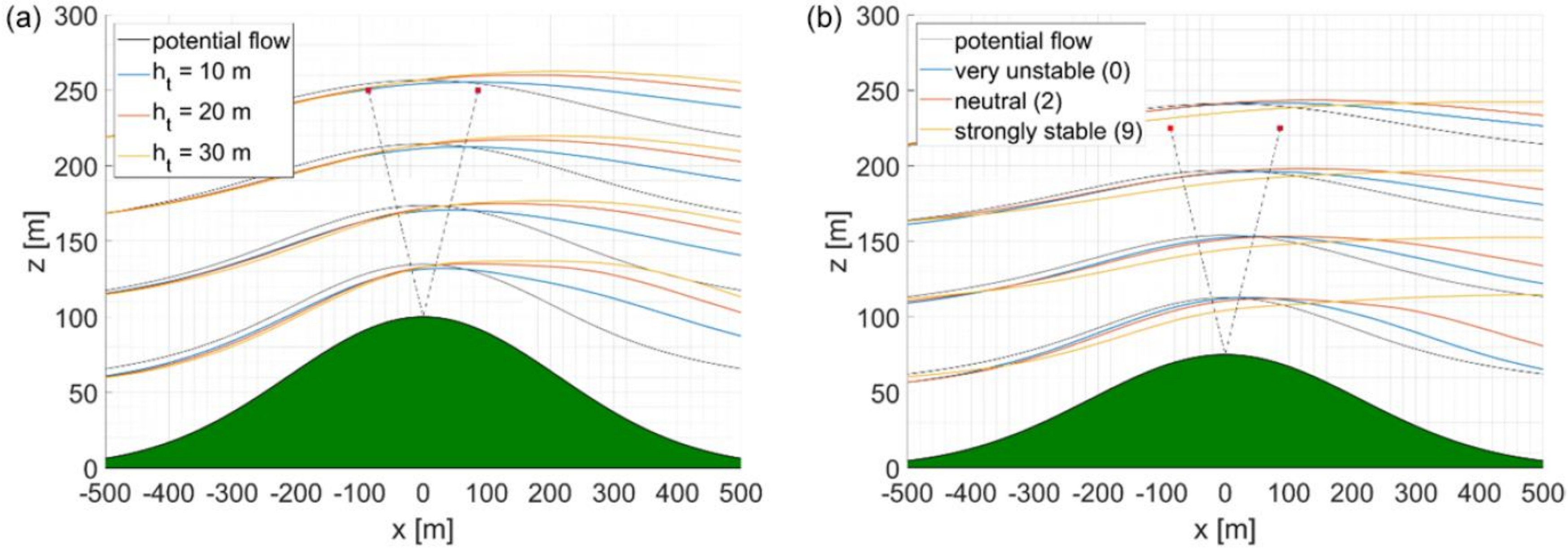
insight 6

complex terrain requires deviations from simple boundary-layer laws

speed-up over hills, deformed vertical profiles

PhD work of
Tobias Klaas-Witt
Fraunhofer IEE, Kassel

Klaas-Witt and Emeis (2022), Wind Energy Science 7, 413-431



wooded hills | **changing stability**

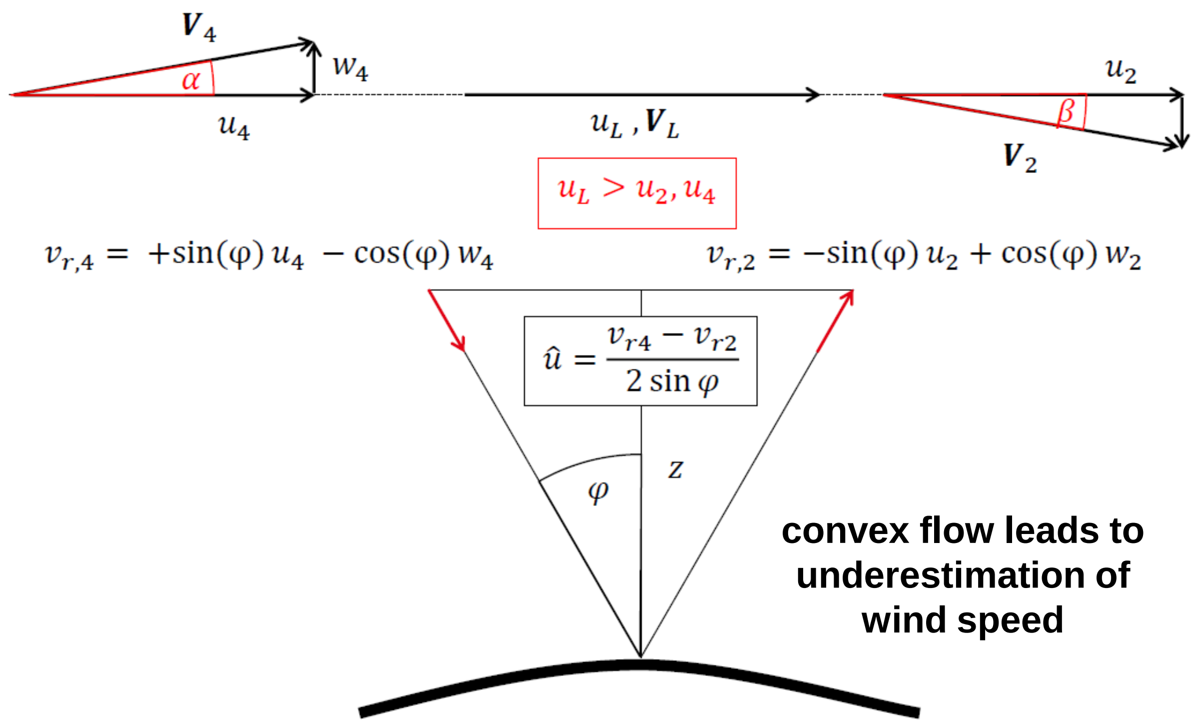
insight 6

remote sensing in complex terrain

PhD work of
Tobias Klaas-Witt
Fraunhofer IEE, Kassel

Klaas-Witt and Emeis (2022), Wind Energy Science 7, 413-431

Partition of lidar error in two contributions



convex flow leads to underestimation of wind speed

definition of lidar error

$$\varepsilon = \frac{\hat{u} - u_L}{u_L} = \varepsilon_c + \varepsilon_s$$

lidar error due to streamline curvature

$$\varepsilon_c = -\frac{\tan\frac{\alpha - \beta}{2}}{\tan\varphi}$$

lidar error due to speed-up

$$\varepsilon_s = \frac{u_4 + u_2}{2u_L} - 1$$

insight 6

remote sensing in complex terrain

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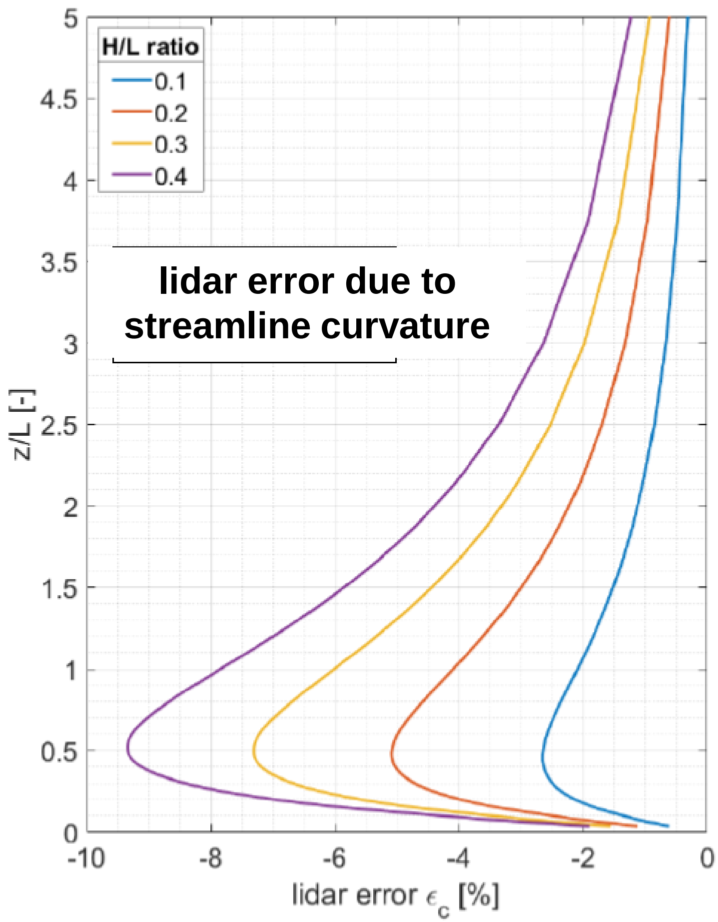
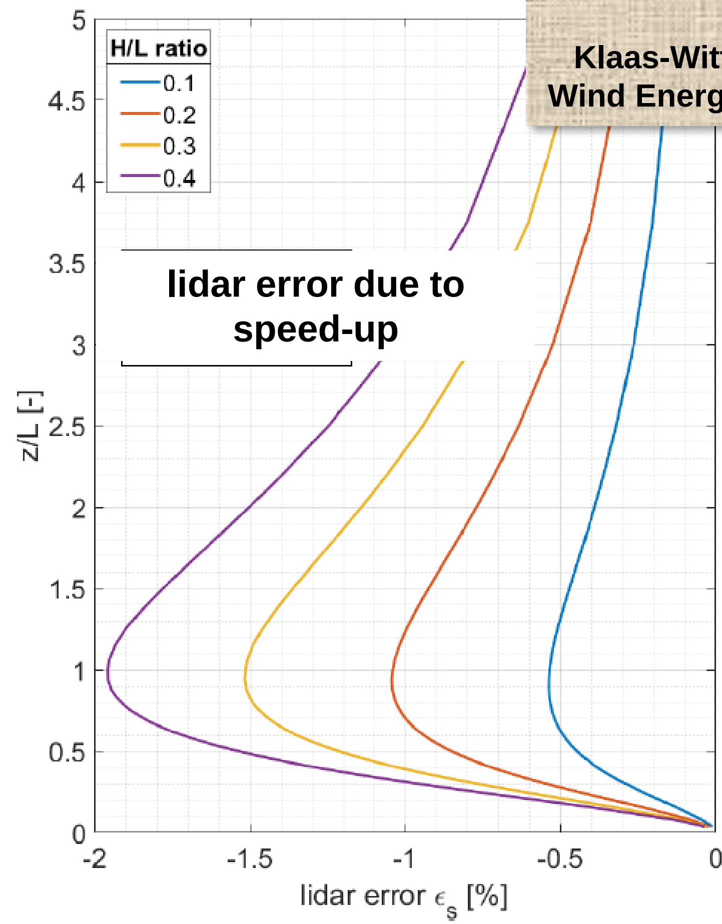




20% von ε

10% von ε

insight 7

boundary-layer meteorology is mandatory in resource assessment

Wakes become more and more important

- turbine wakes

- farm efficiency and farm wakes

- cluster efficiency and cluster wakes

top-down models give first guess on efficiency and wake lengths (EFFWAKE)

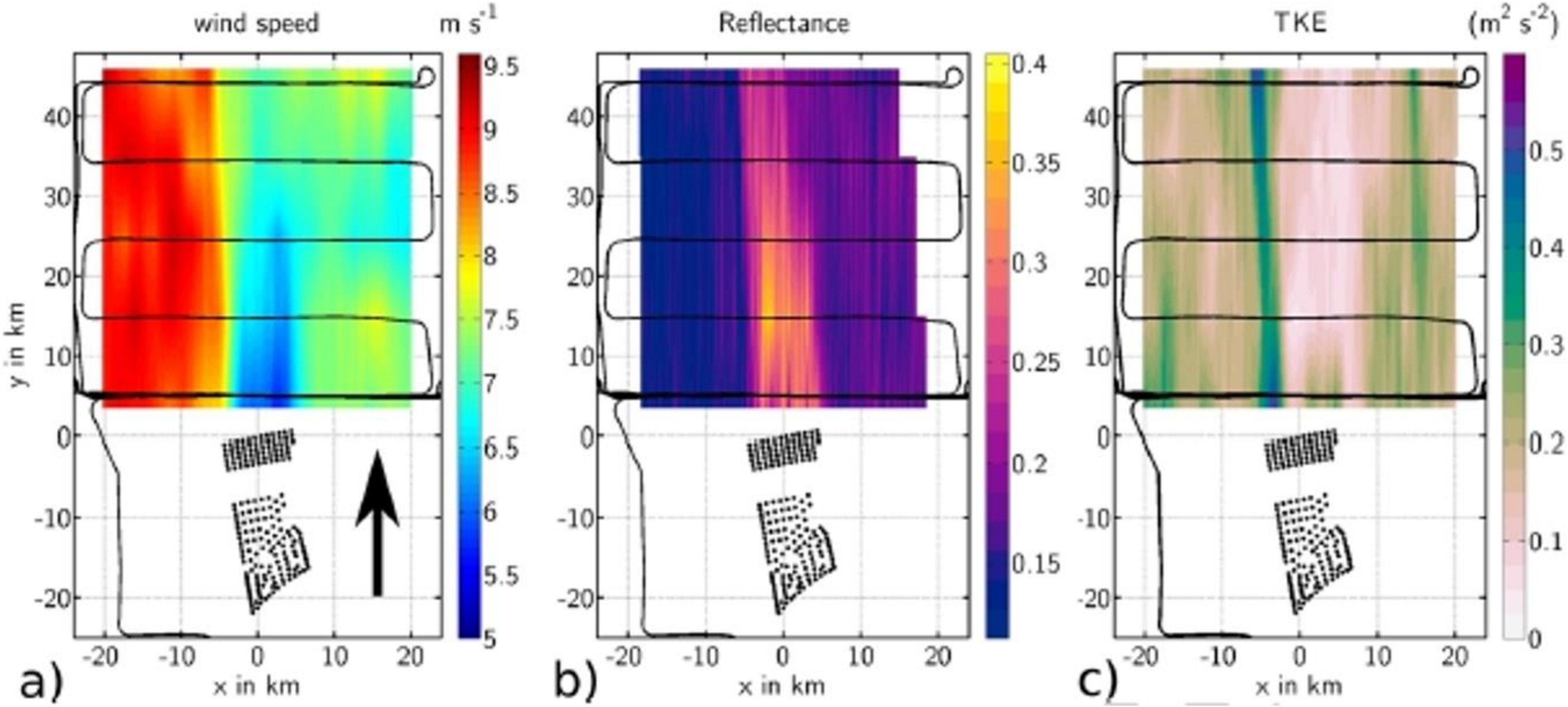
wake length and strength depends on

- atmospheric stability
- surface roughness

WIPAFF
X-Wakes

insight 7

Farm wakes

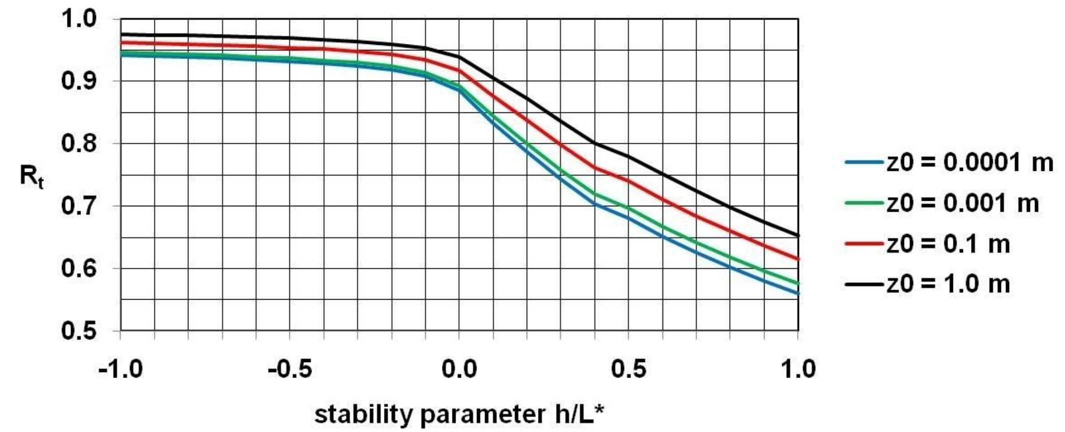


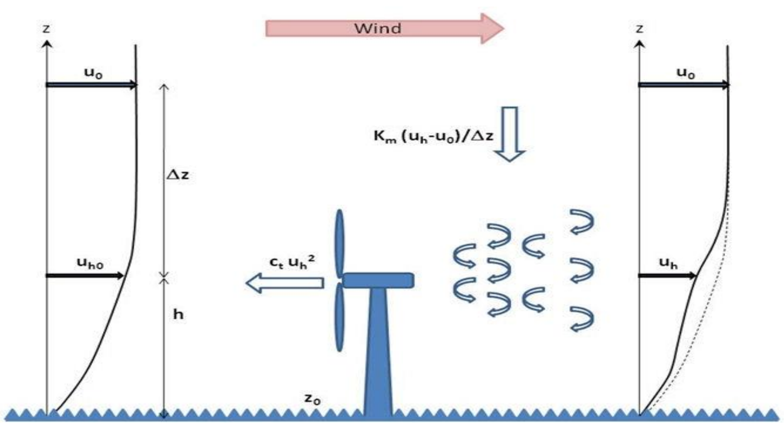
Platis et al., 2018: Scientific Reports, 8, 2163. DOI:10.1038/s41598-018-20389-y

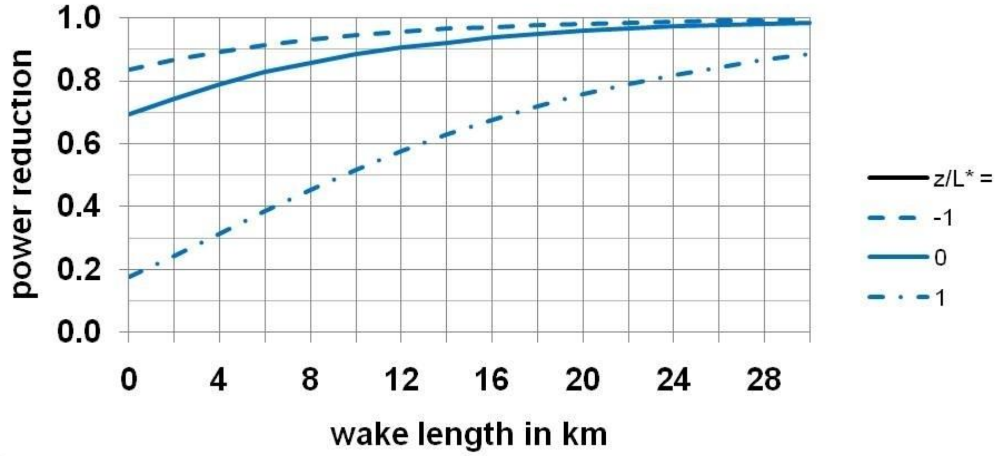
Tools 1

Analytical farm model EFFWAKE for farm efficiency and wake length

simple analytical model for indefinitely large wind farms, based on the equilibrium between momentum uptake and delivery by vertical turbulent fluxes







foresight 1

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wind turbines get larger and larger

➔ meteorological assessment gets more complicated

➔ in-situ wind measurements become unavailable

➔ remote sensing becomes the only option for measurements

➔ numerical models get more important

Tools 2

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Large turbine estimator LATURE

simple analytical model for estimating full load hours and AEP

Windkraftanlagen - ein einfaches Tool zur Abschätzung der AEP und der der Zahl der Volllaststunden [Version 2, 15. Febr. 2022]						Pi		3,142	
Angaben zur Turbine									
Nabenhöhe (in Vielfachen von 50)	150	m		Beiwert	15954,5807	kgm²/s³	(90% des Betzschen Limits)		
Rotordurchmesser	250	m	==>	Rotorfläche	49087,385	m²	Windpotential bei Nennge	31,845	MW
spez. Leistung pro Rotorflächeneinheit	346	W/m²	==>	Nennleistung	16,984	MW	Betz' Limit	18,871	MW
			==>	Nenngeschw.	10,211	m/s	realistisch	16,984	MW
Angaben zum Windklima									
Exponent des Potenzgesetzes	0,14	-							
Weibull - Formfaktor	2,5	-							
Referenzgeschw. in 100 m Höhe	5	m/s	==>	Wind in Nabenhöhe	5,292	m/s			
Angaben zum Standort									
Höhe über NN	0	m	==>	Luftdichte	1,2188	kg/m³			
Jahresmitteltemperatur	12	°C							
Ergebnis									
Volllaststunden	1862,71	h							
Gesamtertrag pro Jahr	31636,77	MWh							

Tools 2

Large turbine estimator LATURE

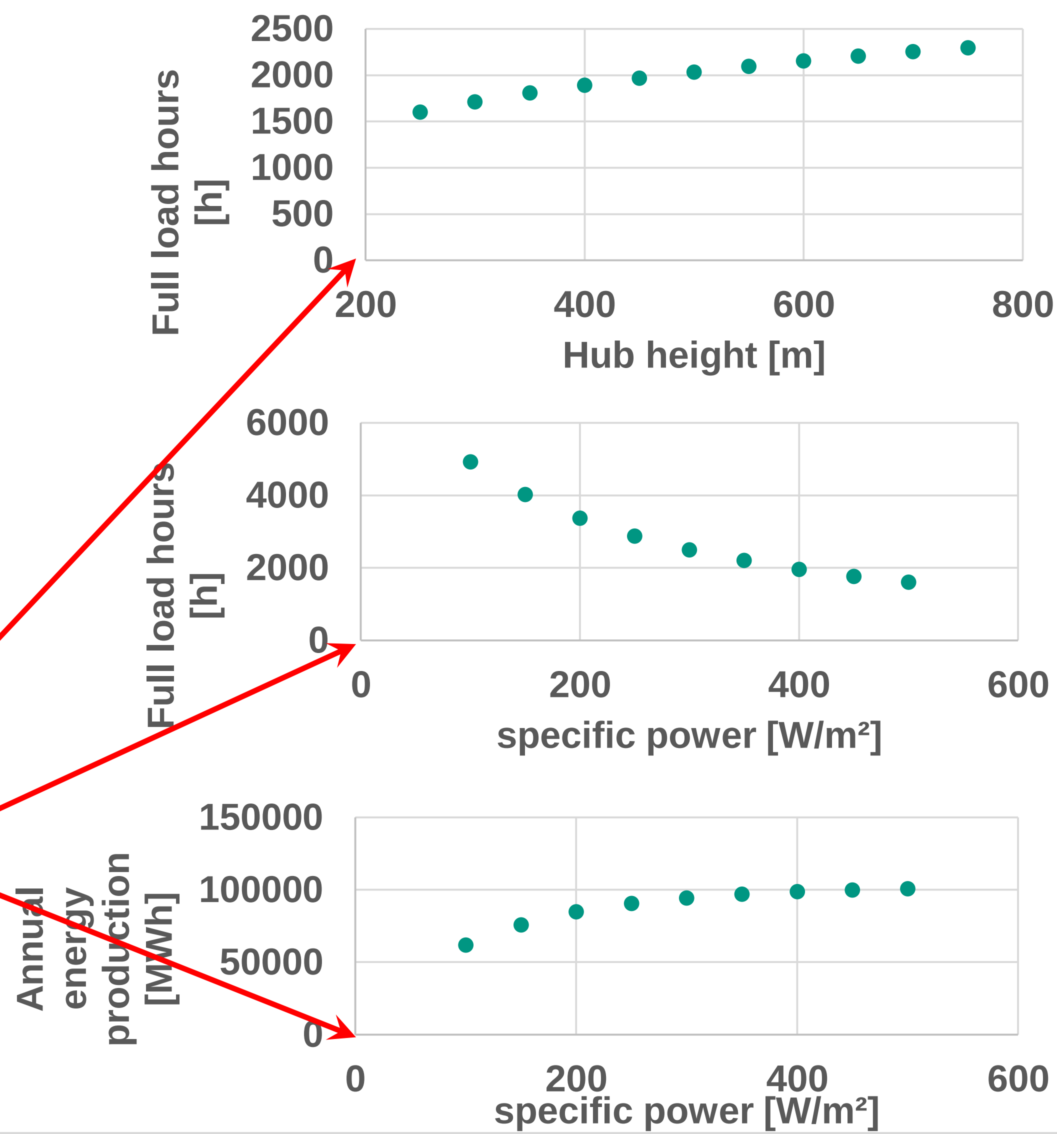
simple analytical model for estimating full load hours and AEP

eight parameters

alpha = 0.14
u_100m = 5 m/s
Weibull_Form = 2.5

Rotor_diam = 400 m
Hub_height = 250 m
spec. power = 500 W/m²

height asl = 0 m
temperature = 12°C



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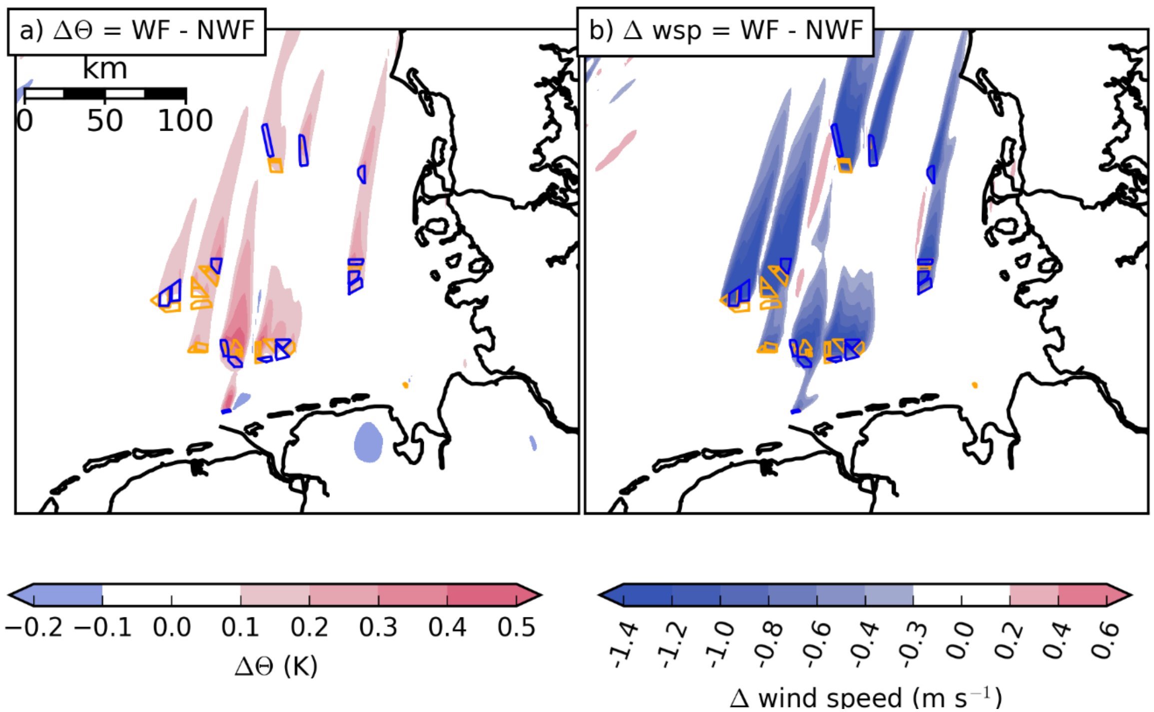
foresight 2

wind farms get larger (especially offshore)

➔ more and stronger wakes

➔ global blockage at the upwind side of wind farms becomes more important

➔ wind farm – atmos. boundary-layer interaction becomes more complex



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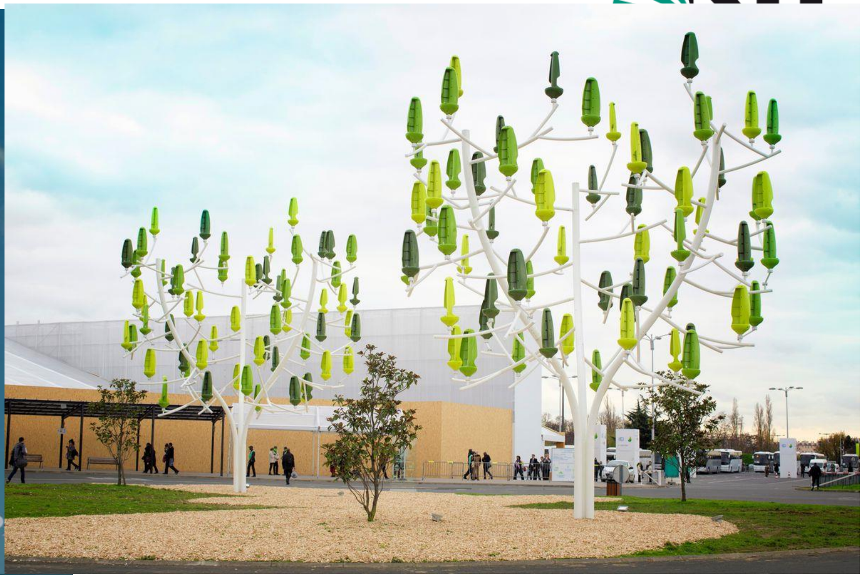
foresight 3

Source: https://www.voanews.com/a/tiny-wind-turbines-offer-sustainable-urban-alternative-to-large-fans/4622403.html

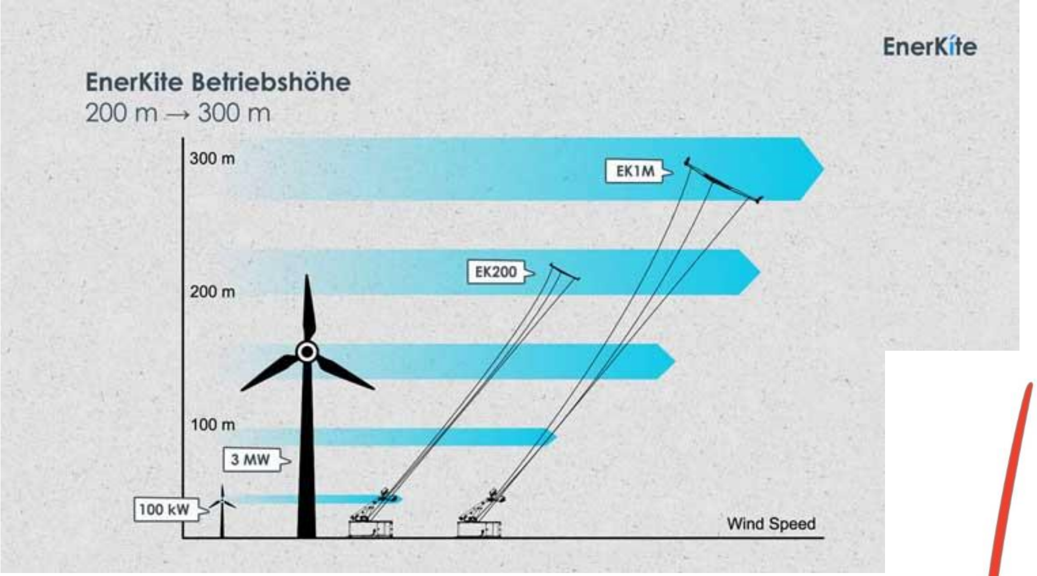


Source: https://www.curbed.com/2017/3/14/14914302/wind-tree-turbine-for-sale

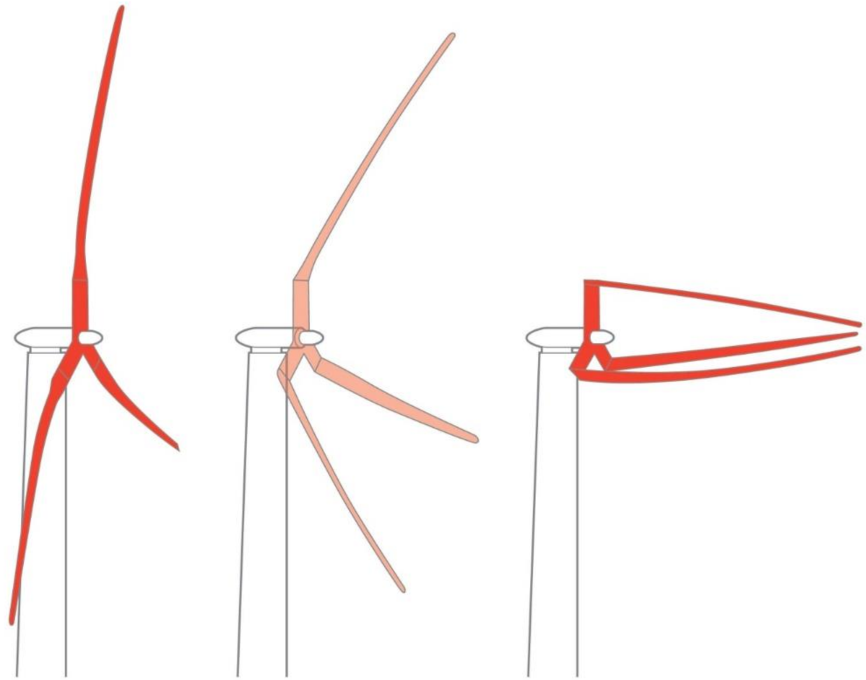
source: http://wind-energy.ucoz.com/

Source: http://news.mit.edu/2014/high-flying-turbine-produces-more-power-0515

foresight 4

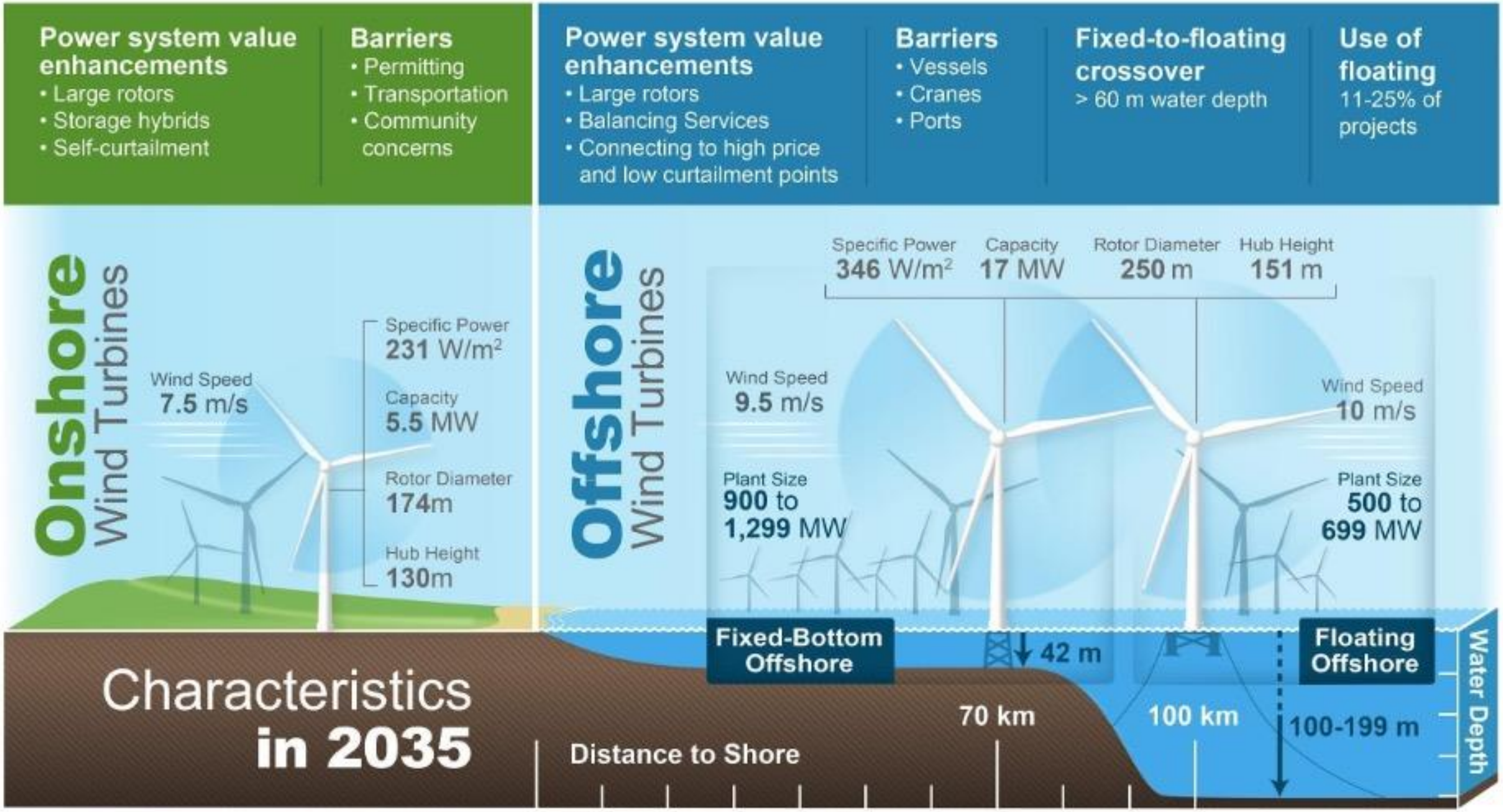


Source: www.enerkite.de



Source: https://share.sandia.gov/news/resources/news_releases/big_blades/#.VrNDfE0wcQ8

foresight 5



https://energycentral.com/sites/default/files/users/211372/on%20off%20diagream.jpg

There’s a lot ahead of you

mit freundlicher Genehmigung des Künstlers

Erik Liebermann

WindForS Wind Energy Research Alliance

KIT Karlsruhe Institute of Technology

Thank you for your attention

mit freundlicher Genehmigung des Künstlers

Erik Liebermann

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