Meteorological aspects of wind energy conversion

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Some wind energy-relevant meteorological aspects

modern observational techniques (wind, turbulence and temperature profiles)

low-level jets (nocturnal boundary-layer wind maxima)

flow over complex terrain (description – simulation – measurement)

marine boundary layer (offshore wind farms)

wind farms, onshore and offshore (analytical model for yields and wakes)

modern observational techniques
ground-based remote sensing devices at IMK-IFU

**SODAR, acoustic**
Doppler analysis ➔ wind, turbulence

**SODAR-RASS (Doppler-RASS), acoustic,**
electro-magnetic backscatter, ➔ sound speed
➔ wind and temperature profiles

**Ceilometer,**
optical pulses, wave length
~ 0.9 µm ➔ aerosol profiles, mixed-layer height, clouds

**Wind-LIDAR,** optical backscatter, Doppler analysis,
wave length ~ 1.5 µm ➔ wind and aerosol profiles
Doppler beam swinging technique (DBS)

remote sensing technique for the 3D wind vector

horizontal homogeneity of the wind field assumed
valley:
vertical component adds to horizontal component

→ SODAR/LIDAR measures too much wind

hill top:
vertical component reduces horizontal component

→ SODAR/LIDAR measures less wind

→ in either case: correction needed
Summary – remote sensing

advantages
- cheaper measurements for great hub heights
- full profile information
- instrumentation is more movable than instrumented masts
- delivers volume-averaged information (more suitable for wind energy)

disadvantages
- assumption of horizontal homogeneity is not fulfilled in complex terrain ➔ correction needed
- data quality may depend on atmospheric conditions
- verification/validation of measurements is still discussed
- not easily comparable to point measurements (e.g., cup anemometers)
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low-level jets
Sodar observation of a low-level jet
vertical wind profiles (30 min mean)

26 June 2005, 00 – 02:30 CET

23-30 June 2005
daytime

well-mixed boundary layer

night

stable boundary layer
sea-level pressure
00 GMT

26 June 2005

asterisk:
observation site
frequency of LLJ over Hannover for 20 months in the years 2001 to 2003
roughly 22% of all nights

over Augsburg in the years 2008-2010, 2014
roughly 17.5% of all nights

Circulation types:

BM bridge Central Europe
HB high Brit. Isles
HM high Central Europe
...
HFA/HFZ high Scandinavia
HNFA high Northern Atlantic
...
Critical Richardson number is limiting condition for vertical shear

(mechanical turbulence is generated if Ri falls below Ri_{krit})

\[
Ri_{krit} = \frac{g \partial \Theta / \partial z}{\Theta (\partial u / \partial z)^2} \approx 0.25
\]

\(\Theta (z)\) potential temperature
\(g\) gravitational acceleration
\(u (z)\) wind speed
\(z\) vertical coordinate
RASS observations Augsburg

Richardson number during LLJ events

![Graph showing Richardson number during LLJ events](image)
maximum possible shear for a given $Ri_{krit} = 0.25$

\[ Ri_{krit} = \frac{g \frac{\partial \Theta}{\partial z}}{\Theta \left( \frac{\partial u}{\partial z} \right)^2} \approx 0.25 \]
Summary – low-level jets

climatology
- LLJ in 17 - 21% of all nights
- core height between 135 and 650 m
- core wind speed between 7 and 23 m/s

correlation with driving forces
- LLJ form for 850 hPa wind speeds between 1 and 18 m/s
- LLJ core speed positively correlated with 850 hPa wind speed (maximum at 13 m/s)
- LLJ core speed slightly negatively correlated with 850 hPa relative humidity

shear
- shear is limited by critical Richardson number

impact on wind turbines
- shear over the rotor plane is about 0.04 to 0.08 1/s during LLJ events
- directional shear is about 0.1 to 0.2 degrees/m
flow over complex terrain (description – simulation – measurement)
speed-up over a hill (analytical – potential flow - model)
speed-up over a hill (analytical model)

as function of thermal stability

dotted: stable
full: neutral
dashed: unstable
speed-up over a hill
Weibull-Parameter over a crest

Weibull scale parameter
\( (A_0 = 10.67 \text{ m/s}, \gamma = 0.035) \)

\[
A(z) = A_0 \left(1 - e^{-\gamma z}\right)
\]

Weibull form parameter
\( (z_A = 10 \text{ m}, z_m = 50 \text{ m}, c_2 = 0.01) \)

\[
k(z) - k_A = c_2 (z - z_A) \exp \left(-\frac{z - z_A}{z_m - z_A}\right)
\]

Wieringa (1988)
flat terrain

hill top

scale parameter

form parameter
Summary – complex terrain

wind speed
- speed-up over hill tops
- strong horizontal gradients in wind speed characteristics *(remote sensing needs corrections)*

vertical profiles
- maximum is reached at lower heights over hill tops

shear
- shear is lower in greater heights but higher close to the ground over hill tops

impact on wind turbines
- large turbines experience less shear over hill tops
- increase in hub heights give less benefits
- wind assessment much more difficult than over flat terrain
marine boundary layer (offshore winds)
vertical structure of boundary layer is different

turbulence intensity depends on wind speed

Hellmann exponent depends
on wind speed and thermal stability
offshore:
vertical wind shear depends on the difference between air and water temperature
offshore: wind direction and thermal stability are correlated

data: FINO1, 2005, wind direction at 80 m, stability at 60 m
offshore: Weibull parameter observed at FINO1
offshore: vertical gradient in humidity $\Rightarrow$ less stability
(FINO1 41.5 m data for turbulent heat and humidity fluxes)
Summary – offshore

wind/turbulence
- higher wind speeds – less turbulence
- no diurnal variation but seasonal variation

shear
- depends on temperature difference between air and water

thermal stability
- coupled (highest wind speeds with stable stratification)

humidity
- humidity usually decreases with height ➔ less stable stratification

impact on wind turbines
- higher yields
- less loads
- longer wakes
wind farms, onshore and offshore


simple analytic wind farm model
power reduction in wind farms

- mean distance between turbines: 10 rotor diameter
  - turbine-induced turbulence 10.1%

- mean distance between turbines: 8 rotor diameter
  - turbine-induced turbulence 12.6%

- mean distance between turbines: 6 rotor diameter
  - turbine-induced turbulence 16.8%
observed reduction in wind power
Nysted wind farm (Baltic Sea)

wind farm wake length, mean distance between turbines: 8 rotor diameter

roughness: onshore \((z_0 = 1.0 \text{ m})\) – offshore \((z_0 = 0.0001 \text{ m})\)

stability: unstable \((h/L_* = -1)\) – neutral – stable \((h/L_* = 1)\)
SAR image of Horns Rev wind farm (4 km x 5 km)

- Wind farm
- Wind
- ~20 km

Horns Rev

Blævandshuk

Esbjerg

http://www.hornsrev.dk/nyheder/brochure/Horns_Rev_TY.pdf

25. 02. 2003

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http://galathea3.emu.dk/satelliteeye/projekter/wind/back_-uk.html
Summary – wind farms

farm yield
- strong dependence on atmospheric stability,
- dependence on surface roughness,
- dependence on mean distance of turbines

farm wake lengths
- strong dependence on atmospheric stability
- dependence on surface roughness

impact on offshore wind farms (compared to onshore farms)
- turbines need to have larger spacing in offshore farms
- offshore farms needs to have larger spacing between each other
coming next in this session
Thorsten Beuth, Camille Porcher, Leilei Shinhoara: Redesign of wind turbines based on LiDAR technology, is it worth it? – A discussion based on a simple model for the tower’s initial costs.
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Thank you very much for your attention
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Wind Energy Meteorology

Atmospheric Physics for Wind Power Generation

- First book devoted solely to the meteorological basics of wind power generation
- Presents the meteorological basics for large wind turbines and wind parks
- Gives guidance to plan offshore wind parks

This book is intended to give an introduction into the meteorological boundary conditions for power generation from the wind, onshore and offshore. It is to provide reliable meteorological information for the planning and running of this important kind of renewable energy. This includes the derivation of wind laws and wind profile descriptions, especially those above the logarithmic surface layer. Winds over complex terrain and nocturnal low-level jets are considered as well. A special chapter is devoted to the efficiency of large wind parks and their wakes.

2013, 2013, XIV, 196 p. 94 illus., 16 in color.

Printed book

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