Observational Needs for Wind Resource Assessment and Forecasting

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American Meteorological Society
Short Course on Wind Energy
August 1, 2010

How much of U.S. power did wind provide in 2009?

A. 0.9 %
B. 1.8 %
C. 2.7%
D. 3.6 %

Why are meteorological observations taken at wind farms?

A. **Resource assessment** to quantify project viability

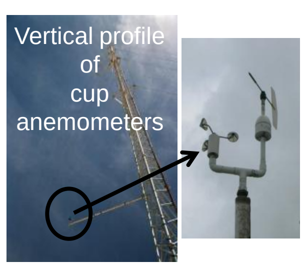
B. **Power performance** verification of turbines

C. Atmospheric science **research**

D. Assimilation into numerical models for wind and power **forecasting**

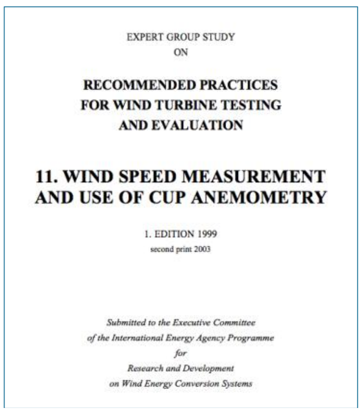
Today's discussion

- Current observational standards
- Research suggesting an expansion of those standards



To finance a wind farm, bankers require adherence to accepted standards codified in guidelines

- International Energy Agency (IEA)
- International Electrotechnical Commision (IEC)



These standards specify:

- How met towers may be installed
- Which type of terrain over which they are considered representative
- What measurements should be taken with which instruments: cup anemometers shall be used to measured wind speed and atmospheric turbulence (turbulence intensity)
  - Later investigations specify what kind of cup anemometers may be used, due to issues of angular response, dynamic effects and bearing friction characteristics
- Little comment on measurements other than wind

Subsequent Risø report delineates "classes" of cup anemometers based on wind tunnel tests of cup anemometers

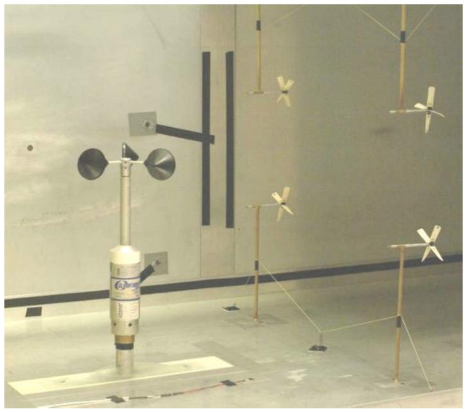


Figure 3-7 A typical setup of the anemometer and the four propeller anemometers in the LT5 wind tunnel. The wind is blowing from right to left. The upper propellers are labelled p2 and p3 from left to right and the lower propellers are labelled p4 and p5 from left to right.

Risø-R-1555(EN)

ACCUWIND - Methods for Classification of Cup Anemometers

J.-Å. Dahlberg, T.F. Pedersen, Peter Busche

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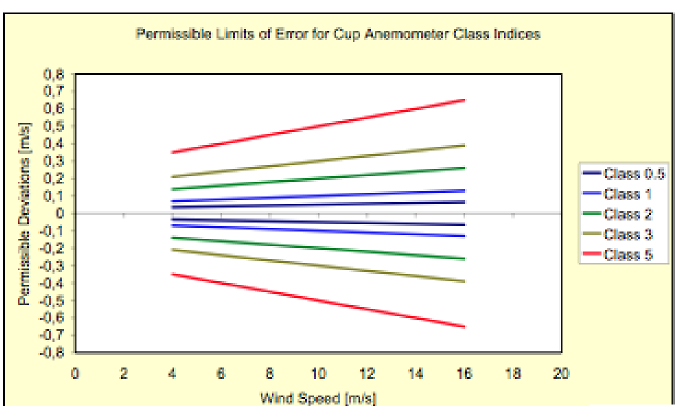

Figure 2-2, IEC61400-12-1 classification class index examples

Deviations arise from:
- turbulence intensity,
- turbulence structure,
- air temperature,
- air density, and
- flow inclination angle

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Assuming ***U=(u,v,w)***, should the cup measure:

A. The horizontal wind speed vector

$$U_{hor} = \frac{1}{T}\int_t \sqrt{u^2 + v^2}\,dt$$

B. The total wind speed vector

$$U_{vec} = \frac{1}{T}\int_t \sqrt{u^2 + v^2 + w^2}\,dt$$

What about the atmosphere and the terrain surrounding the cup?

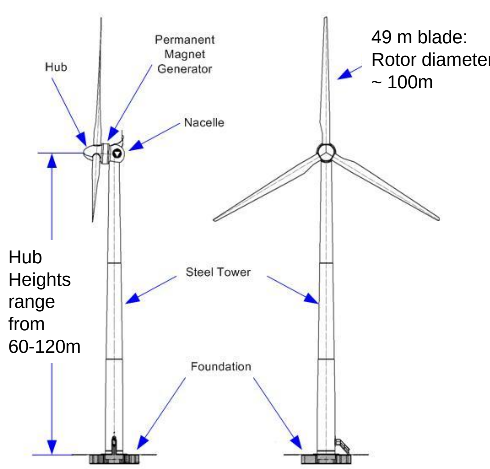
- Class A: "ideal" terrain: flat, little atmospheric turbulence or density variations; flow inclination angle +/- 3 degrees
- Class B: "complex" terrain; flow inclination angle +/- 15 degrees

What do you think is missing from the standard?

- Brainstorming time!

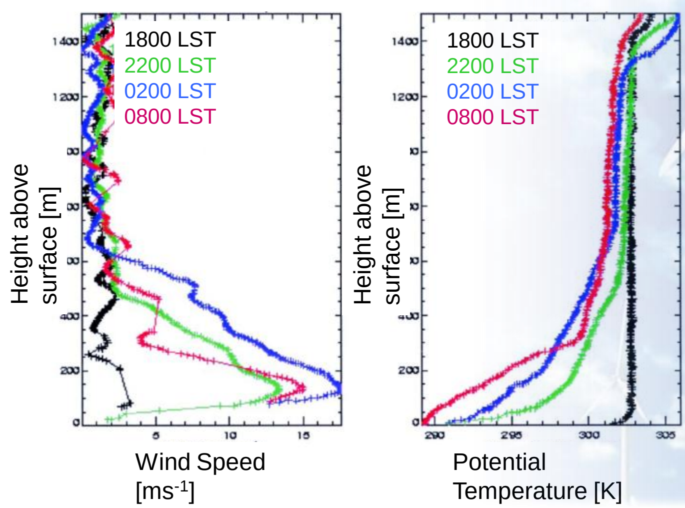
Modern wind turbines span heights ~ 200m, penetrating a complex atmosphere

Siemens 3.0 MW turbine



The diurnal cycle of atmospheric stability strongly influences winds in the turbine rotor disk

Radiosonde profiles demonstrate that the cooling of the surface overnight is accompanied by dramatic accelerations in the winds



Poulos, Blumen, Fritts, Lundquist, et al., 2002

How do meteorologists quantify atmospheric stability?

- Compare buoyancy forces to shear/mechanical forces
- Richardson Number:

$$Ri_{bulk} = \frac{g \Delta \overline{\theta}_v \Delta z}{\overline{\theta}_v \left[\left(\Delta \overline{U} \right)^2 + \left(\Delta \overline{V} \right)^2 \right]}$$

- Monin-Obukhov Length

$$L = \frac{-\theta_v u_*^3}{k g \left(\overline{w' \theta_v'} \right)}$$

g :	Gravity
k :	Von Karman constant, ~ 0.4
z :	Height
U :	West → East wind speed
V :	South → North wind speed
θ_v :	Temperature corrected for pressure and moisture
u_* :	Friction velocity, vertical flux of horizontal momentum
$\overline{w'\theta_v'}$:	Vertical flux of heat

Today's discussion

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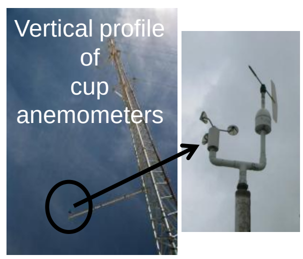
- **Research suggesting an expansion of those standards**



Thinking outside of the cup: turbine response modeling studies indicate the entire rotor disk is critical

- Antoniou et al., EWEC 2007: "Influence of wind characteristics on turbine performance"
- Sathe and Bierbooms 2007 *J. Phys.: Conf. Ser.* **75**, "Influence of different wind profiles due to varying atmospheric stability on the fatigue life of wind turbines"
- Antoniou, Pedersen, and Enevoldsen, *Wind Engineering* 2009: "Wind Shear and Uncertainties in Measurement and Wind Resource"

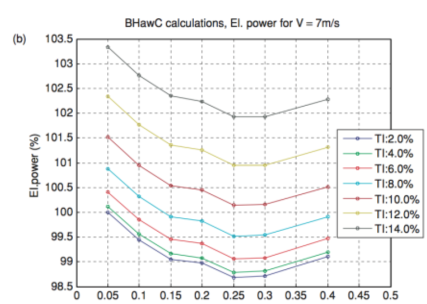


Fig. 1 from Antoniou et al., 2009: the turbine becomes less effective in exploiting additional energy at higher wind shears

Thinking outside of the cup: Accurate resource assessment (and power performance evaluation) should probably include more atmospheric consideration

- Lundquist and Wharton, 2009, *IEA Experts Meeting on SODAR and LIDAR*;
- Wharton, Lundquist, Sharp, Crescenti, and Zulauf, 2009, AGU Fall Meeting;
- Wharton and Lundquist, 2010, in preparation for *Wind Energy*
- LLNL Technical Report, 2010, available at http://atoc.colorado.edu/~jlundqui/wharton_lundquist2010LLNLTR424425.pdf

Widespread impression of wind farm underperformance

- "20% by 2030" depends on sufficient capacity factor, not just installations
- Impression that many US parks underperforming can undermine public perception, financing, etc.
- With support from IRI, we investigate the role of atmospheric variability in one wind farm's performance

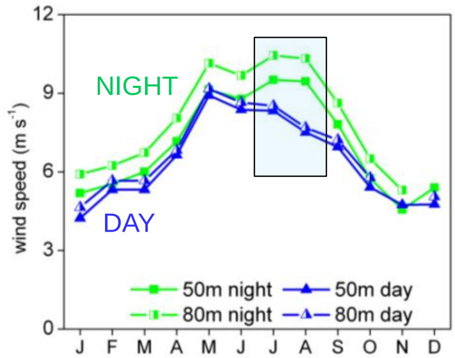
This wind farm provides a unique and valuable dataset

Characteristics:

- Presence of both marine and terrestrial BL over hilly terrain
- Little directional wind shear
- Strongly channeled flow

Large dataset:

- On-site met towers + SODAR
- Turbine power and nacelle wind speeds available
- Four seasons of data; strong seasonality and diurnal signal



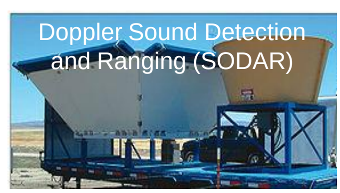
The data surpass those typically available at wind farms

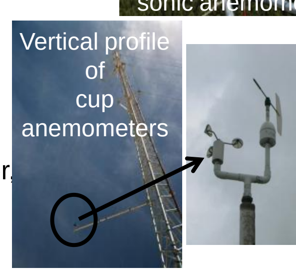
Meteorological data:

- 2 met towers w/ cup anemometers (u, v) at 5 heights (30, 40, 50, 60, 80 m), 10 min. avgs; (T, p measurements unusable)
- SODAR observations (u, v, w) for 19 heights (20 m to 200 m, 10 m resolution), 10 min. avgs.
- Nearby research station with a sonic anemometer (u, v, w, $\overline{w'\theta_v'}$ 30 min. avgs.

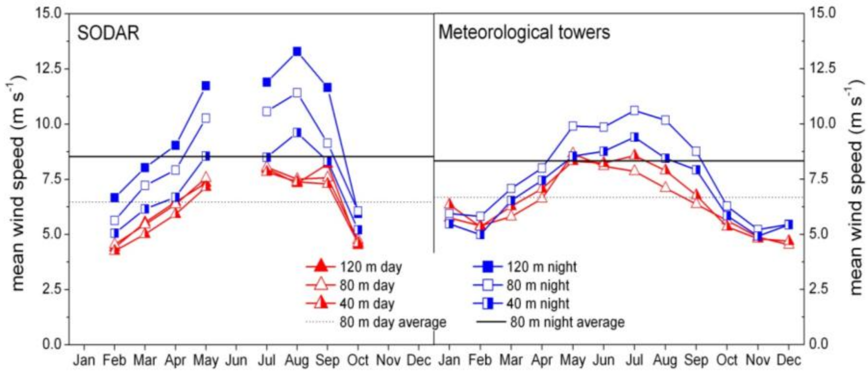
Turbine data:

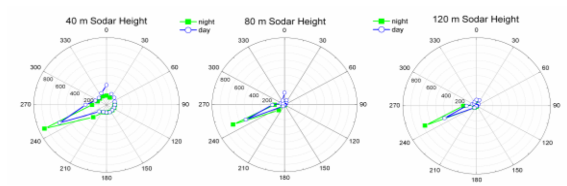
- Leading edge turbines: nacelle U and power, 10 min. avgs, 80m hubs



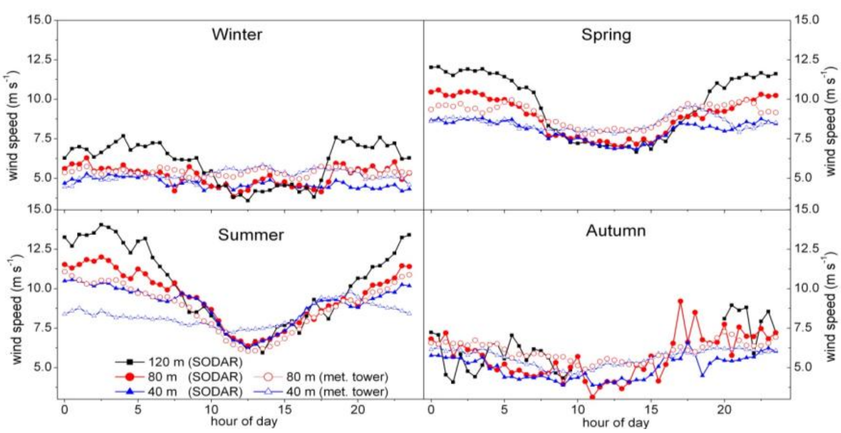


Wind speeds vary with seasons; summer winds exhibit strong wind shear

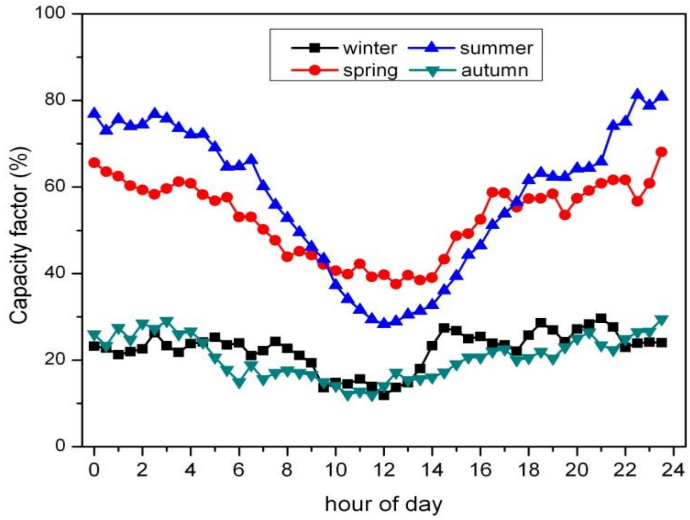




Wind speeds exhibit a strong daily cycle in spring and summer



Seasonal variability in winds is reflected in turbine capacity factor: most power generated on summer/spring nights



How to estimate stability? An off-site research measurement is compared with 3 on-site estimates

(1) Wind shear exponent, α

$$U(z) = U_R(\frac{z}{z_R})^{\alpha}$$

U : mean horz. wind speed at height z or z_R

(2) Turbulence intensity, I_U

$$I_U = \frac{\sigma_U}{U(z)}$$

σ_U : standard dev. of mean horz. wind speed (U) at 80 m

(3) Turbulence kinetic energy, TKE

$$TKE = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

u'^2: variance of wind speed

Obukhov length, L (off-site)

$$L = -\frac{\theta_v \cdot u_*^3}{k \cdot g \cdot \overline{w'\theta_v'}}$$

θ_v : virtual potential temperature
k : von Karman constant
g : gravity
$\overline{w'\theta_v'}$: sensible heat flux
u_* : friction velocity = $(\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$

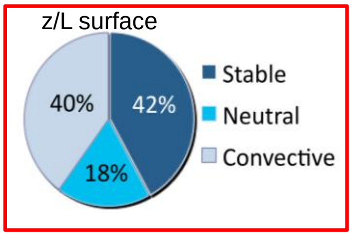
Which quantity exhibited poor agreement with the surface flux (z/L) stability estimate?

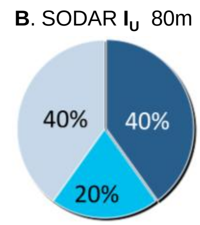
A. Cup anemometer $\mathbf{I_u}$
B. Sodar $\mathbf{I_u}$
C. Sodar α
D. Sodar **TKE**

Which quantity is routinely available at most wind farms?

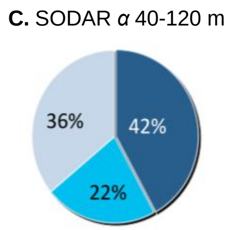
A. Cup anemometer $\mathbf{I_u}$
B. Sodar $\mathbf{I_u}$
C. Sodar α
D. Sodar **TKE**

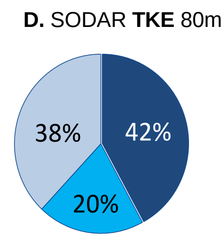
Estimates of stability from a typical cup anemometer fail to agree with more sophisticated measures





The cup anemometer I_u tends to underestimate highly turbulent convective conditions





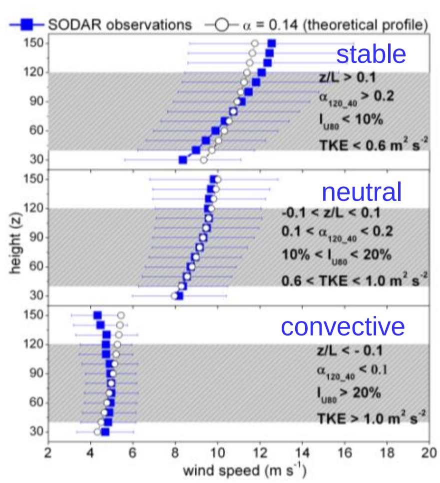
Percentage of summer-time stable, neutral and convective conditions

Stability classes segregate the rotor wind profile

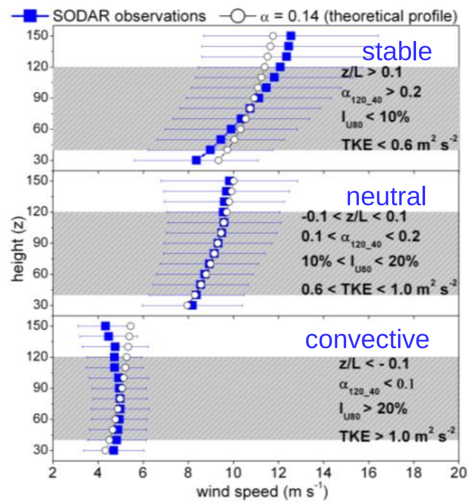
Stable	Neutral	Convective
$z/L > 0.1$	$-0.1 < z/L < 0.1$	$z/L < -0.1$
$\alpha > 0.2$	$0.1 < \alpha < 0.2$	$\alpha < 0.1$
$I_U < 10\%$	$10\% < I_U < 20\%$	$I_U > 20\%$
$TKE < 0.6$	$0.6 < TKE < 1.0$	$TKE > 1.0$

- Stable conditions: high wind shear, low turbulence, and possible nocturnal low-level jets
- Neutral conditions: minimal wind shear
- Convective conditions have lowest wind speeds, very little wind shear in swept-area, and are highly turbulent.

Summer



Hub-height wind speed often fails to represent momentum experienced by the entire rotor disk



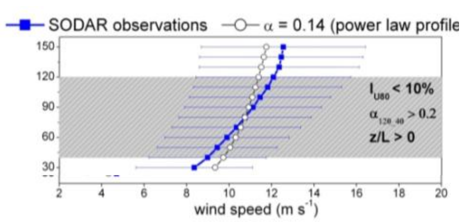
Stable $U_{equivTI} > U_{80m}$

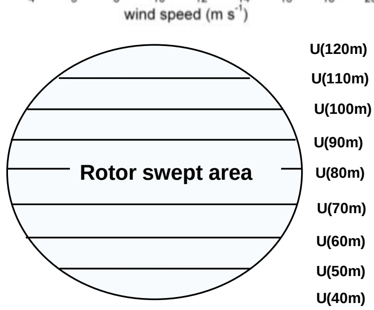
Neutral $U_{equivTI} = U_{80m}$

Convective $U_{equivTI} < U_{80m}$

Hub-height winds are often maximum winds across the rotor disk!

We calculate an “equivalent” wind speed to integrate across rotor disk, because hub-height often fails to indicate the true rotor wind speed





Equivalent wind speed, $U_{equivTI}$

$$U_{equivTI} = \frac{2}{A}\int_{H-r}^{H+r} U_{eff}(z)(r^2 - H^2 + 2Hz - z^2)^{1/2}\,dz$$

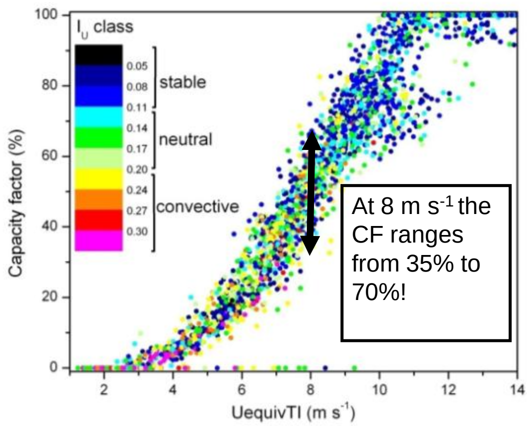
A : rotor area, $U_{eff}(z)$: mean wind speed at height z, r : radius of rotor area, H : hub-height

$U_{eff}(z)$ calculated for each height within the rotor disk:

$$U_{eff}(z) = \sqrt[3]{U(z)^3(1 + 3I_U{}^2)}$$

accounting for the additional energy (turbulence) in the instantaneous wind speed (following Wagner et al. 2009)

A typical summer power curve based on equivalent wind speed still exhibits significant variability



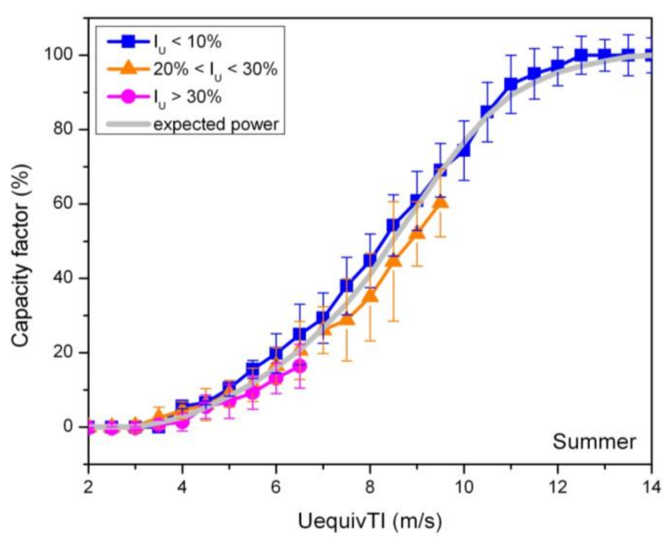
Capacity factor, *CF (%)*

$$CF = \frac{P_{actual}}{P_{rated}} \times 100$$

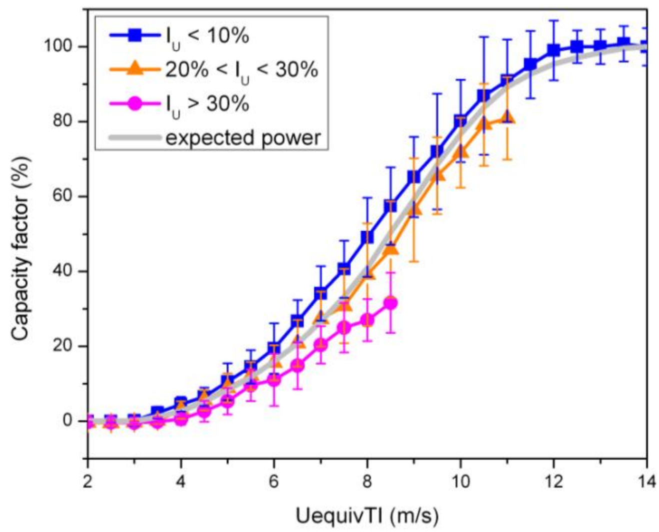
P_{actual} : actual power yield of the individual turbine

P_{rated} : maximum power yield of the turbine as determined by the manufacturer

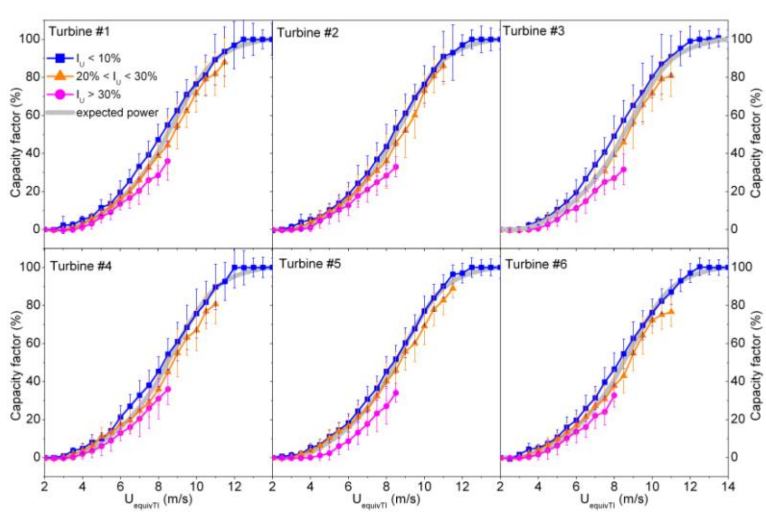
Stratification of power curves reveal stability-related influences on power output



Even stronger variation seen in another leading-edge turbine

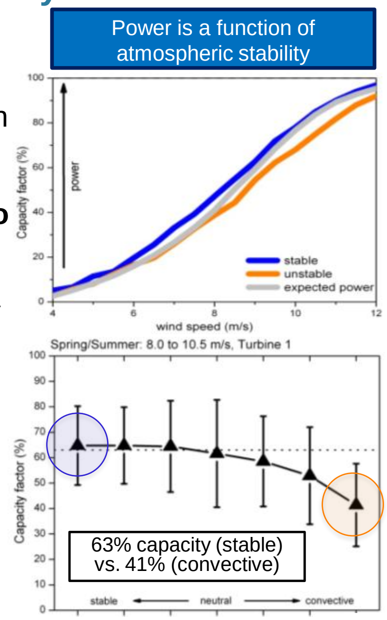


In fact, all leading edge turbines show that power generated is dependent on stability



In summary:

- Atmospheric stability, through the mechanisms of turbulence and wind shear, governs the generation of power at these tall turbines.
- **Power varied by over 20% due to atmospheric stability.**
- “Deficits” in production are actually inaccurate assessments of the available wind speed due to failure to account for variable of wind across rotor disk due to atmospheric stability variations.



Wind farm “underperformance” can in part be explained due to incomplete resource assessment

- Resource assessment **instrumentation should be upgraded**:
  - SODAR stability parameters segregate wind farm data into stable, neutra and convective periods in agreement with research-grade observations
  - Cup anemometer data inaccurately estimate stability regimes
  - SODAR performs poorly during precipitation, however – role for LIDAR?
- Because of complex wind profile shapes, power curves should be a function of wind speed and turbulence over entire rotor disk (*UequivTI*) (as in Wagner et al., 2009)
- Power output correlates well with atmospheric stability:
  - Enhanced turbine performance during stable conditions
  - Reduced turbine performance during convective conditions

Ongoing research activities towards expanding observations at/near wind farms

- IEA Remote Sensing Experts meeting in Oct 2009 at NREL
  - SODAR recommended practices document in preparation (contact Kathleen Moore at iedat.com)
  - LIDAR recommended practices document in preparation (contact Dan Jaynes of Garrad Hassan America)
- DOE/NOAA collaboration on “Short-term Forecasting” (DE-FOA-0000343) to demonstrate value of additional atmospheric observations toward improving wind plant power forecast accuracy; observations to begin in early 2011
- Others that you know of?

Questions?

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